LEARNING MECHANISMS BEHIND THE COST DECLINE OF CRYSTALLINE SILICON (c-Si) SOLAR PHOTOVOLTAIC (PV) MODULES

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF SOCIAL SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

EMEL SEMİZ

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY
IN
THE DEPARTMENT OF SCIENCE AND TECHNOLOGY POLICY STUDIES

FEBRUARY 2023

Approval of the thesis:

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ABSTRACT

LEARNING MECHANISMS BEHIND THE COST DECLINE OF CRYSTALLINE SILICON (c-Si) SOLAR PHOTOVOLTAIC (PV) MODULES

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February 2023, 378 pages

This dissertation aims at understanding different learning mechanisms behind the cost decline of c-Si solar PV modules. Among all renewable energy technologies, solar PV energy has had the highest installation rate and the largest cost decrease in the last 10 years.

Learning curves, which demonstrate a constant change in unit costs against each doubling of global cumulative output, have been the most often used tool in the PV roadmaps to explain the mechanism that causes the insistent fall in costs. However, this approach attributes the decrease in cost merely to one factor which is known as learning by doing, thereby bringing along some risks like overestimation of the investigated effect and suppression of other potential causes. Hence, it prevents the resources to be allocated more efficiently.

In the study, first, an econometric panel data analysis was carried out based on 11 PV manufacturing companies listed in the US Stock Exchange between 2003 and 2019.

Following, semi-structured interviews were conducted with 19 PV experts from multiple regions of the world. By this qualitative part, the underpinning causes and instruments that enabled the learning patterns examined in the preceding quantitative analysis were inquired. As a result, some factors that were associated with different dimensions of learning were investigated under control of some external technological and industrial factors. Thus, the researching and interacting attitudes within the firms and the dynamic capabilities that they might have embodied were directly or indirectly revealed and justified through successively carried out econometric analysis and expert elicitations.

Finally, based on the overall findings attained upon expert interviews, policy recommendations at international and national levels as well as firm level strategy suggestions were made in order to maintain the technology and cost improvements in the PV manufacturing industry.

Keywords: learning curves, photovoltaic, panel data estimation, cost of PV modules, Technological Innovation Systems

ÖZ

KRİSTAL SİLİSYUM (k-Si) FOTOVOLTAİK (FV) GÜNEŞ MODÜLLERİNİN MALİYET DÜŞÜŞÜNÜN ARDINDAKİ ÖĞRENME MEKANİZMALARI

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Şubat 2023, 378 sayfa

Bu tez, k-Si FV güneş modüllerinin maliyet düşüşünün arkasındaki farklı öğrenme mekanizmalarını anlamayı amaçlamaktadır. Tüm yenilenebilir enerji teknolojileri arasında güneş fotovoltaik, son 10 yılda kurulum hızı en yüksek olan ve maliyeti en fazla azalan enerji türü olmuştur.

Küresel kümülatif üretimin her iki katına çıkmasına karşı birim maliyetteki değişime dayanan öğrenme eğrileri, FV yol haritalarında ısrarlı maliyetlerde düşüşe neden olan mekanizmayı açıklamak için en sık kullanılan araç olmuştur. Bununla birlikte, bu yaklaşım, maliyetteki düşüşü yalnızca yaparak öğrenme olarak bilinen bir faktöre bağlar ve böylelikle bu etkinin olduğundan fazla tahmin edilmesi ve diğer potansiyel nedenlerin görünürlüğünün baskılanması risklerini bünyesinde barındırarak nihayetinde kaynakların daha verimli tahsis edilmesini engelleyebilir.

Tez çalışmasında ilk olarak, 2003 ve 2018 yılları arasında ABD Menkul Kıymetler Borsasında işlem gören 11 FV imalat şirketinin verilerine dayalı olarak ekonometrik panel veri tahminleri yapılmıştır. Niceliksel analizlerin ardından dünyanın çeşitli bölgelerinden 19 FV uzmanı ile yarı yapılandırılmış görüşmeler yapılmıştır. Bu nitel kısımda, önceki nicel analizde incelenen öğrenme kalıplarını mümkün kılan temel nedenler ve araçlar sorgulanmıştır. Sonuç olarak, öğrenmenin farklı boyutlarıyla ilişkilendirilen bazı faktörler, bazı dışsal teknolojik ve endüstriyel faktörlerin kontrolü altında incelenmiştir. Böylece, firmalar içindeki araştırma ve etkileşim tutumları ve barındırdıkları dinamik yetenekler, art arda yürütülen ekonometrik analizler ve uzman çıkarımları yoluyla doğrudan veya dolaylı olarak ortaya çıkarılmış ve gerekçelendirilmiştir.

Son olarak, uzman görüşmelerinden elde edilen genel bulgulara dayanarak, PV üretim endüstrisindeki teknoloji ve maliyet iyileştirmelerini sürdürmek için uluslararası ve ulusal düzeyde politika önerileri ile firma düzeyinde strateji önerilerinde bulunulmuştur.

Anahtar Kelimeler: öğrenme eğrisi, fotovoltaik, panel veri analizi, FV modül fiyatları, Teknolojik Yenilik Sistemi

To my family.

ACKNOWLEDGMENTS

First of all, I would like to thank to my supervisor Assoc. Prof. Dr. Hakan Ercan who enlightened my path with his practical and result oriented approach, provided his guidance to improve my analyses and listened to my worries with patience and kindness throughout my thesis studies. I am grateful to Prof. Dr. Erkan Erdil for his guiding views and supports which made me feel motivated and resilient at certain times. Moreover, I thank him for being a member of my thesis progress committee and sharing his valuable comments. I am glad to know Prof. Dr. Teoman Pamukçu and feel lucky to have experienced his fruitful teaching and authentic personality by being a student of him in more than half of the courses I took during my PhD. I would like to thank Prof. Dr. Semih Akçomak for his mind opening and dynamic talks in both lectures and at free discussion times as well as his helpful advice throughout my PhD. I would also like to thank Prof. Dr. Hakan Berument who contributed to my work with his comments by being a member of my thesis progress committee.

I am also grateful to Prof. Dr. Raşit Turan who opened my path to be an expert in solar PV technology. He always trusted me in my work and did not let me give up when I was tired of different handicaps. I would also like to thank to Dr. Fırat Es who had somehow been in my life from 2015 to 2021. I am happy to see that our synergetic efforts and dreams that we together planted their seeds years ago have grown up and contributed to our institute, our country and maybe ultimately to the PV industry. I am grateful to my friends, Dr. Mona Borra, Dr. Hisham Nasser, Dr. Makbule Terlemezoğlu and Dr. Salar Habibpur Sedani for their friendship and accompanying my joyful days at GÜNAM. I am also thankful to Dr. Talat Özden for his encouraging words to finish my PhD thesis and other enlightening talks. I would also like to thank my colleagues in Science and Technology Policy Studies, Selin Gökpınar, Mustafa Can, Dr. Yelda Erden Topal and Dr. Muhsin Doğan with whom I have had fruitful discussions and shared good moments in different periods of my PhD years.

I owe special thanks to my interviewees who enriched my findings with their valuable views and substantial experiences. I am grateful to: Dr. Arnaulf J-Waldau, Dr. Arthur Weeber, Dr. Carlos del Canizo, Dr. Christian Buchner, Dr. Fırat Es, Dr. Gangadharo Rao, Dr. Ivan Gordon, Dr. Joseph Haase, Dr. Lotfi Bounaas, Dr. Mehul Raval, Dr. Mete Günöven, Dr. Paul Ni, Dr. Peter Fath, Dr. Pierre Verlinden, Dr. Pietro Peter Altermatt, Dr. Raşit Turan, Dr. Stefaan de Wolf, Dr. Yang Yang and Dr. Wolfgang Jooss for their contributions and allocating their valuable time despite their very busy agendas. I am once more appreciated to Dr. Pietro Peter Altermatt's for his help in increasing the number of my participants in the qualitative part and his guiding suggestions to finish my thesis writing. In addition, I would also like to thank to Johannes Bernreuter (Bernreuter Research) and Paula Mints (SPV Research) as well as Bloomberg New Energy Finance (BNEF) for answering my questions regarding their market research data and allowing me to utilize them in my thesis study.

Beyond their longtime friendship almost throughout 20 years, I also have special thanks to some of my friends who somehow made my tough PhD days bearable: Dr. Işıl Gerçek Beşkardeş & Eren Beşkardeş for sharing their home with me in the early times of my PhD; Çağla Tekin and Özlem Çördük for supporting me with their kind and close friendship during my troublesome PhD days; Tuğba Arabacı Özcan for her listening, encouragement and sincere friendship during my toughest days within this period, Dr. Hasret Tolga Şirin and Dr. Ebru Akdoğan for their joyful talks and making me feel their faithful friendship.

Finally, I might not dare to start and be able to finish this PhD without the encouragement and support of my mom Zekiye and my dad İsmet. They allowed me to be my authentic self in every step of my life and supported me to pursue my way even when the light was not evident. They have always given their love, trust, patience, support and they have endured and believed me whenever I tried to overcome all inner and external obstacles during my PhD as well as in my all life. I feel very lucky to have my sister Dilek who has always encouraged me by believing my competences and efforts and has given me her compassionate love since I was a little girl. I am also grateful for having my nephew, my little one, Derin. His charm and wonder were sometimes the only things that made me go on when I suffered being far away from my family and we missed each other so much.

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LIST OF ABBREVIATIONS

Al-BSF	Aluminum Back Surface Field
APAC	Asia-Pacific Countries
ASP	Average Selling Price
BOS	Balance of Systems
CAPEX	Capital Expenditures
COGS	Cost of Goods Sold
CPIA	China Photovoltaic Industry Association
C-D	Cobb Douglas
c-Si	crystalline Silicon
EC	European Commission
EU	European Union
FBR	Fluidized Bed Reactor
FD	First Differencing
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GMM	Generalized Method of Moments
GW	GigaWatt
IEA	International Energy Agency
IPR	Intellectual Property Rights
IRENA	International Renewable Energy Agency
IS	Innovation Systems
ISE	Institute for Solar Energy Systems
ITRPV	International Technology Roadmap for Photovoltaics
JPL	Jet Propulsion Laboratory
JRC	Joint Research Center
KS	Knowledge Stock
kWh	kilowatt hours

LBD	Learning by Doing
LBI	Learning by Interacting
LBR	Learning by Researching
LBU	Learning by Using
LC	Learning Curve
LCOE	Levelized Cost of Electricity
LFD	Lagged First Difference
LR	Learning Rate
MFLC	Multi Factor Learning Curve
MW	MegaWatt
NASA	National Aeronautics and Space Administration
NIS	National Innovation Systems
NREL	National Renewable Energy Laboratory
OEM	Original Equipment Manufacturer
OFLC	One Factor Learning Curve
OLS	Ordinary Least Squares
O&M	Operations and Maintenance
PERC	Passivated Emitter Rear Cell
PR	Progress Rate
pSi	polysilicon
PV	Photovoltaic
PVPS	Photovoltaic Power Systems Programme
RE	Renewable Energy
R&D	Research and Development
SEM	Structural Equation Models
SIS	Sectoral Innovation Systems
SPP	Solar Power Plants
TF	Thin Film
TFLC	Two Factor Learning Curve
TIS	Technological Innovation Systems
TRL	Technology Readiness Levels

UCC	Union Carbide Corporation
UMC	Unit Module Cost
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USD	United States Dollar
VIF	Variance Inflation Factor

CHAPTER 1

INTRODUCTION

Vamos aquecer o sol
José Mauro de Vasconcelos

As the world has faced the deteriorations in environmental conditions and worsening impacts of climate change, international attempts to reverse these drawbacks of the industrial era have become prominent. The Kyoto Protocol which was adopted in 1997 and entered into force by 2005, steered industrialized countries towards reducing their greenhouse gas (GHG) emissions in the scope of the United Nations Framework Convention on Climate Change (UNFCCC) in two commitment periods till 2020 (UNFCCC, 2022b). Thus, it pioneered the international commitments on prevention of global warming which has been escalated by the increasing GHG emissions. Then, since globally more widespread and continuing actions were required to mitigate the urgent temperature increase, the Paris Agreement was adopted by 196 parties in 2015 to be put into force in 2016. Based upon, all parties are expected to implement their plans regarding nationally determined contributions for emission reductions to meet the target of keeping the warming below at highest 2 degrees Celsius, compared to the period before the industrial revolution (UNFCCC, 2022a).

Carbon dioxide (CO2) has the highest portion (65%) in the overall GHG emissions and its major source is the energy use (UNEP, 2020). When it is considered that 79% of the global energy supply is based on fossil fuels (IEA, 2021b), utilization of renewable energy (RE) resources can be seen as an important alternative to decrease the CO2 emissions. However, by 2020, electricity covers only about 20% of the global final energy consumption (IEA, 2021b). Therefore, through the electrification of different segments in energy supply like road transportation, building heating, high temperature industrial processes as well as use of fuels produced by utilizing electrical energy (e.g. Hydrogen), the renewables are expected to have a substantial role in global warming precautions (IEA, 2021a, 2021b).

The deployment of RE technologies utilized in power generation has accelerated in the last 20 years aligned with the decarbonization policies in the pursuit of green transformation and mitigation of the climate change. Meanwhile, persistent cost decline in certain energy technologies led to a sharp rise in their share in the overall energy mix. In that sense, solar photovoltaic (PV) has been the technology that has had the fastest installation rate (IRENA, 2022a) and the largest cost decrease in the last 10 years (IRENA, 2021). Moreover, by 2050, PV is anticipated to reach to 20-fold of its installed cumulative capacity in 2020 (IEA, 2021a). According to this scenario, solar PV will be the largest source in terms of capacity with its 20% share in the overall energy supply and thus will be able to provide 33% of the global electricity generation[1] (IEA, 2021a).

With the underpinning arguments above, understanding the cost decline in PV technology is very critical to maintain its deployment and this dissertation is ultimately dedicated to this purpose. In the following subsections, the backbones of the study are explained in a more detailed way. First, how the limitations in the relevant literature underpinned the motivation of this dissertation is discussed. Then in the two following subsections, the aim of the study and the research question(s) that were utilized to satisfy this aim are addressed respectively. In the fourth subsection, how the study was designed around the methodological pathways is described. In the fifth subsection, the

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[1] Solar PV was utilized for 3% of the global electricity generation in 2020 (IEA, 2021a).

novelties of the study and the contributions made are mentioned. Finally, in the sixth subsection, the outline of the thesis and the brief content of the chapters are provided.

1.1. Statement of the Problem

Learning curve approach is a widely used methodology to explain and forecast the cost trend of PV systems or PV modules (de La Tour et al., 2013; Elshurafa et al., 2018; Gan & Li, 2015; Isoard & Soria, 2001; Kobos et al., 2006; Mauleón, 2016; Papineau, 2006; Pillai, 2015; Trappey et al., 2016; Wiebe & Lutz, 2016; Yu et al., 2011; Zheng & Kammen, 2014; Yi Zhou & Gu, 2019). Learning curves exhibit a constant change in unit cost of a technology per doubling of cumulative installation or production. This behavior is attributed to "learning by doing (LBD)" effect brought along by accumulating experience within years and is usually associated with the cumulative output (Arrow, 1962; Dosi & Nelson, 2010; Thompson, 2010).

Historically, the first relevant empirical evidence was observed by Wright in airplane manufacturing as increased labor productivity through accumulated output (Arrow, 1962; Dosi & Nelson, 2010; Thompson, 2010; Wright, 1936). In the following years it was shown to be valid for the cost estimation as well when it was implemented for a wide range of technologies (Berndt, 1991; Dutton & Thomas, 1984; Thompson, 2010). Also, it is noteworthy that though some authors emphasized that it might be the cumulative investment that provided the new knowledge and capabilities to the firms rather than the static output (Arrow, 1962; Thompson, 2010), the LBD effect was found valid even when the rate of output was constant i.e. the annual amount of operations remained same (Alchian, 1949; Arrow, 1962; Berndt, 1991)[2]. This also reveals the learning effect to be a separate phenomenon than the scale effect.

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[2] Arrow (1962) builds his model on cumulative investment and advocates that since knowledge is embedded in the new machinery, the real stimuli of learning is new investments. However, he also emphasizes that since with constant rate of output the learning affect is still observable in the literature, his model should be improved by taking it into account.

A deeper understanding of experience or so-called learning curve phenomenon is very critical since it may affect the decisions of firms in favor of early entry to take the advantage of learning that comes along with the accumulated output (Berndt, 1991; Dutton & Thomas, 1984; Nemet, 2006; Rout et al., 2009). Moreover, they may decide towards making learning investments i.e. capacity additions regardless of any other advantages (Dutton & Thomas, 1984; Rout et al., 2009). On the other hand, it may encourage the governments or other policy makers to plan their strategies accordingly and design proper tools.

The most often used version of learning curves is One Factor Learning Curve (OFLC) which merely depends on LBD. Though there are variations in the literature, the sectoral roadmaps or trend analysis reports which utilize PV learning curves mainly build their estimations on this basic version (Feldman et al., 2021; Fraunhofer ISE, 2022; IEA PVPS, 2022b; ITRPV, 2021). They examine the decrease in aggregate average unit price (as a proxy of cost in a mature market) against each doubling of global cumulative production or installed capacity. Due to its basic structure, data is relatively accessible and the future estimations can be easily made by using the learning factor drawn from the learning equation.

However, the PV learning factors calculated in the literature variate in a wide range (Candelise et al., 2013; de La Tour et al., 2013; Neij, 2008; Nemet, 2009; Rubin et al., 2015; Samadi, 2018). This can be caused due to the miscellaneous factors like differences in unit of analysis in terms of the technological domain of the dependent variable,[3] employing explanatory variables other than cumulative output, selection of samples which belong to different time periods or geographical domains[4] (Neij, 2008; Samadi, 2018). But, even when the dependent and independent variables remain same,

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[3] There are authors who conduct estimations for “PV system costs” while much of the studies examine cost decline in “PV modules”. The technical differences of these units are described in Chapter 2.

[4] The reasons of these variations and their outcomes are systematically discussed under section 3.3.

there is a wide range of variation reported in the literature (de La Tour et al., 2013; Rubin et al., 2015; Samadi, 2018)[5] which weakens the reliability of the global rates (or the rates that are referred as global) and ultimately can lead to confusions in policy design.

Learning curves that are based upon only experience accumulation through cumulative output have some drawbacks. First, they create the risk of overestimation which leads to excess allocation of limited resources to only one factor; second, they prevent the other underlying reasons which may be related to different learning mechanisms or external effects to be discovered (Samadi, 2018; Wiesenthal et al., 2012; Yeh & Rubin, 2012), thereby making them lack of sufficient support or attention. Ultimately, relying on one factor may impede the economic and social return of the policy instruments.

Some authors address these problems by incorporating various knowledge related parameters like R&D expenditures, knowledge stock or patents (de La Tour et al., 2013; Kobos et al., 2006; Wiebe & Lutz, 2016; Zheng & Kammen, 2014) into their models. These are usually called Two Factor Learning Curves (TFLC) in the literature. Moreover, many other variables like plant size, the feedstock price, energy prices, other input prices, breakthrough times or external technological progress, etc. can also be included in addition to (de La Tour et al., 2013; Wiebe & Lutz, 2016) or without using (Gan & Li, 2015; Isoard & Soria, 2001; Mauleón, 2016; Papineau, 2006; Pillai, 2015; Trappey et al., 2016; Yu et al., 2011) knowledge associated parameters. In both cases, these models can be called Multi Factor Learning Curves (MFLC).

Despite the attempts to improve the PV LCs with additional variables, there are still some problems in reliable and/or functional interpretation of the estimation results due

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[5] It should be noted that time, geography and data source as well as estimation methodology may still differ.

to the chosen sample frame, the variables employed or inadequacy of the estimation methodology. The major causes are briefly summarized below:

- Learning curves were first observed at plant or firm level (Berndt, 1991; Dutton & Thomas, 1984). But, in the current PV learning curve studies, substantially, global or national aggregate data is used except a few ones that depend on country (Kim et al., 2017; Papineau, 2006) or company panel data[6] (Pillai, 2015; Reichelstein & Sahoo, 2018)[7]. The aggregate approach does not allow to capture spatial level effects like country or firm specific dynamics that variate within time. As a result, it is not possible to make implications in terms of national policies or company strategies.

- On the other hand, time series estimations with cross-sectionally aggregate data are based on low number of observations which usually start with the year 1976 at earliest (Feldman et al., 2021; ITRPV, 2021; Samadi, 2018) because of unavailability of relevant data for the relatively new PV industry. Many of the academic publications make estimations with a number of data lower than 35 (Samadi, 2018) which doesn't allow use of too many variables since it decreases degrees of freedom of the model and may ultimately affect the significance of the estimates.

- Overestimation of LBD effect and overlooking the contributions of other parameters cause biased outcomes in technology experience curves (Samadi,

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[6] Please note that the "panel" term here indicates the type of data that is a combination of time series and cross-sectional data. It should not be confused with solar "PV panels". Therefore, the PV panels in the text above and thereafter are mentioned as PV modules if technically otherwise not required. The slight difference between the PV panel and PV module is described in Chapter 2.

[7] Kim et al. (2015) investigate PV system prices with panel data that belongs to OECD countries (Kim et al., 2017) while Papineau (2006) makes panel data estimations for PV module costs by consolidating data of three countries (Papineau, 2006).

2018; Yeh & Rubin, 2012) and as mentioned above, various additional variables are utilized to solve these problems and ultimately to make correct and useful implications. Though these variables are determined by the authors, their selection or utilization in the models are also limited by availability and quality of the data, and the statistical requirements as well. The most common variables used in PV LC studies and their drawbacks are addressed in detail under subsection 3.3.

- Moreover, there may still be some effects that either cannot be captured by the learning curves due to data originated problems or of which causality cannot be understood comprehensively via quantitative methods. Engineering assessments or bottom up cost approach is proposed as an alternative or complementary method to overcome the limitations of PV learning curves (Candelise et al., 2013; Kavlak et al., 2018; Neij, 2008; Nemet, 2006). They mainly decompose the cost change to primary technical factors but do not provide an understanding about any industrial or firm-based dynamics that may have effect on or interaction with them.

- Expert elicitations may be a good complementary method for PV LC estimations. But usually they are utilized in ex-ante analysis i.e. to provide data input for the quantitative estimations (Bosetti et al., 2012; Nemet & Baker, 2009; Verdolini et al., 2015). While some authors directly refer to expert opinions to forecast the future costs under certain R&D scenarios (Bosetti et al., 2012; Verdolini et al., 2015), some follow an indirect way and use expert views only to identify the impacts of research efforts on selected scientific/technological parameters that they utilize in their bottom up cost estimations (Nemet & Baker, 2009). There are a few studies found that focus on finding out the drivers behind the cost decline of PV technology through qualitative analysis (Lam et al., 2018; Nemet, 2019). But, there is not any study found that complements the quantitative PV learning curve estimations with a qualitative analysis in a successive way to understand the causality behind the significant econometric findings and to investigate the further factors that could not be incorporated into or omitted from the models.

As can be understood from the brief discussion above, there is still a room to investigate the factors that affect the cost decline in PV technology through different models and complementary methods. In sum, addressing or enlightening the points that remain ambiguous in the precedent studies have underpinned the motivation of this study.

1.2. Aim of the Study

The main aim of this thesis is to find out the learning mechanisms behind the cost decline of solar PV modules to enable design of more effective policy instruments.

In this study, all issues mentioned above were addressed through an econometric analysis that was conducted with the highest number of observations met until now in the literature regarding c-Si PV module learning curve estimations based on annual data[8]. By using firm level disaggregate data; internal learning mechanisms, independent external effects and their interactions represented by some combined variables were examined in terms their effects on cost decline of c-Si PV modules. Then the quantitative findings were complemented by a qualitative research for a deeper analysis.

As a result, the impacts of multifaceted learning mechanisms within PV firms together with sectoral dynamics were investigated quantitatively as far as possible, while the causality of the significant findings and the effect of insignificant or omitted variables were examined through expert elicitations. This composite way of analysis facilitates

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[8] One study had a higher number (213) since it utilized quarterly data for 5 and a half year in between 2008 and 2013 for 10 PV firms (Reichelstein & Sahoo, 2018).

to make more reliable and functional implications in terms of innovation policy design and industrial strategy, which is the ultimate aim to be attained by this study.

1.3. Research Questions

This study is designed around the main research question as follows: What kind of learning mechanisms are effective in cost reduction of c-Si PV modules?

The answer of this question was inquired by using both quantitative and qualitative analyses which were based on econometric estimations and expert interviews respectively. The main question was strongly supported by the sub-questions below to elaborate the findings and deepen the implications that can be made out of them.

- At what extent do the internal learning mechanisms affect the cost of c-Si PV modules under control of or in combination with external sectoral dynamics?
- What can be the underlying causes of effective or ineffective learning in c-Si PV industry?
- What can be further ways of learning in c-Si PV industry and how can they be enabled?

The first sub-question above was addressed in the quantitative part by regressing multiple variables -that were associated with different factors- on unit cost. The second question was partially answered based on the econometric findings and the innovation capabilities theory that provided a foundation for joint effects of internal learning efforts and external stimulus. Finally, the parts of the second question that still required further elaboration or support and the third sub-question were investigated in the qualitative part through the semi-structured expert interviews. Thus, the potential channels or instruments that might have induced learning in the PV industry and the attitudes that might have triggered or hampered them were enlightened.

1.4. Design of the Research

In a PV system, though it variated within years, in ground mounted large-scale installations, PV modules alone have usually constituted more than 50% of the cost structure in many parts of the world in the last 15 years.[9,10] Rest of the cost was covered by Balance of Systems (BOS) and the other remaining constituents such as land, project and soft costs (ITRPV, 2021; A. Jäger-Waldau, 2019; Wenham et al., 2007). BOS is composed of many individual electrical and structural parts like inverters, construction materials, wiring, other electrical/mechanical units and the rest of the cost includes multiple components which are highly location and country dependent. In sum, it is much more effective, easier and reliable to choose cost of PV modules as a unit of analysis since: first, it alone covers the substantial part of the overall PV system cost; second it has a non-composite cost structure as an integrated end product; third, though there may be some differences arising from the location of manufacturing, cost of PV modules do not variate too much when the impact of land and, labor and other soft installation costs on overall PV system costs is considered. On the other hand, among different PV module technologies, crystalline silicon (c-Si) PV modules have always been the dominating technology in the market with 95% share in 2021 (Fraunhofer ISE, 2022). As a result, the technology unit in this study was determined as c-Si PV modules.

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[9] For 2012 and later, the annual ITRPV reports give an insight (ITRPV, 2013, 2014, 2015, 2016, 2017, 2018, 2019a, 2021); for 2010-2011 please check (Chase, 2014) and for 2009 and before, check (Price & Margolis, 2010).

[10] Please note that the values for the last 10 years exclude soft costs in a PV system (the details are defined in Chapter 2) which may vary based on the region but still include land/ground costs since the values were given for ground mounted utility scale systems. Therefore, though the share modules was higher than 50% for Europe and Asia within the mentioned time frame, due to the land/ground costs in the initial investment, it was lower for the US for certain years (ITRPV, 2019b). Since 2021 values were aggregated at global level, the overall value decreased slightly below 50%.

The research is designed in two successive steps. First, a quantitative analysis was carried out by utilizing econometric estimations based on firm data. By this part, it was aimed at investigating the effects of some firm dynamics -which were associated with multiple learning types- on cost decline of solar PV modules jointly with some industrial trends and external progress factors. Then, the qualitative research which contributed to the study in multiple ways was conducted through semi-structured interviews with PV experts from academia and industry in different regions of the world. Based on the expert elicitation, first, the findings of the econometric estimations were justified by revealing the causality behind. Second, it enabled to investigate the effects of some learning related factors which could not be incorporated into or kept in the model due to data unavailability, variable quantification problems or statistical concerns.

As to the analytical framework of this study, it was fundamentally inspired from the learning curve literature which is underpinned by the empirical studies that mainly rely on learning by doing and -less often- learning by researching. However, there are also further ways of learning in the literature that were attributed to the cost decline of energy technologies (de La Tour et al., 2013; Elia et al., 2021; Gan & Li, 2015; Junginger et al., 2005; Rout et al., 2009; Samadi, 2018; Wiebe & Lutz, 2016; Wiesenthal et al., 2012; Yu et al., 2011).

Moreover, learning has more sophisticated dimensions in the innovation literature. The concepts like absorptive capacity (Cohen & Levinthal, 1990) and dynamic capabilities (Teece & Pisano, 1994) which trigger innovation and thereby leading to competitive advantage (Ferreira et al., 2020; Zahra & George, 2002) are closely associated with learning. While these competences can boost learning performance or at least ease learning (Teece & Pisano, 1994; Wang & Ahmed, 2007), improvement of these abilities may rest on learning activities (Nielsen & Lundvall, 2003; Zahra & George, 2002). In other words, learning can be both the outcome and cause of these capabilities which means they are closely intertwined and they can even be considered interchangeable at some extent. Therefore, precursors or indicators of certain types of learning are sometimes used as proxies of these capabilities, too. As a result, in addition to utilizing learning curve concepts, both the quantitative and the qualitative results were evaluated by considering these capabilities as well.

Finally, expert interviews were utilized to validate the findings in the quantitative part and reveal their causalities and enablers. Moreover, the semi structured surveys allowed the interviewees to elucidate their views in a wide extent. This made to identify the inducement and blocking mechanisms behind the improvement of c-Si PV industry possible. There, functional dynamics approach which is a stream under Technological Innovation Systems was utilized as the analytical frame.

In the end, based on the conclusions attained in the two successive steps in Chapter 4 and Chapter 5 as well as by considering the inferences made from the industrial history and recent trend analyses of PV in Chapter 2, three sets of policies were recommended at international, national and firm levels.

1.5. Novelty of the Study and Contributions to the Literature

The study carried out have certain novelties in terms of the variables investigated through the econometric analyses and the way they were evaluated as well as the utilization of the expert elicitation the quantitative study was followed by.

First of all, selection of level of analyses and therefore the sample frame is very critical for making statistically correct estimations and functionality of the implications made in the pursuit of designing more effective policies. The mostly used global aggregate data and time series analysis based upon have many drawbacks in that sense. The entity specific effects are suppressed and the time level is usually too short which determines the number of observations since it is the only dimension that the change is observed. Moreover, the technological level like whole PV plant installation or electricity generation costs other than PV modules are aggregate as well since they embody different industries that their components were produced by and also the soft costs for the latter. Therefore, both use of global level data as well as system costs may be misleading when the generalized inferences made from them are utilized in different levels.

There were a very few studies found which investigated PV module costs based on country or firm level data (Papineau, 2006; Pillai, 2015; Reichelstein & Sahoo, 2018). One of them is very old dated for rapidly improving PV industry (Papineau, 2006) and the other two which were based on firm level panel data were not comprehensive enough in terms of the learning factors investigated. Additionally, different approaches embraced in both studies for generating the dependent variable (unit cost of PV modules) were depending on either strong assumptions (Reichelstein & Sahoo, 2018) that did not have a valid background or overlooked the details in the company reports (Pillai, 2015) that invalidated the calculations relied on[11]. In the thesis study, use of price was validated based on the theoretical background but also an empirical demonstration of which details were provided in subsection 4.3.4.1[12]. On the other hand, the variables were diversified to capture the effects of many different possible factors related to learning activities and external stimulus as well as their combined outcomes.

In the estimations carried out within this thesis, R&D intensity was utilized as a measure of dedication to research activities instead of the variables that depends on accumulated research expenditures. The lag and depreciation values were revealed to be too complicated for PV R&D based on the expert elicitations carried out in Chapter 5. In addition, cumulative R&D expenditures may yield insignificant outcomes due to its correlation with other cumulative effects (i.e. learning by doing). Moreover, it was

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[11] If another source that was not revealed in the paper was not used.

[12] Usually price is utilized as a proxy of unit cost in PV LC studies. This approach may have some drawbacks as well. However, as it is discussed in 3.3.2, it can be justified with mature market conditions. Moreover, in the thesis study where the prices were utilized instead of costs, their response to change was shown to be same for half of the observations for which both cost and price data was available.

elucidated by the expert interviews carried out in (de la Tour et al., 2011) that PV firms mostly owed innovation to their activities carried out in the production lines rather than specific R&D departments. Therefore, first, the problem regarding the reliability of the estimates arising from correlation of the independent variables in a multiple regression was eliminated by employing R&D intensity as one of the learning by researching indicators. Secondly, quantity of R&D employment was examined as another learning by researching factor in addition to R&D intensity since this skilled labor force was seen as an important mediator that could have contributed to transformation of the firm's routines through the external knowledge they acquired and assimilated by interacting with the other actors outside the firm. Thus, investigation of this effect was introduced as a novel approach to the PV LC literature. In addition, firm structure in terms of vertical integration was investigated for the first time in PV LCs based on the literature review carried out. It was examined as an interaction term with the raw material (polysilicon) cost to reveal whether the firms that were not integrated were more sensitive to the feedstock crisis compared to the ones that were integrated and remained out of the supply relations in the upstream steps.

On the other hand, improvement in the explanatory power of the models and jointly significant outcomes attained upon incorporation of external effects to the model like structural break in industrial dynamics and external progress terms which were represented by industrial module efficiencies and time trend respectively, were interpreted as validation of the presence of innovation capabilities within the firms. There were some studies that investigated similar effects in the literature like time trend, Chinese share, supply surplus, China dummy, overall industry investments (Gan & Li, 2015; Mauleón, 2016; Papineau, 2006; Pillai, 2015; Wiebe & Lutz, 2016). However, except two studies where so called overcapacity years (Wiebe & Lutz, 2016) and time trend (Papineau, 2006) were found significant, addition of the external effects into the model did not yield significant results jointly with the other fundamental effects. Therefore, both in terms of the variables investigated as well as the interpretation of their joint outcomes from dynamic capabilities perspective was unique in the PV LC literature.

Finally, expert interviews were utilized as a complementary part to confirm the findings in a qualitative way and reveal the causalities behind as well as to unveil the other effects that could have contributed to cost decline. There were some studies that benefited from expert elicitations as well. However, the ways they utilized qualitative research were differentiated from this study. Shortly, by leaving aside the studies that were just focused on qualitative investigation of innovation in the PV industry which might ultimately have contributed to reduction of costs (de la Tour et al., 2011; Huang et al., 2016; Lam et al., 2018; Nemet, 2019); they either used the views of experts to justify some technical foundations in their bottom up cost calculations (Nemet & Baker, 2009) or to estimate the future costs under certain scenarios directly based on their views (Bosetti et al., 2012; Verdolini et al., 2015). In that sense, the way embraced in the thesis study was original in terms of using expert views as a post estimation tool for a deeper understanding of the findings and designing policies.

1.6. Outline of the Thesis

The main backbones of the study are presented in the first chapter. The second chapter provides general information about the status of the PV market, a brief description of PV technologies and the industrial value chain as well as a historical review of the industry and its recent trends. The third chapter depicts the theoretical frame of the study mainly based on the learning curve approach. After the background theory and the empirical studies carried out in the field of RE technologies are addressed, their classification is systematically examined to build an analytical frame. Then it was complemented by discussing the relation of learning concepts to innovation capabilities and providing a brief introduction of innovation systems approach to be utilized in further evaluation of expert elicitations.

In the fourth and fifth chapters, all dimensions of the quantitative and quantitative research are described respectively. The methodologies utilized, the data collected and then the results and discussions attained are provided under these chapters. Finally, in the sixth chapter, the thesis is concluded with the inferences made from the studies conducted and then by making the policy recommendations regarding technological improvement and industrial strategy levels in the field of PV.

CHAPTER 2

TECHNICAL BACKGROUND: A BRIEF OUTLOOK OF PV ENERGY

Collect sun for me
Among the hopes
From the black of eyelashes

Ülkü Tamer

Turkish poet

This chapter aims at creating a familiarity about the market and the industry of PV technology which enables to harvest solar energy as direct electricity. After making a very short introduction to its history in the following section, the attributes of this technology are mentioned. Then in the subsequent section an overview of the PV market including the installations and the cost trends is provided. In the last section, first, the fundamental steps of crystalline silicon PV value chain are introduced; second, the history of PV industry is examined with its characteristics specific to certain time intervals and geographies and finally the recent trends in the PV industry are mentioned.

2.1. A Short Introduction of Solar Photovoltaic Technology

Solar energy is the solar irradiation transferred to our earth through sunlight and it can be harvested in the form of heat or direct electricity by using different technologies. Supply of residential hot water though solar collectors mounted on the roofs and generation of industrial heat by concentrating solar energy through lenses or mirrors are typical examples for use of solar thermal energy (IEA-ETSAP & IRENA, 2015).

In addition, solar thermal energy can be used to generate electricity as well. Except source of the heat, solar thermal electricity generation is principally similar to fossil or nuclear fuel based thermal power plants which are based on rotating turbines through steam. The way to obtain electricity from sun through heat collection is called solar thermal electricity (STE) or concentrated solar power (CSP). Since solar energy is first collected as heat and then converted to electricity, this type of solar energy is an indirect electrical power generation technology and thus it differentiates from PV.

Solar PV is a direct way of generating electricity. When PV devices are exposed to the sunlight, electrical current can be directly collected by the wires on their edges. The scientific phenomena behind (i.e. photovoltaic effect) was first observed in 1876 by the British nature philosopher W.G. Adams and his student R. E. Day (Smets et al., 2016). Thereafter, the first gold-selenium based PV device was demonstrated in 1883 in the US by an inventor called Charles Fritts (Smets et al., 2016). Though different materials were then investigated to have photovoltaic effect, the way to commercial solar cells was paved at the Bell laboratories in the US where the PV potential of silicon was discovered during the studies that had been carried out in the late 1930s and throughout the 1940s. Due to the performances attained, the studies at that time had not been promising in terms of any applications until the fabrication of a silicon based solar cell with 6% power conversion efficiency in 1954 was demonstrated (Green, 2001).

PV can be employed for many different purposes. However, in the early years of PV, its terrestrial use had not been the focus. Just 4 years after the silicon based solar cell had been demonstrated by the Bell researchers, Vanguard 1 was sent to the space in 1958 as the first satellite powered by a solar PV device (Smets et al., 2016; Gerard P. Willeke & Rauber, 2012) with 10% power conversion efficiency (NASA, 2022)[13]. Throughout the 1960s, rapid improvements in PV technology were continued to be

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[13] Solar cells were based on silicon (NASA, 2022).

driven by space applications (Green, 2001; Smets et al., 2016) and until the oil crisis in the 1970s, PV had not been considered as a conventional electricity source (Green, 2001; Hahn & Joos, 2014; Smets et al., 2016; Gerard P. Willeke & Rauber, 2012). Even though some attempts emerged at those years, PV did not become a viable technology in the market until the beginning of this millennium when it exceeded 1 GW cumulative installed capacity[14].

PV has unique characteristics among other energy technologies. For example, it can be easily used without grid connection as stand-alone systems. This is the attribute that make it to be used in space applications as well. Among terrestrial applications, there are many purposes of use some of which are not connected to the grid as well. One example to off-grid terrestrial use of PV devices is small appliances such as calculators working with sunlight rather than a disposable battery. Similarly, electrical vehicles (EV) can be combined with PV devices as well[15]. No requirement for grid connection also allows PV to be used in rural areas where it has not been possible to transmit electricity yet.

In terms of application, either connected to grid or not, PV modules can be integrated on residential roofs, on facades of buildings, constructed as shelter on agricultural fields. All these examples are called as distributed PV power which comprises almost 40% of the overall cumulative PV installations in the world by 2020 and among them, rooftop installations constitute the main segment (IEA PVPS, 2022b). On the other hand, ground mounted utility scale PV power plants that cover 60% the overall terrestrial PV market (IEA PVPS, 2022b) can even be installed in gigawatts (GW) and are utilized as centralized power.

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[14] According to some data sources (BP, 2022) and IRENA (IRENA, 2022a).

[15] Here, the vehicle integrated PV application is addressed which is not exactly the same thing with plug in electrical vehicles. The EVs or gasoline fueled vehicles can both have integrated PV to supply portion of the power required from solar energy.

Based on the purpose of use and the area they are integrated; the PV devices and the materials they are built on may differentiate. However, the market has always been substantially dominated by crystalline silicon (c-Si) PV modules of which share was 95% in 2021 (Fraunhofer ISE, 2022).

2.2. Solar PV Market Overview

As mentioned in Chapter 1, the energy transformation goes hand in hand with electrification according to the scenarios of international organizations (IEA, 2021a, 2021b). When the current share of electricity (20%) in overall energy consumption (IEA, 2021b) is increased and the power supply is substantially provided by RE resources, the emissions are expected to be mitigated (IEA, 2021b, 2021a). Aligned with these scenarios and commitments to the Paris Agreement, forming a power sector that heavily depends on RE resources and reinforcing energy efficiency constitute one of the three key principles in the European Union's energy strategy for clean energy transitions. The other two are providing affordable and secure energy supply, and developing an energy market that is integrated, interconnected and digitalized (European Commission, 2022a).

It is seen in Figure 2.1 that in the last 10 years, the share of renewables in overall electricity supply has insistently increased while the nuclear, coal and oil have shown a decreasing or stagnant trend (BP, 2022). As to solar, its share reached to 3.6% by 2021 while it was a negligible source of electricity supply in 1996 with its 0.005% contribution to electrical power generation (BP, 2022)[16].

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[16] The data is given for solar energy rather than PV. However, the share of solar thermal electricity installations in overall solar energy has been below 1%.

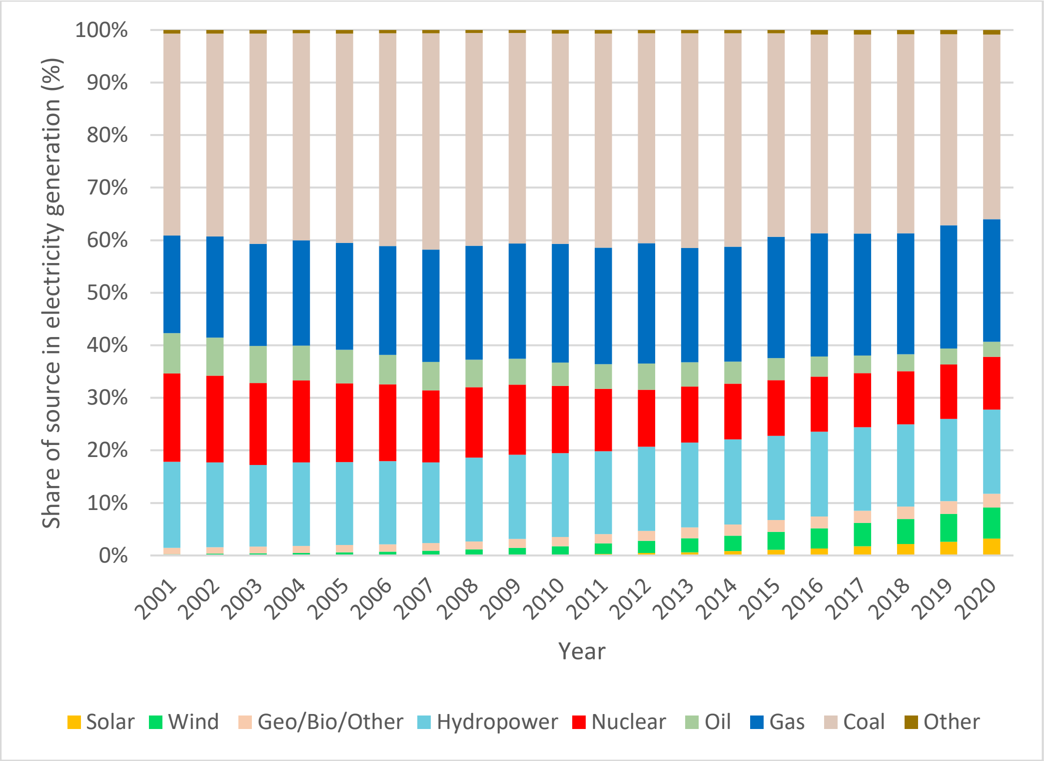

Figure 2.1. The global breakdown of electricity generation resources

As to the installations, PV has the fastest installation rate among the renewables which is shown in Figure 2.2 (IRENA, 2022a). Breakdown of the installation capacity is different than of the generation or of the supply due to capacity factor. Therefore, though solar PV has the highest installation rate almost in the last 10 years and has almost caught up wind energy in cumulative installations by 2020, its share in electricity generation is still significantly lower (3.2%) than wind energy (5.9%) in 2020 as depicted in Figure 2.1[17]. The contributions of different regions or countries to this rate have been different as depicted in Figure 2.3 (IRENA, 2022a). After the years when Japan, the USA and Germany had substantial part of the demand, in the last 7-8

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[17] Some characteristics like intermittency of certain renewable energy resources, maintenance breakdowns, failures, seasonal effects can hamper the continuous availability of the electric power. The actual power attained with respect to the maximum net capacity is called the capacity factor. The capacity factor of PV is almost half of the wind power (IRENA, 2021).

years, the markets have started to become relatively more balanced except aggressive growth of Chinese market.

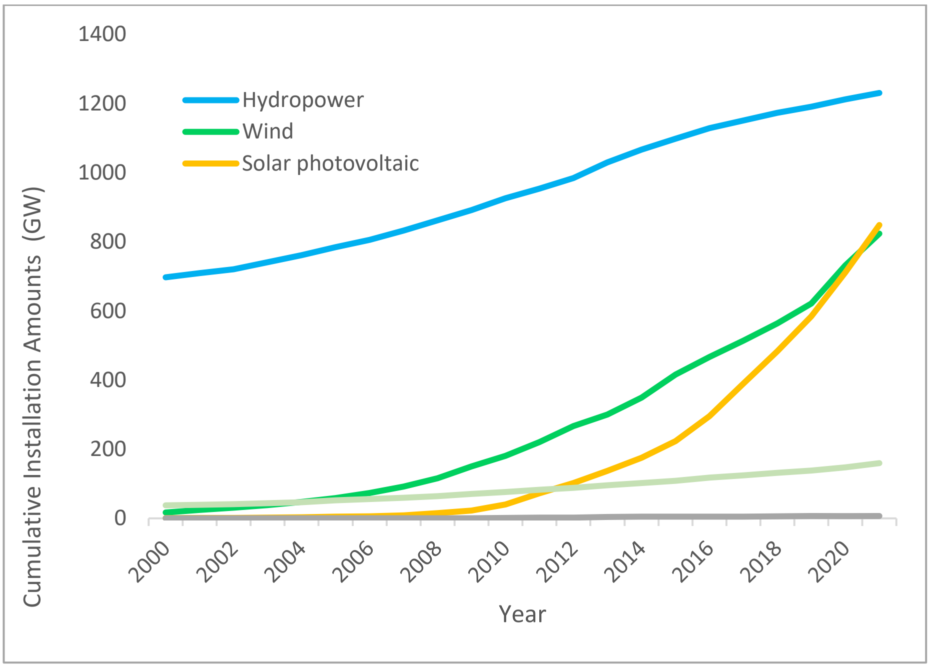

Figure 2.2. Global installation rates of renewable energy resources

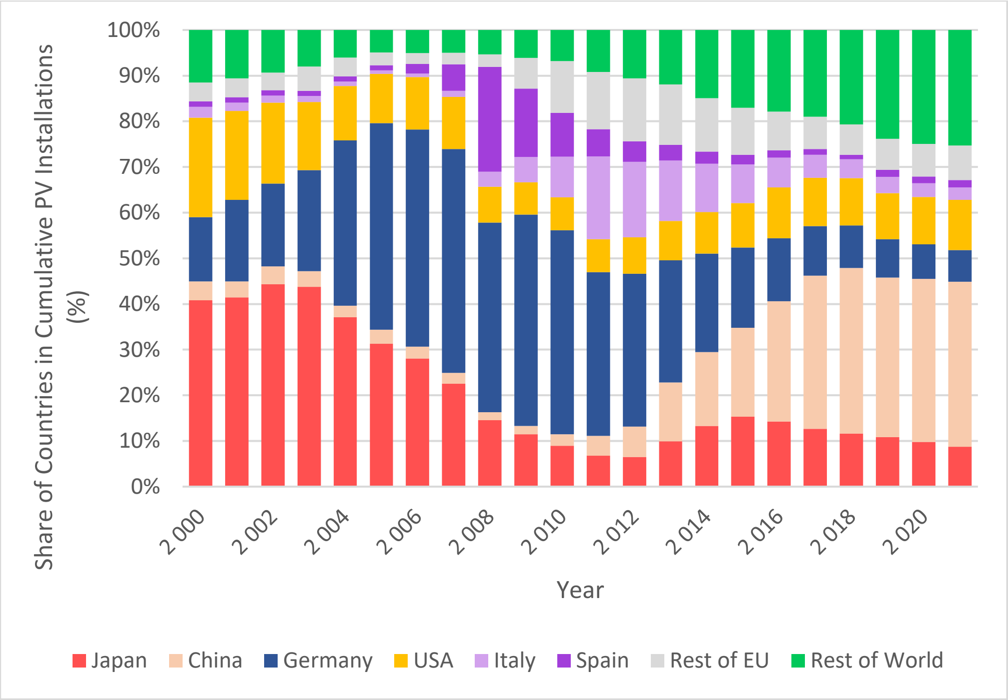

Figure 2.3. The global breakdown of cumulative PV installations

In addition to the installation trends, PV has been the leading RE technology in terms of the decrease in power generation costs for the last 10 years (IRENA, 2021). The substantial decrease in the cost of PV can be identified by comparing its Levelized Cost of Electricity (LCOE) with other energy technologies. The most common used basic LCOE formula is seen in Equation 1 and the definition of the parameters it includes are given in the text below (Huld et al., 2014). For PV, the fuel term drops since free sunlight is utilized instead. In addition, the Operations and Maintenance (O&M) cost constitutes only a small percentage of PV power plants (Huld et al., 2014). As a result, for PV, the initial investment cost or in other words PV system cost remains as the main component in the LCOE equation. On the other hand, PV system cost is composed of PV modules which is the main device unit that generates electricity and the complementary parts which include Balance of System (BOS) components as well as land, project and soft costs (arising from legal permits, insurance, finance, etc)[18].

These latter elements of the systems cost other than modules and BOS are highly variable based on the region and/or the country that that the power station is installed.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad \text{(Equation 1)}$$

- I_t is Investment Expenditures or Capital Expenditures (CAPEX) in year t
- M_t is Operation and Maintenance Expenditures (O&M) in year t - i.e. variable and fixed costs regarding operation, maintenance/repair, service, insurance.
- F_t is Fuel expenditures in year t
- E_t is Electricity generated in year t (kWh)
- r is Discount rate (%)
- n is Lifetime of the plant (year)
- t is Year within lifecycle (1,…,n)

The global aggregate data regarding the total installed costs and the LCOE of the RE technologies for the years 2010 and 2020 are given in Table 2-1 (IRENA, 2021). Though PV has the lowest total installation cost among all by the year 2020, the intermittency attribute causes it to be ranked third in the costs of electricity generation, which is calculated based on LCOE, after onshore wind and hydropower[19].

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[18] Inverters, cables/wiring parts (electrical), construction materials and mounting parts (structural) and other mechanical and electrical units (Wenham et al., 2007). Inverters can either be included as a BOS component (IEA PVPS, 2022b; Wenham et al., 2007), or are treated as an individual component in a PV system (ITRPV, 2021; A. Jäger-Waldau, 2019).

[19] It should be noted that since solar radiation is geographical location dependent, for regions where the available energy to be harvested is higher, value of the electricity generation term in the LCOE equation increases.

Table 2-1. Change in installation and generation costs of RE technologies from 2010 to 2020.

	Total installed costs (2020 USD/kW)			LCOE (2020 USD/kWh)		
	2010	**2020**	**Change (%)**	**2010**	**2020**	**Change (%)**
Solar PV	4731	883	-81%	0.381	0.057	-85%
Concentrated Solar Power	9095	4581	-50%	0.340	0.108	-68%
Onshore wind	1971	1355	-31%	0.089	0.039	-56%
Offshore wind	4706	3185	-32%	0.162	0.084	-48%
Bioenergy	2619	2543	-3%	0.076	0.076	0%
Hydropower	1269	1870	47%	0.038	0.044	18%
Geothermal	2620	4468	71%	0.049	0.071	45%

To reach net zero goals by 2050, PV is anticipated to reach to 20-fold of its installed cumulative capacity in 2020 (IEA, 2021a). According to this scenario, solar PV will be the largest source in terms of capacity with its 20% share in the overall energy supply and thus will be able to provide 33% of the global electricity generation (IEA, 2021a). The cost decrease it recorded so far and the capacity anticipated for the future makes solar PV one of the most interesting technologies contemporarily. Hence, it is worth examining in terms of the learning mechanisms that enabled it to have been developed and deployed with the rate until now.

2.3. Crystalline Silicon PV Value Chain and the Industrial Trends

Crystalline silicon, very basically, defines the semiconductor material that PV devices are fabricated on. Due to its superior properties like reliability i.e. long-term stability, abundance, non-toxic structure as well as externalities from microelectronics industry, the PV industry has been developed upon c-Si material (Green, 2001).

The state-of-the-art technology in a complete c-Si PV module is “solar cell” which is the unit device that enables to convert sunlight to electricity. However, there are also up- and downstream manufacturing steps which are partially similar to microelectronics manufacturing but mostly specialized for c-Si PV production. To provide a general understanding of the industry, the steps of c-Si PV value chain are shortly addressed below without going into process details.

2.3.1. Main Steps of Crystalline Silicon PV Value Chain

Solar power plants (SPP) and any type of applications that provide electricity based on solar PV, can be defined as the ultimate downstream step and called as PV systems. The components of a PV system PV modules, Balance of Systems (BOS) and other complementary units. As mentioned before, BOS is composed of electrical and structural parts (i.e. inverters, construction materials, cables, etc) and the rest covers land, project and soft costs. In the end, PV modules alone still constitute more or the less 50% of the cost structure in a PV system as it has been in the last 15 years[20].

PV modules[21] are the final output of the PV manufacturing[22] industry which is composed of 5 main steps as follows: polysilicon purification, ingot growth, wafering, cell fabrication and module assembly. The outputs of each value chain step are depicted in Figure 2.4 (Woodhouse et al., 2019).

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[20] For the details and references please see the subsection 1.4.

[21] It can also be called as PV panels. But, to prevent the confusion regarding the panel data as mentioned in Section 1.1. and since it is more specific to the c-Si PV industry, the “PV module” term is preferred to be used in this study instead of PV panel. In a PV module, the cells as the main unit components are required to be modulated through wire connections and encapsulation. However, in technologies other than c-Si, the PV device can be directly deposited on an entire glass or different flexible materials. Therefore, PV panel is a general definition while the term module is more specific for the c-Si PV.

[22] From hereinafter, PV will stand for c-Si PV.

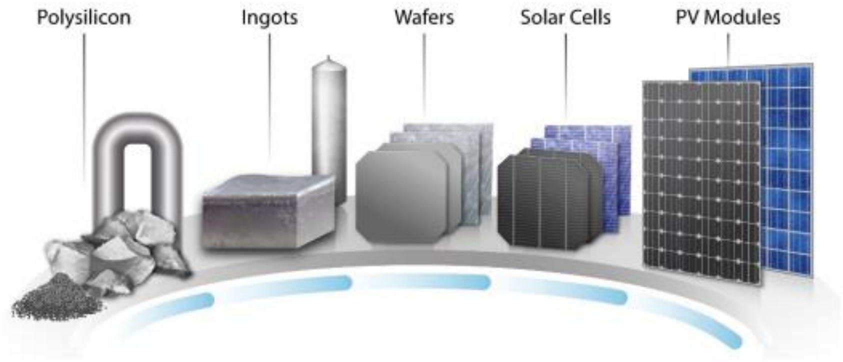

Figure 2.4.Outputs of five main steps PV manufacturing value chains

Silicon (Si) is the second most abundant element on the earth crust (Green, 2012). Until the first modern silicon based solar cell was demonstrated in 1954 by the researchers at the Bell Laboratories in the US (Green, 2001). Due to its semiconductor properties, silicon had been mainly used by the microelectronics industry to produce mainly transistors (Ceccaroli & Lohne, 2012; Green, 2001) which are the most fundamental components of chips.

Silicon atom is usually found in silicon dioxide (SiO_2) form. Though SiO2 is also the main material of sand, for metallurgical silicon production high quality minerals like quartz are utilized (Fabry & Hesse, 2012). Metallurgical silicon production basically depends on separation of silicon metal from silicon oxide through carbothermic reduction (i.e. interaction of silicon oxide with carbon at extremely high temperatures around 1900-2000 oC) (Fabry & Hesse, 2012)[23]. Clearly, this process is explicitly far different from the main steps of PV value chain in terms of technological context. In addition, metallurgical grade silicon is used as feedstock in different industries other

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[23] It is noteworthy that despite requiring too much heat, including the vast contribution of polysilicon production, the energy payback time of whole PV value chain decreased to <1.5 year by 2020 when average solar irradiation in Europe was considered (Salibi et al., 2021).

than polysilicon production like aluminum alloys or polysiloxane manufacturing (Ceccaroli & Lohne, 2012). Therefore, it is kept outside the PV manufacturing value chain.

Polysilicon (pSi) Purification

In this first step of PV value chain, the impurities that can especially affect the electrical performance of the silicon material are removed and based on the purpose of end use (i.e. solar or electronics), a certain degree of purity is attained (from 9N to 12N).[24] Metallurgical grade silicon which is the feedstock of pSi production, is used with a purity of >98 % (Fabry & Hesse, 2012; Woditsch & Koch, 2002). In pSi production or purification processes, very basically, the impure silicon is first converted to different gas phase compounds upon its interaction with hydrochloric acid and then deposited as solid on electrically heated graphite rods after many long-lasting reactions (Ceccaroli & Lohne, 2012; Fabry & Hesse, 2012). This is called Siemens process and it is the most well-known and widely used technology in polysilicon purification (Ceccaroli & Lohne, 2012; Fabry & Hesse, 2012). The product of Siemens process i.e. polysilicon chunks are then used in ingot growth which is the next step of PV value chain. In sum, this step is comprised of both simultaneous and successive chemical reactions as well as distillation steps which enable to get rid of impurities in metallurgical grade silicon.

Though c-Si PV industry starts with this step, it is differentiated from the rest of the value chain in various dimensions. While pSi industry is substantially built on chemical reactions and separation processes, the downstream manufacturing steps are a combination of many chemical, physical and electrical processes/operations somewhat similar to semiconductor device fabrication. In terms of production scheme,

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[24] The degree of purity is usually expressed by the total number of nines exist in the percentage. For example, 99.999 % is shown as 5N.

the downstream manufacturing processes are relatively modular and have shorter production cycles when compared to pSi purification (Bye & Ceccaroli, 2014; Woodhouse et al., 2019). It is possible to mention an entry barrier for the pSi industry since pSi facilities have usually been constructed in large scale and require high capital investments (Fu et al., 2015). On the other hand, while pSi production is measured in mass units, the outputs of the following steps are directly or indirectly (i.e. corresponding value) identified in power units and hence, the unit costs are defined in per watt (Woodhouse et al., 2019). As a result, it can be said that polysilicon purification requires different investment characteristics that following steps in terms of technical, economic and operational dimensions.

Ingot Growth

This is a crystallization process where the purified silicon during polysilicon production is melted and then crystallized in the desired orientation. Therefore, this type of solar cells and thereby the modules produced from them are identified as "crystalline silicon (c-Si)".

If the structure is composed of one crystal, it is called mono crystalline silicon and if more crystal orientations are included within the final structure of the material than it is called multi crystal[25]. There are two main techniques widely employed by the solar industry to produce either mono or multi crystal silicon. Depending on the crystal structure, long mono crystal cylinders or rectangular multi crystal blocks are grown from the silicon melt through casting or directional solidification, respectively (Smets et al., 2016). These output of these processed are called ingots.

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[25] In some sources, "polycrystalline/poly" can be used instead of multicrystalline/multi" silicon solar cells.

Ingot growth is the first step where the semiconductor property of silicon is improved. To make silicon gain semiconductor property, a dopant material which is usually phosphorous or boron (and nowadays gallium[26]) atom is added into the pot. Based on the dopant element added into the silicon melt, the dominant charge in the base material is determined. The electron rich one produced with phosphorous is called "n type", while the one doped with boron is called "p type" (Wenham et al., 2007).

These characteristics are important since they can affect the unit cost due to both the complexity of their production and fabrication and/or their effect on the final product performance. Among the crystal structures, mono was the dominant technology in the early years but lost its position against multi by 2000 (Fraunhofer ISE, 2022). However, in the 20 years competition between mono and multi crystalline was mainly in favor of multi, while mono had still a significant share. In 2019 mono surpassed multi and by 2021, the share of multi decreased to a much lower level (~15%) (Fraunhofer ISE, 2022).

As to the dopant types, p type has always been dominant against n type by far (>90%) (ITRPV, 2012, 2022). Because, n type has some complexities in both crystal growth and the following fabrication steps despite promising a better product performance (Fabry & Hesse, 2012; Smets et al., 2016). As a result, within the time frame of the sample utilized in this thesis, n type silicon was not so visible in the industry, yet. However, as happened to mono, n type is expected to surpass p type in the following years (ITRPV, 2022).

Wafering

This step is usually combined with the ingot growth. The crystal silicon bricks cut from the ingots grown in the previous step are sliced to very thin square or pseudo

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[26] The boron has been replaced by gallium very fast within the last 3 years (ITRPV, 2020, 2022).

square plates via steel wires or diamond coated steel wires. The thin silicon plates obtained are called wafers. Before 2015, the slurry based technique which was based on steel wires and SiC particles suspended in a fluidic medium (Hahn & Joos, 2014) was still the dominant wafer cutting method (ITRPV, 2018). However, it was then challenged by the diamond wire technology which brought along some superiorities in terms of wafer quality, throughput and easier recycling of the Si material lost during cutting (i.e. kerf loss) (Pontevedra et al., 2018). This improvement certainly required a capital investment by the PV firms and by 2018, within 2 years, almost all industry including multi and mono crystalline wafer producers was transformed (ITRPV, 2019b).

In terms of dimensions, the current wafers produced are 165-170 µm in thickness and may have a varying edge size (in square or pseudo square shape) such as 158.75, 161, 166, 182, 210 mm (ITRPV, 2022). The evolution of wafer dimensions i.e. thickness and edge size is important since it affects the unit cost due to either enabling less use of polysilicon per unit power or increasing the throughput per unit processes, respectively[27]. The change in wafer edge size and thickness is strongly related to both the upstream and the downstream processes which require optimizations to be able to maintain or improve the final device performance and operational throughput[28].

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[27] Within the time frame of the sample employed in the thesis study, in between 2008 and 2019, wafer thickness did not change too much and remained around 180 µm (Fraunhofer ISE, 2022; ITRPV, 2022). But for the preceding time (2004 to 2008), there had been a gradual decrease from 300 to around 180 µm (EPIA & Greenpeace, 2008; Fraunhofer ISE, 2022). As to the surface area, sizes around 156 mm have been dominant in between 2009 to 2019 (CTM Group, 2010; ITRPV, 2022).

[28] When it is considered in terms of upstream processes; as it can be clearly understood, the wafer edge size is limited by the diameter of the silicon ingots grown and the wafer thickness is determined by the thickness of the sawing wires (ITRPV, 2022). As to the downstream processes, due to the weakened mechanical strength and change in light absorption behavior of the thinner wafers, following cell fabrication processes should be adapted accordingly (Möller, 2015). On the other hand, wafer size requires reconfiguration of the cell design as well as optimization of the module design properly (Trina Solar, 2021).

Therefore, any novelty in the ingot and wafer steps production technologies and/or the product characteristics may entail redesign, adjustment or optimization in the whole value chain steps. However, beyond new technological advances, some efforts like recycling or decreasing the material losses during cutting can also decrease the polysilicon amount used and thereby the unit raw material cost (Möller, 2015; Woodhouse et al., 2019). All of these can certainly be enabled with internal efforts and capabilities together with the ability to absorb and adapt to the external improvements in the field by the PV companies.

Cell fabrication

The solar cell structure is constructed on the semiconductor silicon wafers which are used as the substrate material. Solar cell fabrication is composed of many different chemical and physical processes (Hahn & Joos, 2014; Smets et al., 2016). Though these steps may vary based on the unique cell design, the main backbone is almost similar. First, in wet chemical baths surface texturing and cleaning operations are carried out to decrease the reflection from the surface and prepare the wafer to semiconductor processing. Then under high temperature and usually in vacuum medium, phosphorus or boron atoms are inserted into the silicon material up to a certain depth to form the junction which creates the electrical field in the cell and ultimately leads to separation of positive and negative charges when the sunlight is absorbed. In the following steps, the surfaces are coated with different layers under plasma medium to prevent electrical current losses and harvest the sunlight as much as possible. Finally, on the front and rear side of the cell, a metal grid/layer is formed through screen printing technique to collect the electrical current generated.

Cells can be produced in very different designs. However, the most basic version which is called standard solar cell or aluminum back surface field (Al-BSF) had been dominant for years. In 2019, the passivated emitter rear contact (PERC) cells surpassed the market share of these standard cells due to their higher efficiency values (ITRPV, 2020). Although the main design of the cell and the manufacturing facility requirements are almost similar, fabrication of PERC cells includes some additional process steps (Hahn & Joos, 2014).

Cell efficiency is the most important device characteristic which determines the ultimate performance of the cell. Very basically, it is the ratio of the output power obtained from the device to the input power coming form the sunlight (Hahn & Joos, 2014). More practically it means, higher efficiency cells can generate more power under same solar radiation compared to the ones with lower efficiency values. Therefore, research has mainly been focused on increasing the efficiency of the solar cells (Hahn & Joos, 2014) since when the relative increase in power output is higher than the increase in cost, the unit cost of the solar cell decreases.

Module Assembly

Module production is basically an assembling process. Certain number of cells[29] which are connected through conductive wires are then encapsulated in between some polymeric materials and glass. Finally, in many of the module types, the edges are surrounded in aluminum frame (Wirth, 2013). This process is called module assembly. As mentioned above, the power conversion efficiency or shortly efficiency is the most important parameter to evaluate the product performance of a PV module as well. However, reliability and the lifetime of the module are also critical parameters since they affect the final cost of the investment. (Wirth, 2013). Though module is seen as a basic assembly, the power output is not exactly the sum of the power of solar cells. Some losses (or even sometimes gains) that arise from modulation can cause the

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[29] Typically the number of solar cells used in a solar PV module is usually 60 or 72. However, In the recent years, to increase the performance, the half cut technology has been introduced (ITRPV, 2022). In this technology, since the full cells are cut into two pieces, the number of pieces is doubled as 120 and 144, respectively.

overall efficiency of the PV module to differ from the solar cell. Nevertheless, in overall, efficiencies of solar modules dramatically have increased in the past years and thus have contributed to decrease in unit cost substantially. The average efficiency of commercial PV modules was recorded as 9% at industrial level in 1980 and have continued to increase at different rates until today (ITRPV, 2022). The evolution of the industrial c-Si module efficiencies in the last 17 years can be seen in Figure 2.5 (ITRPV, 2022; Pillai, 2015)[30].

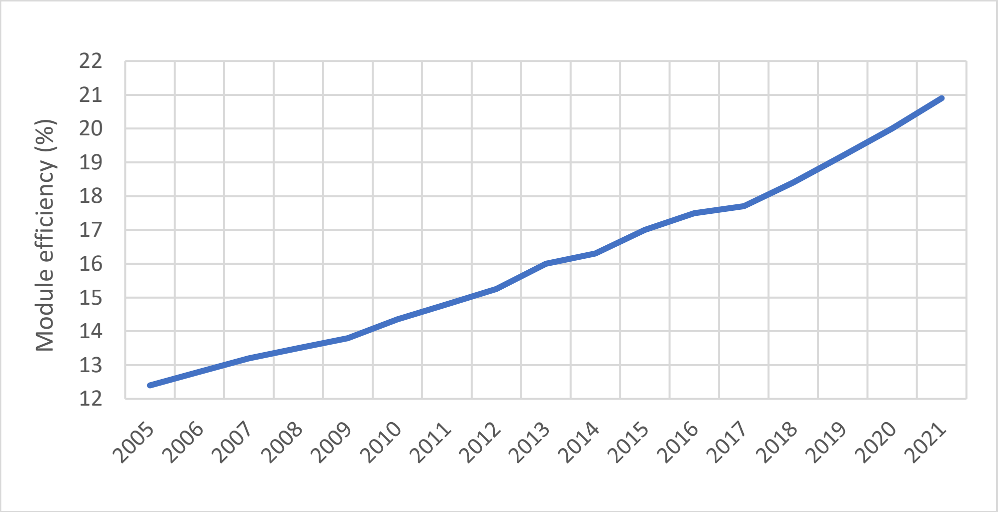

Figure 2.5. The evolution of industrial c-Si module efficiencies

However, it should be noted that due to spectrum losses and material limits, there is a theoretical maximum efficiency that can be obtained from a photovoltaic solar cell (Wenham et al., 2007) and this limit is known to be 29.43% for a single junction silicon

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[30] The efficiency values are average of commercial PV modules in the market. The values from 2010 are available in (ITRPV, 2022). For the years from 2005 to 2012, they can be found in (Pillai, 2015) where average values of 14 companies which constituted a significant portion of the global shipments (31.4% on average) in the corresponding years are provided. For the intersection years between two data sources (2010-2011-2012), the average of two sources was taken.

devices[31] without considering practical losses that arise from manufacturing restrictions (Smets et al., 2016). Although there is still a space to approach the limit, material savings, process optimizations or any efforts to decrease the cost of operations may be more prominent in the upcoming years, in addition to the new material combinations to overcome the limitation of a single junction silicon solar cell.

2.3.2. History of c-Si PV industry

There are many sources where the readers can find exhaustive stories about PV technology and industry at country level or as benchmarking of countries as well as global level (Jacobsson et al., 2004; Lee, 2011; Nemet, 2019; Gerard P. Willeke & Rauber, 2012). This subsection, rather aims at providing a brief and clear outlook for the history of PV industry from the domain of leader countries that substantially contributed to shape the current situation of the industry. Therefore, the history of PV was examined and evaluated with a structured way based on the details that had especially triggered disruptive changes in the industry and less focus was directed on the factors of which impacts remained merely at technology or market level. Though there are subperiods observed in the main stages defined, consolidation of the periods was made by considering the corresponding transitions in the national PV strategies of the countries mentioned or the global industrial trends. As a result, this part includes supportive information and quantitative analyses to enhance the understanding of industrial dynamics that underpinned the choice of the sample frame as well as some variables utilized in the quantitative part.

There are different approaches that authors embrace to define the phases of development of PV industry at local or global levels (Jacobsson et al., 2004; Lee, 2011; Nemet, 2019; Gerard P. Willeke & Rauber, 2012). Although there were more detailed

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[31] The solar cell structures may have single or multi junctions. However, since except some very niche applications, single junction has been the common technology in the market up to now, the details of this technological difference are not described within the thesis study. But in the near future, multi junction Si solar cells with novel materials can emerge to overcome the efficiency limit.

divisions made based on narrower time intervals in the literature, they converged at a certain extent. The period until 1975s was categorized under the name of “space age” in (Jacobsson et al., 2004) and “creating technology” in (Nemet, 2019). Then it was followed by the period from mid-1970s to mid/late 1990s. This stage corresponded to combination of two periods called “solar vision” and “commercial off-grid market” in (Jacobsson et al., 2004) and alternatively to “R&D” and “demonstration” stages in (Elia et al., 2021), respectively. On the other hand, same time interval was investigated under “creating a market” title in (Nemet, 2019). The reviews of the term after 1995 were more differentiated based on the year that the studies were published in. While in one source, the efforts after 1995 was examined as a “make it cheap” period in (Nemet, 2019), the same period was addressed by two subperiods called “market formation” and “full commercialization” in (Elia et al., 2021). Also in an old dated study, the title “roof-top programs” was used to define the stage after 1995 (Jacobsson et al., 2004) since the date of the paper was early enough to observe the upcoming market situations.

The market formation stages can also be defined from the perspective of technological innovation systems (TIS) in (Bergek et al., 2008). The distinction of the “nursing”, “bridging” and “mature” market stages can be easily adapted to the industrial phases of PV identified from the brief historical analysis carried out in the detailed country analyses in the following text of this subsection and in the recent trends review in the following subsection. For the background information in terms of the historical occasions, other studies from the literature can be reviewed as well (Jacobsson et al., 2004; Lee, 2011; Nemet, 2019; Gerard P. Willeke & Rauber, 2012).

In the “nursing stage” where the demand is very low yet, a space is enabled for learning where TIS can be formed. This stage leads to the “bridging stage” where the volume increases and TIS enlarges with the new actors involved. In the “mature stage” the mass market reaches higher volumes in a successful TIS. When the stages that are used to identify the historical phases of PV in the literature were examined, the phase between 1954 and 1974 was found to correspond to the “nursing stage” where the market was limited to space use and very small terrestrial applications. In that period, some countries were able to develop their own solar cells based on their domestic R&D efforts which then became more structured by means of the large programs commenced in different countries near the end of this stage. The next phase from mid-1970s and mid/late 1990s can be defined as the “bridging stage”. In that phase, large R&D and industrial programs as well as the emergence of deployment-oriented programs were seen. Also, some activities regarding acquisition of foreign firms and international collaboration agreements appeared near its end. After that period the “mature stage” arrived. During this stage, the PV market grew fast, significant structural changes happened in 10 years and industry was reached to more than 3 orders of magnitude within 20 years. The history of the PV industry is examined in the text below by utilizing the distinctive periods which are renamed based on the same frame.

To draw a general frame and provide a basic understanding, in this study, the phases are examined in three main steps each of which lasted roughly 15-20 years. Some indicative policies and the data utilized to define these stages are provided in the following paragraphs. As mentioned above, these periods correspond to roughly the breakthrough times when some common policy or industry trends were observed in different regions of the world.

The first phase i.e. “embryonic stage” (1954-1974); starts with the demonstration of the first modern c-Si solar cell that initiated the use of solar power in spacecrafts and lasts until the attempts that were stimulated by the oil crisis emerged. The second phase i.e. “development stage” (1975-1995); is characterized with the public efforts dedicated to the creation of the required knowledge stock for development of terrestrial PV module technologies as well as to the initiation of the industrial investments needed for mass manufacturing as a solution to the energy problem. The third phase i.e. “maturation stage” (1996-2011); begins when more aggressive deployment policies emerged which resulted in an accelerated production near the end of the decade and ends when China which started to be noticeable actor in the first years of this period became the world leader in all PV value chain steps. In this last stage the value chain and the production dynamics were almost settled just before the market boom. Especially in the last stage some clear-cut sub-stages were observed as well. The polysilicon prices, which had started to show significant increase near 2005 as a response to the boosted supply needs arising from the demand side policies that had been put into force at the late 1990s, rocketed in 2008. This period known as polysilicon crisis in the literature was then mitigated and when China attained the dominant position around 2011-2012, the prices remained relatively stable for a while. After then, PV market can be accepted as a mature market.

Starting from the first use of solar cells in a satellite by the American Navy in late 1950s, for two decades more PV research and the required manufacturing were mainly continued to be supported through public procurement policies of the governments for space use (Green, 2001; Lee, 2011; Nemet, 2019). However, the oil crises caused the governments to reorient their focus. Thereafter, some countries started to initiate some programs or actions to accelerate the development and deployment of PV energy for terrestrial purpose as well as scape applications. Various policy tools like mission-oriented research and public procurement supports as well as direct involvement of state-owned companies or public institutes in research and industrialization activities triggered both technological improvements and early stage manufacturing. More detailed information is available in (Christensen, 1985; Green, 2001; Nemet, 2019; Gerard P. Willeke & Rauber, 2012) for the USA; in (Kurokawa & Ikki, 2001) for Japan; in (Jacobsson et al., 2004; Lee, 2011; Gerard P. Willeke & Rauber, 2012) for Germany and in (Center for Renewable Energy Development, 2000; Lee, 2011; Sicheng, 2006; Yuwen et al., 2008) for China.

Therefore, from 1975 to roughly 1995, it can be defined as the development stage which was aggressively supported by the governments in a technology-oriented way. In that period, contributions of the US, Japan and especially Germany in Europe to both scientific and industrial development were known to be substantial. Relevant R&D expenditures of these three countries which pioneered the development of PV technologies throughout the emerging stage can be seen in Figure 2.6 and Figure 2.7 below which were drawn based on the data IEA Energy Technology R&D Budgets (IEA, 2022). Thus, after space-oriented research evolved to more energy focused agenda, from the mid-1970s till almost the end of the 1990s, a lot of progress was made as an outcome of the mentioned efforts; but they did still yield a sudden and big boost in the market until 2000s.

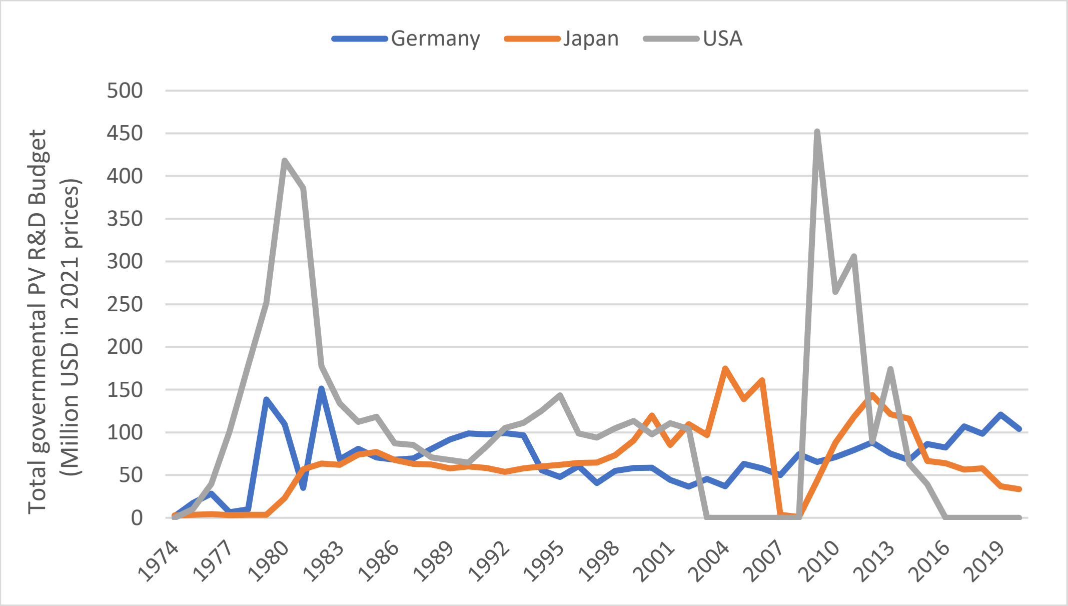

Figure 2.6. The PV R&D budgets of Germany, Japan and the US.

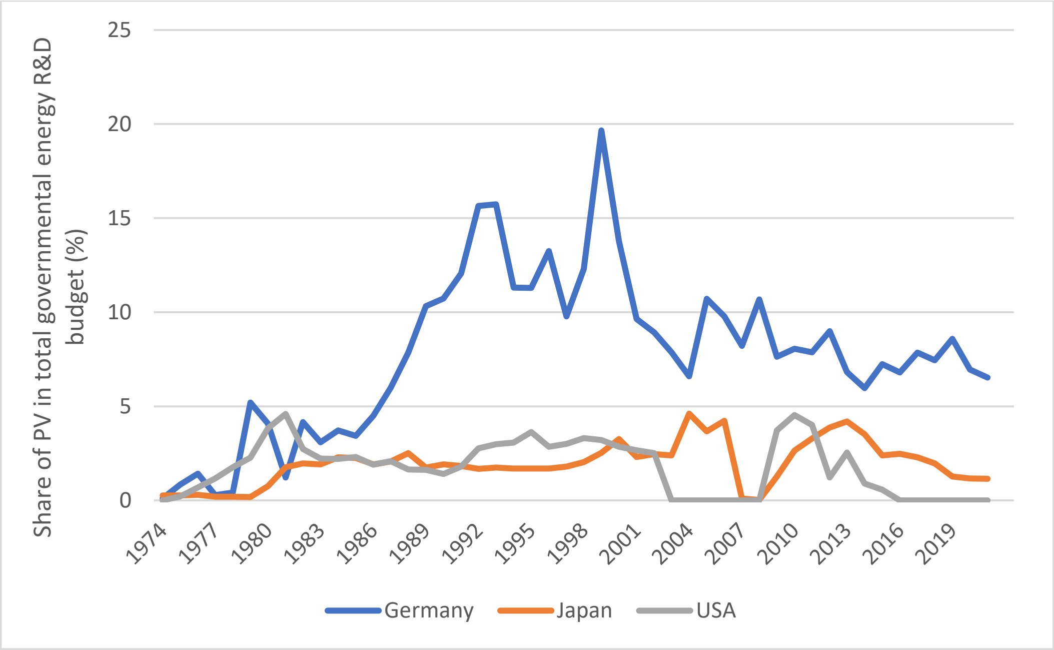

Figure 2.7. Share of PV in total governmental R&D budget for selected Japan, Germany and the USA

The US, Japan and Europe which harnessed the development stage, dominated the market in the further period as well from the 1990s till mid-2000s in terms of both supply and demand. Hence, they continued to be the most important actors in the maturation stage, too (please see Figure 2.3 for distribution of global cumulative installations & Figure 2.8 for the production). The acceleration of the production near as a response to the deployment policies that had started by the mid-1990s can be observed in Figure 2.8 (Maycock, 2005). Breakdown of global production within that period based on the selected countries/regions[32] can be seen in Figure 2.9Figure *2.9* (Maycock, 2001; Mints, 2011). As depicted there, except China, the share of these

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[32] Old data regarding PV production is usually available in a combined form as "cells and modules". The author (Maycock, 2001) of one of the references utilized as the data source explained how double counting was prevented as follows: the amount of the modules made of a company's own cells and the amount cells it sells were counted as its total production, while the production of the companies which bought cells from outside are not counted. Thus, country data describes the production of companies which are involved in at least cell production.

countries in PV manufacturing was between 80-90% till 2007. On the other side, as can be seen from the same figure, China (including Taiwan) started to become a visible actor by the mid-1990s when the other governments directed their strategies towards deployment. To understand the effects of technology policies of the selected countries in the development stage and how they might have led to the maturation stage with the successive demand side policies, some indicative programs conducted in the leader countries are addressed below[33].

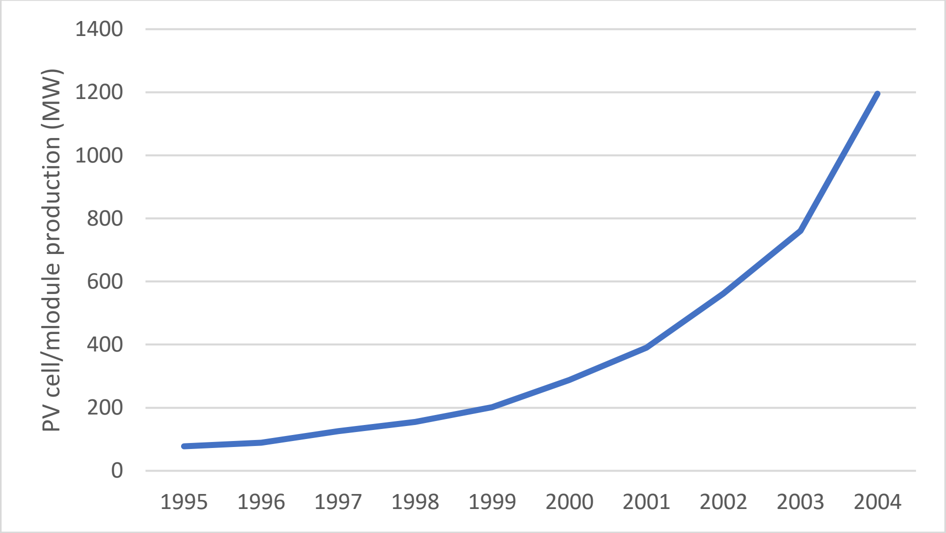

Figure 2.8. Global PV production in the first half of maturation stage

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[33] The main focus of this thesis is not the diffusion of PV installations through application/system policies. Therefore, relevant macro level market policies were not in the focus and they were not examined in a full extent not to deviate from the scope of the study. However, since they played a certain role in the evolution of PV technology and had impacts on industrial growth, they were mentioned briefly for certain time periods when they had indicative effects.

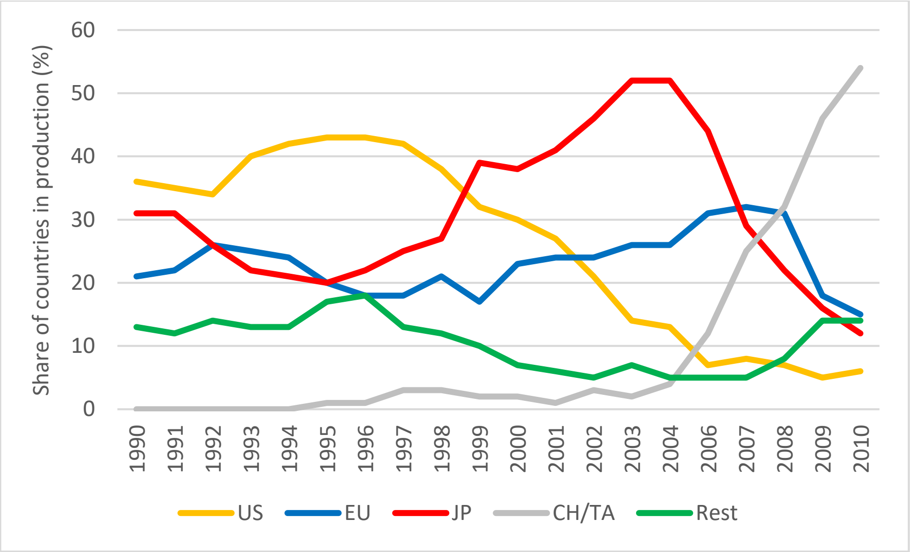

Figure 2.9.Share of countries in global PV cell/module production in the early years of PV industry

The US

The Cherry Hill Conference held in the USA in 1973 was seen as the first attempt that fueled the government programs for the development of terrestrial PV and the required industry (Nemet, 2019; Gerard P. Willeke & Rauber, 2012). At this conference, with 130 attendees from the industry, academia and the government, the goals, milestones, cost targets to be achieved were specified and a budget around 250 million $ was foreseen for the research and development activities to be carried out between the years 1975 and 1985 (Nemet, 2019). However as noted by Nemet (2019), the expenditures would be four times the estimated even though in the beginning of 1980s, at the acceleration stage of the program, the annual budget allocation was cut considerably by the government (Christensen, 1985; Nemet, 2019). Based on the IEA Statistics, the US government is seen to have spent around 750 million US dollars in nominal prices for PV R&D in the time period between 1975 and 1986[34] (IEA, 2022).

The most important output or impact of this conference was the Flat-Plate Solar Array (FSA) Project that was commenced in 1975 and phased out by the September of 1986 (Cuddihy et al., 1986). Jet Propulsion Laboratory was assigned as the responsible entity of the project on behalf the US government. The ultimate aim of this project was to make PV module technologies preferable for the widespread energy supply and the specific objectives of the project were to develop modules that would have higher efficiencies and longer lifetimes with reliable performance and which were economically feasible to be used in large utility scales (Christensen, 1985). Despite the fact that the ultimate goal was not met at the time interval targeted (Nemet, 2019), this multi-dimensional and well-structured project led to many fruitful outcomes. Some of the solutions developed regarding mass manufacturing and product reliability were adopted and utilized by the industry as common techniques and technologies in commercial products (Green, 2001). In the scope of this project, though there were some tasks for thin film technology, various c-Si oriented initiatives in research (i.e. conceptual understanding, process development, improved product designs, test & characterization methods), industrialization (i.e. pilot and mass manufacturing investments, automation compatible machine designs for mass manufacturing) and commercialization (optimizations for economically feasible solutions, standardization, product order guarantees with defined specifications) levels were promoted and funded along the whole value chain.

The FSA project was also supported by a public procurement program called Block Buy which was in force in between 1975 and 1985 (Christensen, 1985; Nemet, 2019). This program was based on purchase of certain quantity of products with pre-determined qualifications by the JPL at compelling price levels. The process was not carried out in the form of an arm’s length contact. It was roughly realized in the

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[34] In the literature, there are also higher amounts mentioned as the budget of this project. In one of references, it was said to be 1.5 million USD (Willeke & Rauber, 2012). However, in nominal prices, the sum of the annual expenses in the same time interval is almost half of it according to IEA Statistics.

following way: based on the requirements and plans, the design and specifications were defined by the JPL; the contractor delivered the design; if it was approved, the prototypes were produced by the contactor; then JPL carried out the tests and gave feedbacks to the contractor; based upon, the contractor conducted the required design and process modifications; JPL repeated the tests; after final approval, JPL prepared the user handbook as a construction guideline and finally reported the performance results of different contractors (Christensen, 1985). Thus, this program enabled incorporation of the research outcomes of the FPA project to industrial manufacturing and created entrepreneurial variety, benchmarking of different product designs and production methods and made different parties collaborate in a fast and effective way (Christensen, 1985). As counted from the final report of the project, it is seen that 11 firms had provided modules upon these contracts (Christensen, 1985). The products purchased by the US government constituted 17% of the global demand in the corresponding time (Nemet, 2019). Ultimately, some of the methods and designs developed were embraced by the other manufacturers globally and became the industry standard in years (Green, 2001). Furthermore, the definition of different specifications by the government for the final product and the requirement for the development of upstream products as well, led firms to be diversified as well as created specialization in different steps of value chain (Nemet, 2019).

As a result, the following key achievements were attained within the time period of the project which lasted almost 10 years (Christensen, 1985; Cuddihy et al., 1986). These are summarized below by elaborating the outcomes of some:

- The module efficiency was achieved to be increased to >15% from 5-6%.
- The cost decreased from 75 $/W to 5 $/W (based on the 1985 USD values).
- Industry was stimulated to set a standard in module lifetime and as a result, 10 years commercial module lifetime warranty was enabled.
- In terms of fabrication steps and manufacturing methods:

- A twostep new feedstock purification method (obtaining silane from metallurgical silicon and converting silane to polysilicon in a Fluidized bed Reactor (FBR)) was improved and verified in a pilot plant. This phase was achieved with collaboration of Union Carbide Corporation (UCC) and Jet Propulsion Laboratory (JPL) and was funded by the government within the scope of this project. In the end, a low-cost high purity precursor (Silane) and the promising optimization results were attained by means of industry-governmental research institute collaboration which was reinforced by the contributions of some private research institutes like Caltech, Westinghouse R&D Center and others. In the next phase, first step was continued to be funded by UCC for further development and moreover, the company invested in a large-scale manufacturing plant that utilized the first step developed in the first phase (silane manufacturing) and completed it with a production methodology developed by another US company i.e. Hemlock Semiconductor. This phase was carried out fully with private funding. JPL did not go on funding the project since the method employed in the second step was not found cheaper than the conventional production technique (i.e. Siemens method) which has remained as the mainstream technology in the industry so far with 95% share in 2022. But the FBR based pSi purification technology that was on the focus of the activities mentioned above is still expected to increase its share (ITRPV, 2022) since it promises less capital cost and less energy consumption (Bye & Ceccaroli, 2014).
- New wafering, solar cell metallization and modulation techniques were developed. The screen-printing method to form the metal connections on a solar cell was introduced with a protype of mass production equipment and process sequence compatible with automation requirements. Secondly, encapsulation of solar cells with new materials

which enabled significantly higher module lifetime and reliability was demonstrated and verified with contributions from the materials industry (Christensen, 1985; Green, 2001). Although there has been some modifications due to later improvements, those technologies introduced by this project set the industry standard for the modern PV production techniques which are still valid as it was articulated by Martin Green 20 years ago as well (Green, 2001)[35].

- Moreover, design requirements and concepts for different applications, test methodologies and standards regarding performance, failure and reliability of PV systems as well as economic analysis methods for manufacturing and life costs were developed.

Despite the fact that these efforts planned for one decade had achieved these enthusiastic outputs in the first half, the US government changed its strategy upon revival of the oil market. As a result, cutting of the PV research budget by 1981 caused the FPA project to weaken and the 4th and 5th blocks of Block Buy Program to be unfruitful (Christensen, 1985). Also, the government terminated the four 3-year purchase contacts that were initiated in 1980 (Nemet, 2019) and the Mass Production phase of the FPA project was cancelled (Christensen, 1985). When the project ended in 1986, it was feared in the US that the competitive and innovative power would be lost against Germany and Japan as an outcome of this trajectory change (Nemet, 2019). In the following years, German spent too much on PV R&D but still, German companies preferred to acquire some established companies in the US to refrain from too much spending on new investments (Gerard P. Willeke & Rauber, 2012). Then, the US remained as the world leader in manufacturing of PV modules until it gave its place to Japan near end of 1990s (see Figure 2.9 above). The US maintained its top position in PV related scientific publications until 2011 (Gandenberger, 2018)

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[35] The techniques were mentioned in the description of value chain steps in 2.3.1.

although Germany exceeded the USA in PV related R&D expenses in certain years in terms of both absolute amount and share in overall energy R&D budget.

The PV market had remained mainly based on consumer products (watches, calculators, scientific kits) and off-grid applications (road and garden lights, PV for lighting and refrigeration in rural areas, communication and signal systems for both military and civilian use, diesel-PV hybrid systems) till 1995 when the expected acceleration in the US started after the supports for utility connected systems were put into force one by one (Maycock, 2001). Photovoltaics for Utility Scale Applications (PVUSA) i.e. competitive procurements with partial financial support from the Department of Energy (DoE) to the customer who teamed up with utilities; The Sacramento Municipal Utility District (SMUD) Solar Pioneer Program i.e. homes equipped with either municipality owned and maintained PV installations or PV systems offered by the municipality with a subsidized price to be owned by the resident; California PV Subsidy Program which provided cash support for the installers who were encouraged by the brown-outs which became frequent upon higher prices due to deregulation in the state; various state programs, etc were some of the policy tools employed in the second half of 1990 (Maycock, 2001). These policies in the maturation stage seem to have kept the US industry survived until the first few years of 2000 when it started lose its competitive position in the market significantly (see Figure 2.9)

Germany

First manufacturing steps in Germany started with Siemens and Telefunken upon export restrictions from the US against European Space Agency in the 1960s (Jacobsson et al., 2004) which led the German/French satellite which was powered by the Siemens solar cells to have been launched in 1970 (Lee, 2011). Following, as a response to the exacerbated oil prices, the German government started to give R&D supports to PV in 1974 for the first time which then accompanied by a boost in private research expenditures on PV. The expenditures of firms became visible near the end of 1970s and by 1987, it almost covered half of the overall PV research expenses in Germany (Lee, 2011). In between 1977-1989, 18 universities, 39 firms and 12 research institutes benefited from the relevant federal fund (Jacobsson et al., 2004). As a result, great knowledge accumulation in the field was created before 1990s.

The German government had already allocated significant amount of resources to PV by mid 1980s. But still, the notion was in the direction of seeing this technology at research level and keeping the efforts accordingly since it was far from industrialization. This could be inferred from the attitude of the German research administration against establishment of the Institute for Solar Energy Systems (ISE) by the Fraunhofer Gesellschaft in 1981. According to the governmental authority this institute would only provide jobs for the university educated solar energy experts who were not able to find jobs in the industry (Gerard P. Willeke & Rauber, 2012). In that sense, it can be said that in the first three quarter of the development stage there were resources mobilized but guidance of the German government which did not be sufficient to build a self-sustained industry was limited (Jacobsson et al., 2004). Later on, acquisition of the US established companies by some German companies in the beginning of 1990s, instead of investing in their own country would be disapproved by the German politics because of migration of the educated labor and transfer of the accumulated knowledge that had been enabled by the public funds (Gerard P. Willeke & Rauber, 2012).

When the 1990s arrived, demand was not sufficient while on the other hand there were no reliable products that were transferred to the industry as well as radical cost reductions were not achieved yet by sufficient mass production (Gerard P. Willeke & Rauber, 2012). Upon all of these situations, despite important achievements in research which were mainly led by the Fraunhofer ISE and entrance of some big companies like Bayer to the field, the second half of the development stage (1985-1995) did not be fruitful for the German PV industry (Jacobsson et al., 2004; Gerard P. Willeke & Rauber, 2012).

On the other side, near the end of development stage by 1990, market creation had started to be promoted by the demand side policy supports in Germany. By means of the financial subsidies provided to private houses in the scope of 1,000 rooftop program which was in force from the 1990 to till mid-1990s, the central administration and the federal states ultimately supported installation of around 2500 rooftop PV systems in Germany (Gerard P. Willeke & Rauber, 2012). This was seen as one of the actions that the Federal government took against the Chernobyl nuclear accident in 1986 (Jacobsson et al., 2004). Despite important experience and knowledge gained from the installations, the impact did not be as much as expected in terms of demand and industry (Jacobsson et al., 2004; Lee, 2011; Mints, 2011). The low feed in tariff [36] price given at that time for PV (Lee, 2011) and the German companies that caused the potential production in the country to shift to the USA by acquiring the American companies (Jacobsson et al., 2004), did not allow the critical mass required to be built for a sustainable demand and supply in the country. Still, this program is known as a milestone in the PV history in terms of being inspiring for the following programs in both Germany and other countries (Gerard P. Willeke & Rauber, 2012).

In that sense, it can be said that when the development stage was coming to the end, the maturation stage was ignited by the end of this program. The 100,000-rooftop program commenced by the German government in 1999 and the subsequent German Renewable Energy Law (EEG) enacted by March 2000 yielded effective outcomes (Lee, 2011; Mints, 2011). Meanwhile, PV R&D funds mobilized by the government from 1990 to 1999 were utilized by 5 universities, 41 firms and 17 research institutes (Jacobsson et al., 2004). As a result, by the first years of 2000, while the production in the US was decreasing, both PV installations (Figure 2.3) and production started to increase in Germany where PV manufacturing reached 9 times of the value it had been in 1997 (Jacobsson et al., 2004). This was also accompanied by the boosted overall

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[36] Purchase guarantee of grid connected renewable energies by the governments at a certain fixed price of electricity for a defined time period.

global production that started to climb more steeply (see Figure 2.8). From the beginning of 2000s till 2007, Germany lagged behind Japan in the production race. But the amendment in the guaranteed purchase price of electricity in the EEG in 2004, made PV installations more attractive in Germany and within few years it was accompanied by increase in domestic production and Germany became the world leader for a few years afterwards (Gerard P. Willeke & Rauber, 2012). But the challenge of Germany against Japan only lasted only a few years (around 2005-2008) and as soon as it got the leadership, China entered the game as a significant player and changed everything by near the end of the maturation stage.

Japan

When the oil crisis broke out, solar energy was appeared as an option in the energy policy of Japan (Kurokawa & Ikki, 2001). However, in the beginning, strategy of Japan was different than the two other countries mentioned above. Based on a well-studied strategy, Japan commenced the Sunshine program for the time period 1974-2000 to support research and development activities in various energy technologies related to coal, hydrogen, geothermal, solar energy (Hamakawa & Kenichi, 1993). In that program, the solar energy research budget was primarily allocated to solar thermal energy and PV systems rather than PV device fabrication (Kurokawa & Ikki, 2001). The strategy was built on supplying certain amount of residential energy from rooftop PV systems based on the considerations regarding the national status, limitations and requirements like the mountainous geography, the cost of land, status of the houses and their energy needs in Japan (Kurokawa & Ikki, 2001).

Later on in 1980, the strategy was revised with a new trajectory that the energy technologies which would not only significantly contribute to future energy supply but also would be promising in terms of technological development and commercial aspects were decided to be promoted with priority (Takashi, 1989).

In the same year (1980), New Energy Development Organization (NEDO) was founded as a semi-governmental research entity which was responsible for supporting R&D in energy technologies and promoting relevant activities in both public and private sectors (Kurokawa & Ikki, 2001; Takashi, 1989). NEDO was supervising all R&D projects within Sunshine program (Kurokawa & Ikki, 2001). This can be interpreted as the first signs of reorientation of the strategy towards being an actor in development and production of PV devices and materials. Then, in 1993 when the Sun Shine program was reorganized into the New Sun Shine Program and extended until 2020 (Hamakawa & Kenichi, 1993), various PV related R&D projects on development of different solar cell structures; mass manufacturing processes of c-Si from feedstock purification to module assembly; characterization of materials and products; design of PV systems and components, etc. were started to be supported (Kurokawa & Ikki, 2001). As a result, near the end of development stage defined above (1975-1995), by 1992, the solar cell production capacity of the industry in Japan was 20 times of the one decade ago while the prices were less than one sixth (Hamakawa & Kenichi, 1993).

By the beginning of 1990s, policies became more diverse and the focus was partially shifted to faster diffusion of PV applications through electricity utility regulations and ambitious targets determined for 2000 (400 MW) and 2010 (5000 MW) (Kurokawa & Ikki, 2001). As said in a paper published in 2001 (Kurokawa & Ikki, 2001), the technologies had been already established at that time; therefore the new policies in Japan were oriented to commercialization and deployment of PV systems afterwards. In the mid-1990s, Japan was in a race with the US in terms of reaching efficiency records as well as the lowest cost (Hamakawa & Kenichi, 1993). Therefore, in the New Sunshine program that started in 1993, mass production of low cost high efficient PV cells and solar grade polysilicon production tasks were continued to be supported in the scope of specific contractual R&D projects coordinated by the departments under NEDO (Kurokawa & Ikki, 2001).

In 1993, 12 industrial groups, 3 public institutes and 6 universities had been supported for basic research in PV (Hamakawa & Kenichi, 1993). Moreover, there were eight PV firms in Japan that had 49 MW production by 1998 (Kurokawa & Ikki, 2001) when Japan’s leadership in PV production was imminent. As can be seen from Figure 2.9, then Japan remained as the world leader in PV production for one decade until the last years of the maturation stage when it was first challenged by Germany and then all market was dominated by China.

China

China, although it has had an underestimated image in terms of research efforts and innovation performance, and its success has mainly been attributed to its technology acquisition and transfer capabilities (Gandenberger, 2018), had already started to invest in PV device R&D by 1958 (Zhe & Chen, 1990) and the first Chinese solar cell that had a practical value was fabricated in 1959 (Center for Renewable Energy Development, 2000) which was only 5 years after the discovery of the modern solar cell in the USA. As the first application, China utilized solar cells for the first time in its second satellite launched in 1971 (Yuwen et al., 2008; Zhe & Chen, 1990), just one year after the take-off of German/French satellite equipped with a PV device in 1970. Then, the terrestrial use of solar cells in China was realized for the first time in 1973 (Sicheng, 2006; Yuwen et al., 2008).

The first PV company in China, Kaifeng Solar Cell Factory, started production in 1975. After the entries of Ningbo Solar Power Source and Semiconductor Component factory of Yunnan to the industry, the number of PV production factories in the country reached to three before the 1980s. They were either state owned or collectively run companies which had been mainly involved in semiconductor/electronics production previously and then transformed their lines accordingly for PV manufacturing (Center for Renewable Energy Development, 2000; Hopkins & Li, 2016; Lee, 2011). Till the mid-1980s, the existing production facilities manufactured solar cells for research purposes or small terrestrial applications like road lights, weather stations, railway signals, insect trapping lights, etc. (Sicheng, 2006; Zhe & Chen, 1990). The prices were too high till the end of 1980s since the existing factories were making production in very small scale by using space type solar cell fabrication techniques.

Within the sixth (1981-1985) and seventh (1986-1990) 5-year plans of the central government in China, PV was started to be supported in a wider extent including the industry and larger applications such as household systems, village power, civilian/military communication and security systems (Sicheng, 2006; Yuwen et al., 2008). Towards the 1990s, the electronic originated companies mentioned above started to upgrade their lines by purchasing the equipment and transferring the techniques suitable for mass manufacturing of terrestrial type solar from the US companies and machine vendors (Center for Renewable Energy Development, 2000; Zhe & Chen, 1990). Also, Huamei PV Equipment Company of Qinhuangdao which was a state-owned company as well had joined to the PV industry by 1989 and the number of c-Si manufacturing facilities increased to four before 1990 (Center for Renewable Energy Development, 2000; Lee, 2011). Thus, near the end of development stage, in the 1990s, PV companies had improved their own techniques and approached to similar qualities with the US counterparts as well as research and manufacturing staff had been raised (Zhe & Chen, 1990).

After China had given the signal of becoming a market for production machines as well as a manufacturing location, in 1995, an agreement was signed between the State Science and Technology Commission (SSTC) of China and the DoE of the US (Center for Renewable Energy Development, 2000). In the scope of this agreement, a collaboration project between the National Renewable Energy Laboratory (NREL) in the US and the Renewable Energy Development Center in China was carried out for development of mutual understanding between RE companies in two countries, enabling business collaborations, improving financial channels, carrying out personnel trainings and creating markets China (Center for Renewable Energy Development, 2000). As a joint activity of this project, experts from two countries investigated the status of PV technologies, manufacturing and sales companies and PV systems in China. Meanwhile, governmental bodies responsible for economics/trade and planning in China commenced a RE development program to be carried out between the years 1990-2010. This program had multi-dimensional aims like raising awareness, increasing international collaboration, improving R&D, speeding up industrialization, incorporating advanced technologies, attracting foreign funds with strong guidance tools and proper policies. The specific objectives of the projects formulated in this program were as follows: conducting research for high efficiency and low-cost solar cells; realizing industrialization of small PV electric systems with less system costs; installation of household small scale systems; installation of large-scale grid connected PV power stations for electrification of millions of rural houses aligned with the solar power generation program designed for 1996-2020. In sum, they were designed for improving the research capabilities, promoting establishment of domestic PV industry as well as formation of the market.

While the number of c-Si PV factories were recorded as 4 in a 2000 dated study[37] (Center for Renewable Energy Development, 2000), in an older source (Zhe & Chen, 1990), including the companies above, by 1990, 14 domestic PV device factories were listed. However, it seems only 5 factories that were specialized in c-Si solar cells and modules had significant capacities (above 0.1 MW) that covered 70% of the overall PV production potential in China (Zhe & Chen, 1990). It is also noteworthy that, in the later study, it is seen that these 4 factories and the research level fabrication facility as well were run under capacity. Therefore, in years, some companies might have discontinued production or never utilized their existing capacity due to lack of demand. Consequently, upon all efforts, there were at least 4 active PV device manufacturing

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[37] A public institute that fabricated solar cells for research and small application purposes was not counted.

factories operating at mass production level in China by 2000. In addition, 24 research institutes of which 16 were focused directly on c-Si and/or amorphous silicon solar cell and materials were being involved in PV research by 1990 (Zhe & Chen, 1990). These reveal that though China had not been a visible actor in PV technology and manufacturing before 2000, it seems that it had already built the foundation for its imminent leap.

On the other hand, as explained in (Lee, 2011), due to multifaceted reasons, the production amount and the competitive power of Chinese PV industry remained stagnant during the age of the traditional firms that were mainly active in the development stage i.e. 1975-1995. As it can also be seen in Figure 2.9, the Chinese began to be a visible player in PV industry after 1995 and but still lagged behind the other global players until 2004-2005. In sum, the reasons that were identified to cause China to lag behind in (Lee, 2011) can be summarized as being technologically limited due to multi-dimensional reasons; not having the updated technology in the manufacturing lines; not being able to carry out a well-organized research and lack of feedbacks from the users[38]. When these findings are examined in detail, they are seen correspond to different domains of functional dynamics in a technological innovation system (TIS) which is defined in (Bergek et al., 2008) and will be introduced in the section 3.5 in Chapter 3. Shortly, they can be associated with the blocking mechanisms under the relevant functions of TIS i.e. *knowledge development, entrepreneurial experimentation, resource mobilization, market formation.*

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[38] The mentioned study explains this slow progress with multi-dimensional reasons as follows. First, the production outputs of these traditional companies had technologically remained limited due to various handicaps: i) the products were not competitive due to lower quality which hampered the demand in both domestic and global market; ii) the production was being limited by the shortage of upstream products in the country as well as iii) lack of operation finance and problems in access to credits due to quality problems and market uncertainty and iv) finally, lower capacities that did not allow to exploit the advantages of economies of scale. Second, they had upgraded their lines before but they were still not able to incorporate updated state of the art fabrication techniques and designs. Third, they were not able to carry out a well-organized research which was mainly being supported by the government incentives. Fourth, there was a lack of feedback from the users of their products which were mainly located in rural areas of China and not caring about the performance.

Despite the invisibility of a clear achievement in the periods before the early years of 2000, based on the historical analysis made above, it is clear that the domains of PV TIS had well-functioning parts as well. Starting PV research in the very early years of technology; soon after in 1970s; already having at least a few firms appeared in the industry; providing governmental funds to PV research and industry; encouraging demand through demonstrations and PV based electrification policies; making an energy focused bilateral agreement that had PV specific programs under with the US and commencing 5-year plans that included PV strategies of the central government can be some representative efforts that induced the PV innovation system in China. In addition to the functions above, knowledge externalities arising from semiconductor background and a certain legitimacy enabled by means of governmental actions seemed to exist. Nevertheless, they did not be sufficient to move China to the leaders' league in the development stage.

When the first years of 2000 came, despite the deployment policies carried out near the end of 1990s, domestic demand did not increase too much (Lee, 2011; Yuwen et al., 2008) and the production started to become export oriented. As mentioned in other country reviews, the global PV demand especially arising from Germany rose dramatically in the first half of maturation stage (1995-2004). This corresponds to almost the same period when the new generation firms started to appear in China between the end of 1990s and the first years of 2000. These companies which were not state owned and would soon have been listed in the US Stock Exchange such as (Trina and Yingli) had procured their production lines mainly from Germany[39] (Lee,

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[39] Including the ones mentioned above, many of the firms that were included in the econometric analysis carried out within this thesis belonged to this group. While these firms were entering to the market one by one, the share of other countries decreased and near the end of maturation stage by 2010, the share of China approached to 60% which would soon exceed 70% gradually (see Figure 2.9). The observations utilized in the thesis study mostly cover these new generation Chinese companies which dominated the Chinese market more than 40% in 75% of the timeframe employed and the global market more than 40% as well at certain times (for more details please see section 4.3). Therefore, these firms of which establishments trace back to the early maturation stage and that mostly have survived till recent

2011; Gerard P. Willeke & Rauber, 2012). Especially as the world market demand improved near 2005, financial resources were mobilized in China and these firms were able to access finance trough bank loans and investments of local state companies to them (Lee, 2011). The institutional motivation of the local governments behind these supports can be found in (Lee, 2011). Moreover, these companies were collaborating with top PV research institutes in the world such as ECN in the Netherlands, UNSW in Australia and SERIS in Singapore which was founded by the former director of Fraunhofer ISE in Germany (Gerard P. Willeke & Rauber, 2012).

Consequently, within the development stage, production of solar cells which was seen as the most critical part of the technology increased to 3 order of magnitude from 1976 to 1990 in China of which 80% was c-Si while the costs decreased to one tenth (Zhe & Chen, 1990). At the end of the development stage, in 1995, by means of the internal efforts discussed above, the production was nearly tripled in 5 years (Center for Renewable Energy Development, 2000; Zhe & Chen, 1990). However, the turning point of PV production in China would arrive in ten years. In 2005, cell production reached to 145 MW[40] which almost corresponded to 100 times the value in 1995 (Consulting & Training Center for Renewable Energy Power & IEE CAS, 2009). With the appearance of new generation firms, the production was not only rocketed more but also it was imminent that China would catch up the other countries. Finally, near 2008, China was the world leader (A. Jäger-Waldau, 2009).

Based on qualitative studies and descriptive statistics analyses carried out, Lee also examined how different characteristics of Chinese PV industry such as technological

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dates are indicative in terms of understanding how learning led to insistent and continuous cost reduction after once the technology more or the less settled. In sum, this study examines what kind of learning mechanisms could have driven the cost decline of PV modules in these companies in combination with the industrial trends and firm strategies in the maturation stage and thereafter.

[40] In the same year, 95% of the overall cell production in China was already c-Si and the module production was 200 MW.

learning, cost advantage, vertical integration and support of central government, had leveraged China after the period that China lagged behind (Lee, 2011). In the study mentioned, technological learning was mainly associated with the machines imported, the scientists who studied abroad especially at UNSW in Australia, the complementary assets such as sufficient level of expertise in machine tools industry and background in semiconductor industry, and the labor formation in PV industry[41]. On the other hand, the cost advantage was explained by not only having cheap labor but also with the presence of low-cost skilled labor as well as capital advantages attained by means of partially local equipment supply and the contributions made by the local states through land provisions for factory investments. Additionally, vertical integration was found one of the effective factors that secured raw material price as well as lowered production costs by eliminating transaction costs. Finally, the central government's deployment programs were thought to have an impact on the knowledge development in new generation firms in the early 2000s and then their survival in 2008 crisis without having export pressure.

Evaluation of the findings in (Lee, 2011) for the development stage was made from the point of functional dynamics approach in the previous paragraphs. Similarly, when the examination he made for the later stage which corresponded to the maturation stage defined above are evaluated from technological innovation system perspective, the domains in the Chinese PV TIS that functioned well can be listed as follows: *knowledge development* through further upgrade of imported production tools, *resource mobilization* in labor force based on abroad education and the commercial activities of PV firms, *resource mobilization* in finance through local states, *knowledge externalities/exchange* arising from already established semiconductor and machinery industry, *guidance of search* and *legitimacy* provided by the governmental

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[41] One example for merger and acquisitions was mentioned to have been effective in technological learning of one company. But since it remained discrete, it was not summarized among the general findings of the study mentioned here.

deployment policies that led to *market creation* which hence enabled new firms to nurture and survive and finally *entrepreneurial experimentation* in terms of being involved in different steps of value chain thereby securing and lowering the cost of upstream products. As a result, the problems that were identified for the Chinese PV industry in the development stage in (Lee, 2011) and associated with the blocking mechanisms arising from *knowledge development, entrepreneurial experimentation, resource mobilization, market formation* functions above, seem to have been improved by overcoming the barriers identified or addressing different functions like *guidance of search and legitimacy.*

2.3.3. Recent Trends in c-Si PV industry

The graph in Figure 2.10 below[42] depicts the change in the amount of PV production together with the PV installations in the last 20 years in logarithmic scale[43]. From the slope of the lines, it can be understood that starting with 2003, China made a consistent progress in PV manufacturing and by 2007, the increase in global production was almost perfectly aligned with the increase in Chinese manufacturing. On the other hand, the amount of installations did not support that the production was triggered by the domestic demand. It is seen that though in the early years till 2004, the production in China was almost corresponding the national demand, during the stage that the

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[42] For all installation and world production data IEA PVPS Trends Report 2020 (IEA PVPS, 2020) was utilized and the data regarding Chinese production were collected from various data sources for different time periods as follows: 2000-2003 (ter Horst & Zhang, 2006); 2004-2005 (Sicheng, 2006); 2006-2007 (Yuwen et al., 2008); 2008 (Consulting & Training Center for Renewable Energy Power & IEE CAS, 2009); for 2009 (Honghua et al., 2012) and from 2010-2019 (CPIA, 2016, 2018, 2019, 2020).

[43] The data depicted represent all PV panel shipments however as mentioned before share of c-Si modules in the last 20 years rarely went below 90% globally and although the breakdown of Chinese module shipments was not available in terms of panel material for all years, in many of the data sources it was either indicated that the market was dominated by c-Si modules or the provided values was proving that the share of c-Si was above >98% and usually >99%. Since the production lines cannot be changed from year to year, the trend seen in the graph can be perceived as representative for c-Si technology.

Chinese PV shipments were rocketed until 2011, there was a certain amount of gap between them in favor of production. By considering the logarithmic scale in Figure 2.10, the share of Chinese installations in global demand can be seen to have become significant after 2011. Hence, it can be concluded that the first leap of China in production was not related to its internal demand.

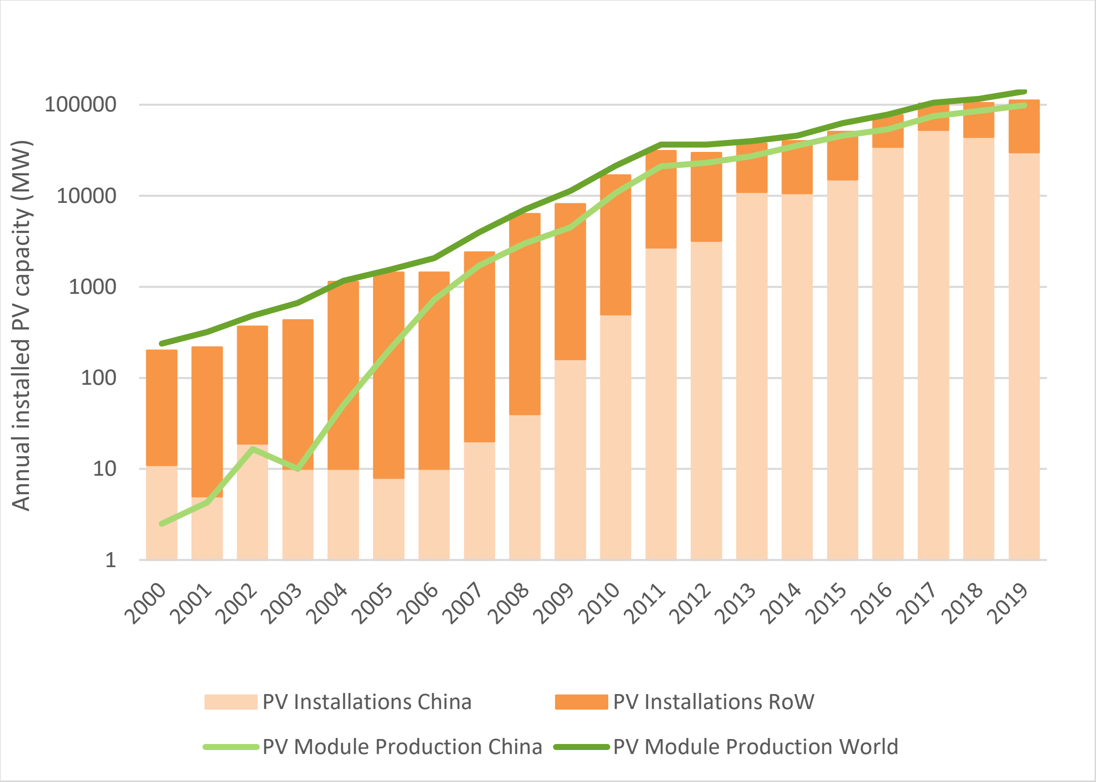

Figure 2.10. Annual PV installations and production of the World and China

When the PV industry is examined in a wider scope than the modules which is the end product of PV manufacturing, the share of China in all steps of value chain exceeded 50% threshold in 2011 except the feedstock material polysilicon. Even if it would take 6 years more to reach the same level in polysilicon, by 2011 China was already the world leader in it as well (Bernreuter Research, 2022b). The graph in Figure 2.11

shows[44] how China achieved to meet the increasing demand in the world gradually as well as to sustain its climb that had started in 2003[45]. This period corresponds to the time frame of the observations that were utilized in the econometric analyses of this thesis study.

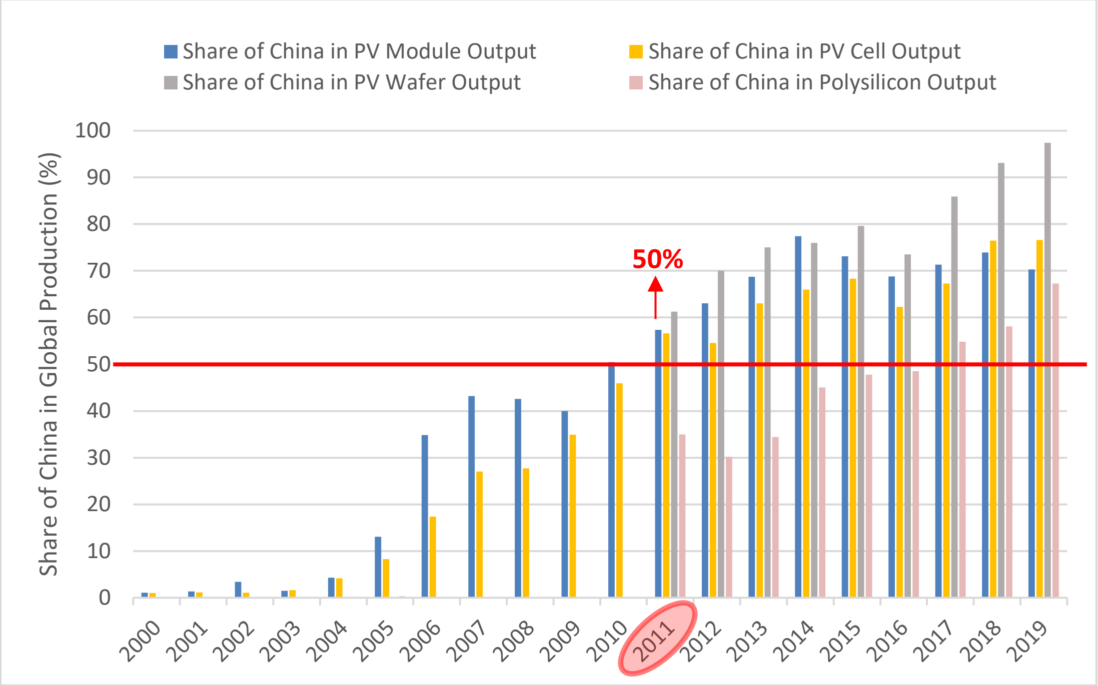

Figure 2.11. Share of China in different steps of value chain

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[44] In addition to the data sources utilized for module production in Figure 2.10, Figure 2.11 was drawn based on the data collected from various sources as follows: for global cell production data in 2000-2005, JRC PV Status Report 2006 (Arnulf Jäger-Waldau, 2006) and until 2019, following year's JRC PV Status Reports which are available at (European Commission, 2022c); for Chinese cell production between the years 2000-2008 (Consulting & Training Center for Renewable Energy Power & IEE CAS, 2009), in 2009 (Fang et al., 2013), between the years 2010-2019 (CPIA, 2016, 2018, 2019, 2020); for data regarding wafer and polysilicon, data in (CPIA, 2016, 2018, 2019, 2020) were utilized.

[45] Since reliable and consistent data regarding the upstream stages (i.e. wafer and pSi) could be found after 2010, they are seen in the graph for the later years.

As to the share of semi products in the overall cost, PV modules and cells together constituted the substantial part of it in the last decade. In Figure 2.12, it is seen that the combined added value of these last two steps were between 60-70% for almost 10 years[46][47]. The share of polysilicon is not too high in the graph below; however, it is a very critical step and can have very destructive effects on PV industry. As mentioned before, it is not used only in PV industry, but since the demand from the PV market boosted starting from the first years of 2000, the polysilicon industry dynamics have heavily depended on PV.

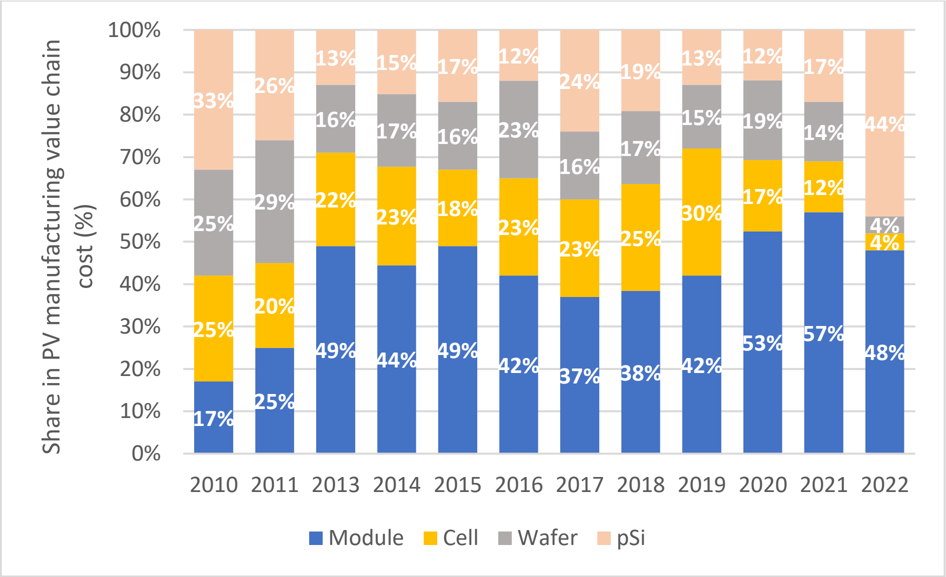

Figure 2.12.The breakdown of PV value chain costs

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[46] The graph data is compiled from ITRPV reports (ITRPV, 2014, 2015, 2017, 2020, 2021, 2022). The available data starts with 2010. Data regarding the year 2012 was not found in the ITRPV periodic reports and for sake of consistency, the data in other sources was not included. Except a few years, the values given are based on current year's first month. Data of the year 2015 belongs to February and 2021 and 2022 data belong to December 2020 and 2021 respectively.

[47] PV value chain products listed in the commodity market are usually available for pSi, wafer, cell and module (InfoLink Consulting, 2022; PVinsights, 2022). Ingot growth is one of the value chain steps in production as described in previous sections however since the practical end product of this step is wafer which is fed to the cell lines, ingot/wafer production are usually combined within firms as depicted in Figure 2.12.

Until 2005, pSi production was being executed only in 9 plants owned by 7 companies located in 4 countries (the USA, Japan, Germany, Italy) and their overall production was around 29,000 tons in 2004 (Bernreuter Research, 2022a). The countries that mainly dominated the polysilicon market had also been the pioneers of the PV industry as mentioned in the previous subsection 2.3.2. Additionally, there was one Chinese producer with a very little contribution to output (0.3%) in 2004 as reported in the reference (Bernreuter Research, 2022a). But since it was found negligible as said by the author in the source, it was not counted in the manufacturing locations and among 7 companies. Still, involvement of China in the raw material market in the early years of maturation stage might have contributed to its knowledge stock and encouraged further entrepreneurial experimentation in the pursue of securing the raw material industry when it is considered that by 2011 China was the world leader in pSi manufacturing as well.

As 2020 arrived, the actual global pSi output was almost 500,000 tons (IEA PVPS, 2022c) and despite being less concentrated, 75% of the global pSi production capacity was still provided by only the big six companies (Bernreuter Research, 2022a; RTS Corporation, 2022). When the numbers compared, within almost 15 years, the pSi requirement approached to 20 times of the amount produced in 2004 (Bernreuter Research, 2022a). Hence, the oligopolistic polysilicon industry which was not prepared for the boost in the PV market would soon lead to shortage in the second half of the maturation stage. The outcome of this situation in terms of both pSi spot prices and the response of PV industry can be observed in Figure 2.13[48]. It is noteworthy that during the crisis that lasted a few years around the peak time 2008, the PV installations did not slow down but the unit amount of polysilicon used in PV modules was gradually reduced by means of the advancements in the following downstream processes. It was mentioned in previous subsections (2.3.1.) that wafer thickness also decreased significantly between 2004-2008 which corresponds to the pSi crisis years.

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[48] Data source: (Bernreuter Research, 2022b, 2022c)

It is strongly probable that this improvement was fueled by the crisis since the slope of decrease in polysilicon use within the years 2003-2008 was three times of the value calculated for the time interval 2009-2019. However, since any change in the material directly affects the following processes, the companies which survived within this time period could not have achieved this only by procuring the cost advantageous semi products but also through further efforts to adapt to the required technological and operational changes[49]. Dynamic capabilities of firms, which will be discussed under learning related concepts in Chapter 3, may be seen as an important characteristic of the manufacturing actors who enabled the PV industry to sustain within and after this time frame.

As a result, since pSi purification requires a different specialization as well as relatively much higher capital investments (see the previous subsection 2.3.1), this step has remained concentrated and partially out of the vertical integration within firms comparing with the other following upstream steps of the PV value chain.

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[49] Use of thinner wafers requires certain optimizations in following processes i.e. cell and module fabrication.

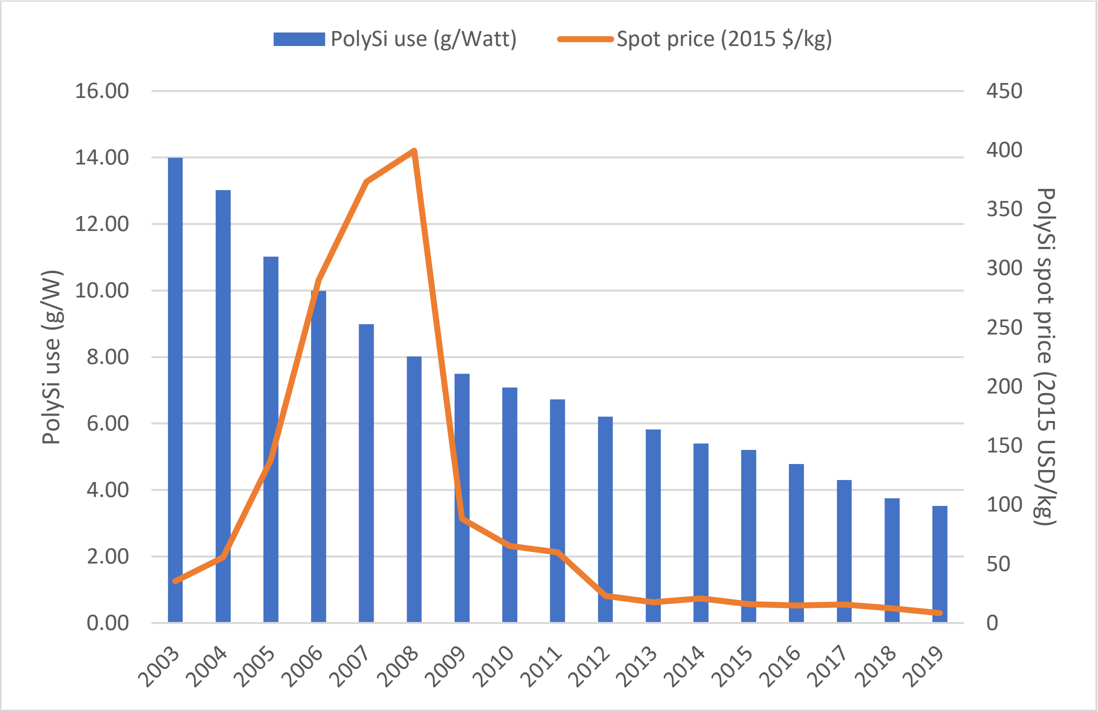

Figure 2.13. pSi spot price trends and change in unit amount of pSi used in solar cells

Consequently, the characteristics of the period starting from the second half of the maturation stage (nearly 2003) and extending today can be listed as; annual shipments reached three orders of magnitude (Figure 2.10), increase in module efficiencies has continued more steeply (Figure 2.5) and the module prices decreased 4-5 times much faster than in the development phase[50] (IEA PVPS, 2022c; ITRPV, 2022). Hence, PV has been the technology that broke the electricity generation cost record among all RE technologies within 10 years (2010-2020) which can be defined as post-maturation stage (please see Table 2-1).

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[50] This will be examined in the next chapter more deeply.

2.4. Concluding Remarks

This chapter was dedicated to creation of a certain level of familiarity with the PV technology and industry. For this purpose, after an introduction to the general attributes of PV technology and status of the market, the value chain was described shortly. Then the history of PV industry was examined in terms of leading countries in the past and currently. Finally, the recent trends were addressed with more details that justify the sample selection and some parameters utilized in the quantitative and qualitative analyses in the following chapters. The historical analysis was critical in terms of reinforcing the underpinnings of the policies recommended in the final Chapter of the thesis study. Therefore, they are summed up below.

When the time period that corresponded to the development (1975 to 1995) and the maturation stages (1995 to 2011) were evaluated together, it can be said that the policies employed in the three leading countries (the US, Germany and Japan) contributed for making PV a major energy source. In the pursuit of this aim, first, they followed a technology push attitude and provided substantial amount of R&D funds. However, the leader of this period became the US which was the mainland of the first practical device invention and had already accumulated sufficient amount of knowledge when the technology was emerging till 1975. In the first 10 years of this term, the well-structured and industry-oriented public programs in the US, which covered the whole value chain and required investment of multiple industrial partners in both horizontal and vertical dimensions, created a diversified knowledge base and enterprises that were competent for mass production and commercial standards. The change in the direction of the policy and end of the programs in the mid-1980s, hampered this enthusiasm and though the previous strategies and efforts made the US sustain its position one more decade till 1997, it was surpassed by Japan by the end of 1990s despite the successive deployment policies enacted in the US.

In the beginning of the development stage, by 1974, Japan was one of the early movers. However, its primary strategy was more focused on PV systems and applications. After then with 5-6 years lag compared to the US, Japan started to focus on development of PV technologies by considering the commercialization dimension. Contrary to the US, sustaining its relevant programs that had long term goals for 25 years and reorganizing the well-known relevant research program Sun Shine in 1993 with an extension till 2020 as well as dedication of the government with consistent technology and deployment strategies, moved Japan to the top by the end of 1990s and made it remain there for a long time nearly until the end of maturation stage. Moreover, Japan’s R&D expenses in PV exceeded the US in absolute amount at certain years within this time period.

On the other hand, although Germany had invested in knowledge creation too much (see Figure 2.6 and Figure 2.7) in the development stage and there was a certain amount of improvements and production in the second half of the development stage (i.e. early years of the 1990s), the production in Germany was boosted with a sharp increase (Gerard P. Willeke & Rauber, 2012) when the deployment policies enacted in 1999 and 2004 managed to create a significant amount of local demand. Despite some disruptions at certain times due to the strategy of private companies to invest in other locations and relatively insufficient dedication of the government to industrialization, the efforts that had started in 1974 was significantly being fruitful nearly after 30 years. But the dominance of Germany in production did not be sustainable and ended up immediately upon the aggressive growth of Chinese production. As depicted in Figure 2.9, production in all Europe had a short-term peak in the corresponding time interval and then lagged behind the new comers. However, more or the less in overall, the EU sustained its share in production along the development and maturation stages.

As to China, in the development stage, though there were a few state-owned firms involved in PV device fabrication, manufacturing did not become visible until targeted policies were defined in the periodic plans and relevant programs were commenced. These policies followed by the emergence of the private companies that constructed their lines on upgraded technology procured from the US and Europe. Thus, from the second half of the development stage to the early years of maturation stage i.e. from 1985 till near the end of 1990s, Chinese PV industry was nourished internally through the efforts of existing companies and guidance of the government gradually for implementation of PV research, emergence of domestic industry and increasing system installations. In this period, a certain amount of the knowledge was accumulated and specialized labor force was raised. Thereafter, concurrently with the growth in global demand, in the mid of maturation stage China became ready for takeoff.

To sum up, development of the PV industry seems to have heavily depended on somewhat similar yet differentiated policies implemented in these countries. While the US followed early stage technology push policies with an industrialization focus, Japan implemented similar policies by fortifying them with long term and consistently dedicated aspects. On the other hand, Germany preferred to keep the research on the front with a less industrial focus and directed its efforts to market creation through the deployment policies which led similar programs to be commenced in the world. China which has been visible in the first years of 2000 completed the maturation stage (1996-2011) as the world leader with the guidance of the government and the public resources mobilized which ultimately triggered the entrance of new actors into the market. Moreover, development/creation of knowledge seems to have been reinforced in China by means of the equipment imports, bilateral collaboration programs with the US as well as labor/student exchanges with the other Pacific countries at a certain extent.

As a result, development of technology supported by public finance mobilization and/or establishment of focused research organizations was important. But the policies that somehow stimulated manufacturing by creating demand through direct policies such as public procurements or indirect ones like market incentives were at the core of growing production in all countries. The common attributes of Asian countries were setting gradual but long-term goals which were persistently sustained. On the other hand, China seems to have been more open to interactions and external knowledge diffusions through internationally collaborative programs, labor exchange and technology imports. Consequently, as the trends in Figure 2.9 and Figure 2.10 reveal, none of the countries except China could maintain their rising position with the increasing market demand for 20 years. These findings attained from the examinations in this Chapter are important in terms of justification of the motivation to understand the mechanisms in China as well as developing policies by learning for the past.

CHAPTER 3

ANALYTICAL FRAMEWORK

Don't fall into the error of the artist who boasts of twenty years of experience in his craft while in fact he has had only one year of experience - twenty times.

Trevanian

This chapter constitutes the theoretical background that underpins the analysis and evaluation frameworks utilized in the empirical and qualitative studies. In this scope, primarily, background of the learning curve approach which constituted the basis of the quantitative study is provided. Second, implementation of learning curves in RE technologies is briefly discussed. Third, a comprehensive analysis is made by reviewing the PV learning curves available in the literature, discussing their general limitations and uncertainties and examining them more deeply based on classification of different levels of analysis. Fourth, the learning types addressed before are examined in terms of their relation to capability-oriented concepts i.e. absorptive capacity and dynamic capabilities described in the innovation literature. Finally, functional dynamics approach which was utilized to identify the well-functioning or hindering patterns of the PV industry based on the findings of quantitative and qualitative studies, is introduced and, some studies that employed this approach for analysis of PV industry are mentioned.

3.1. Background of Learning Curve (LC) Approach

Learning curves have been used to analyze the change in cost of a technology or an industry through learning by doing (LBD) which is usually associated with the cumulative output (Arrow, 1962; Dosi & Nelson, 2010; Thompson, 2010). However,

including its very basic version, it has evolved too much so far since its first appearance in the literature. In the first subsection below, the emergence of LBD concept in its preliminary form, its subsequent variations developed upon further observations and theoretical explanations that came after are described under the historical background. Following, how it was derived under various assumptions is shown and the basic structure that lays the foundation of many models employed in contemporary studies is revealed.

3.1.1. Historical and Theoretical Background

Historically, the experience effect which would be later called as “learning by doing” by Arrow (Arrow, 1962), was first introduced to the literature by Wright in 1936 with his study which showed the empirical evidence that labor productivity had been increased through accumulated firm output in the US airplane manufacturing (Arrow, 1962; Dosi & Nelson, 2010; Thompson, 2010; Wright, 1936). Meanwhile, during the World War II, experience curves were being observed in the processes of US aircraft and shipbuilding manufacturers as an expectation of government (Berndt, 1991; Thompson, 2010) which would later be verified by the post studies carried out in the cool war period (Hirsch, 1956; Thompson, 2010). After then, the findings were generalized to overall aircraft industry in the US upon implementation of experience curves by the RAND Corporation[51] in a more extensive way (Hirsch, 1956; Yeh & Rubin, 2012) and started to be used as a strategic planning tool by the US Air Force

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[51] RAND Corporation was established as a non-profit private organization in the leadership of people from universities, industry as well as the Army and the government of the USA to guide to military planning and take relevant research and development decisions (RAND Corporation, 2022).

(Arrow, 1962). On the other hand, though it was not called differently, in a 1961 dated study a similar effect was also observed in the Swiss steel industry in the productivity of labor which had been increased within 15 years without any new investments (Arrow, 1962; Dutton & Thomas, 1984). This finding which was named as Horndal effect provided an important implication about the validity of experience effect in a different sector and its independence from new or additional capital. It would be addressed again in the 1970s when another study carried out for a textile mill which had been maintained without any new investments for 20 years yielded congruent results (Thompson, 2010).

In the original study of Wright, the word “experience” was preferred rather than “learning”. However, Arrow’s study is well known with introducing the term “learning by doing” to the literature. In his study he mentioned that describing this effect as learning had also been met in the preceding studies (Arrow, 1962). After Arrow’s study, use of experience or learning curves became a common tool in both public and private sectors and plenty of studies that tried to explain unit cost decline with respect to cumulative output in a wide range of sectors at different levels emerged (Berndt, 1991; Dosi & Nelson, 2010; Dutton & Thomas, 1984; Nemet, 2006; Thompson, 2010; Yeh & Rubin, 2012). Thompson listed the chronological appearance of LBD studies as follows (Thompson, 2010): efforts were mostly focused on empirical implementation of learning by doing at industrial levels throughout 1960s and 1970s; in the late 1970s, theoretical studies for utilization of LBD effect in industrial strategy appeared; by the 1990s it was started to be employed in macroeconomic models and in the contemporary term much attention has been given to empirical models and identifying the sources that underly this phenomena.

It is also so often referred in the literature that studies of Boston Consulting Group (BCG) in the 1970s which extended the scope to various industries played an important role in the attention that experience or learning curves attracted (Dutton & Thomas, 1984; Thompson, 2010; Yeh & Rubin, 2012). However, BCG had employed unit price rather than the unit cost or labor productivity with respect to cumulative output (Dutton & Thomas, 1984; Junginger et al., 2005; Neij, 2008; Yeh & Rubin, 2012). The discussion about use of price as a dependent variable can be found in the following subsections of this chapter (please see subsection 3.2.2.4).

The multiple ways of implementation of this observed effect raised the requirement about the distinction of experience, learning and progress terms used to define the advantages enabled by the cumulative output. According to some authors, ‘experience or progress curves’ both cover all dynamics that enhance knowledge and affect manufacturing costs like a process or product related technological improvement, a managerial change or an input variation as well as accumulated knowledge by any type of learning; while ‘learning effect’ was characterized with reduction in unit costs or productivity merely based on accumulated experience in individuals (Berndt, 1991; Dutton & Thomas, 1984; Nemet, 2006). Also progress term could include non-knowledge related activities (Dutton & Thomas, 1984). Another differentiation was made based on the extent of experience area. Learning was seen at level of firm where either a production line, a process or a manufacturing plant was unit of analysis whereas experience was used to define a gain that could be attained at industry level (Dutton & Thomas, 1984; Nemet, 2006; Yeh & Rubin, 2012). Additionally, Dutton also put forward the nuance of progress term from experience by articulating the applicability of the former at the firm level while the latter was attributed to an entire industry (Dutton & Thomas, 1984).

The need to separate the domains of observations was underpinned with the variety of rates attained in the progress studies at firm, plant and process levels (Dutton & Thomas, 1984). In parallel, in an early study it was mentioned that difference of progress ratios was clear among the plants that were manufacturing same type of airframe (Alchian, 1949). The aggregated learning rate for the entire industry was used to calculate the total amount of labor required for the first 1000 airframe in 22 different plants and the standard error between the actual and predicted value was found significantly high i.e. 25%. However, focusing on this spatial irregularity was criticized by one of the authors by attracting the attention to more often met intertemporal deviations (Dosi & Nelson, 2010). The failures arising from the different level of analysis embraced in model construction and the solutions addressed will be revisited in the following subsections.

Still, in its broader meaning, according to some authors learning was not limited to "learning by doing" and could occur in different ways at diverse levels from firms to industry and cause improvements not only in unit product cost or labor productivity (Dosi & Nelson, 2010; Nemet, 2006; Rout et al., 2009) but also in product performance as a tool for innovation (Dosi & Nelson, 2010). Indeed, in his famous study, Arrow mentioned the drawback of his model in capturing other effects that might have ended up with learning (Arrow, 1962). On the other hand, Dutton while defining the progress as an outcome of a set of multiple factors that led to knowledge gain, he also emphasized that the variety in the progress ratios among firms that had identical goods and labor skills might have arisen from the specificity of operating characteristics and differences in product mixes (Dutton & Thomas, 1984). Therefore, if progress is an aggregate of mixed factors and firms cannot be identified with only similarity in their products and labor skills, learning from other influences or conditions cannot be reduced to cumulative capacity. In that sense, learning converges to the definition of experience which was thought to come out as a result of a wider set of drivers by some authors mentioned above. Different types of learning and related dynamics will be discussed later under this chapter. As to the progress, in modern use of learning curves, it is defined as the level reached after a certain learning of which mathematical definition can be found in the following part of this subsection. Therefore, when considered thoroughly, use of either term is different expressions of the same meaning.

Within this text, learning and experience curve terms were used as substitutes; but in the scope of the research performed, the former was intentionally preferred. Because, first, it was assumed to cover not only "learning by doing" but also the remaining direct or indirect learning effects behind the cost decline. In addition, the domain of the quantitative analysis was selected as firm level rather than carrying out estimations based on aggregate industry values which were more frequently defined as experience in the literature.

Beyond empirical studies, from the point of the economics literature, incorporation of learning by doing into the cost equations was first seen as a way to open the "black box"[52] i.e. the constant that represented the technological change or knowledge advance (Arrow, 1962; Berndt, 1991; Thompson, 2010; Yu et al., 2011). In that sense, it was an endogenous factor that was enabled by the firms' accumulated efforts instead of an unknown external technology progress. However, since it embodied the annual output capacity, namely being structurally related to economies of scale, the cumulativeness was subject to questioning in terms of providing an additional contribution to the benefits already enabled by the current scale effect. Moreover, according to some authors it was the cumulative investment rather than the cumulative output that was capable of keeping the learning continuous since it embodied the knowledge gained through new capital and the learning triggered by the change it caused (Arrow, 1962; Thompson, 2010). But learning by doing effect was found valid even when the rate of output (i.e. the amount of operations) remained same (Alchian, 1949; Berndt, 1991) or the rate of investment was zero (Arrow, 1962; Dutton & Thomas, 1984; Thompson, 2010). Hence, both concerns above are unraveled with the conclusion that LBD is a separate economies of scale phenomenon than the plant or the firm scale and is not bounded by the new investments. Nevertheless, certainly there may be further learning effects arising from the cumulative investment enabled

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[52] Some authors discussed the black-boxing approach exhaustively (Dosi & Nelson, 2010; Kline, 1986). Even the endogenous approach that proposed incorporation of knowledge in the aggregate production function was criticized for sustaining the black-box notion. On the other hand innovation systems approach which considers a variety of concepts by especially regarding the role of institutions in a technological change, was found more eligible to open the box due to enabling more parameters to be investigated in both quantitative and qualitative methods (Carlsson, 2007).

through the stimuli created by the new machinery and the changes they cause in their environment (Arrow, 1962; Thompson, 2010). Accumulated output especially when the rate is constant cannot capture the same effect.

As defined by Arrow, learning is strongly based on the attempts to solve a problem and therefore only comes out during an activity which requires a steady evolution beyond repeating, to escape from the trap of diminishing returns (Arrow, 1962). Maybe one of the most important contributions of Arrow's study was his endogenous theory of the changes in knowledge which explained the intertemporal and international shifts in production functions through learning realized upon acquisition of knowledge. Thus it was shown that the cost curve was irreversible in time or in other words had a non-static behavior that prevented to move along the same isoquant up and down based on capital and labor (Antonelli & De Liso, 2005). As a result, exogenous technological change either embodied or disembodied from the other inputs in a production function before[53] was transformed to an endogenous parameter as advocated in evolutionary economics (Antonelli & De Liso, 2005). Schumpeter articulated the incapability of static approach to predict the outcomes of discontinuous change and to reveal the mechanisms behind it (Rosenberg, 2000). Therefore, all attempts that try to associate the learning effects with technological progress, somewhat converge to evolutionary approach. But still they may remain insufficient when learning is considered in only one dimension as discussed in footnote 53. In that sense, Arrow emphasizes the importance of including quality of labor in his study and admits that he fails to incorporate other factors that affect learning such as education, research and institutions embedded in society (Arrow, 1962). Finally, Dosi and Nelson

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[53] According to Solow, Harrod and Hick's neutrality, technical change as an exogenous variable can be modelled in relation with labor; capital and both, respectively. Constant labor to output in Solow's case; constant capital to output in Harrod's case and constant product to output economies in Hick's case can only be valid if technical change does not occur. Thus, these streams in neoclassical approach embrace embodied version of technical change. Despite limited interaction with other inputs, it is still perceived instantaneous (Antonelli & De Liso, 2005).

articulated the need for a deeper understanding of the learning effect on the observed performance as given below (Dosi & Nelson, 2010) (p.72):

> The interpretation of the learning mechanisms underlying the observed performance trajectories and of their variations across different paradigms are indeed important tasks ahead for evolutionary analyses of innovation.

Supporting the discussions above, the illustration in Figure 3.1 shows how learning can affect the cost-quantity relation. While the cause of vertical shift in the cost-scale curve is attributed to LBD, scale effects are found responsible from the horizontal shift (Berndt, 1991; Isoard & Soria, 2001; Yu et al., 2011). Therefore, it can be said that learning by repeating actions i.e. learning by doing can still be observed as an additional and long-term effect which is irreversible even if the output remains unchanged as can be seen in Figure 3.1.

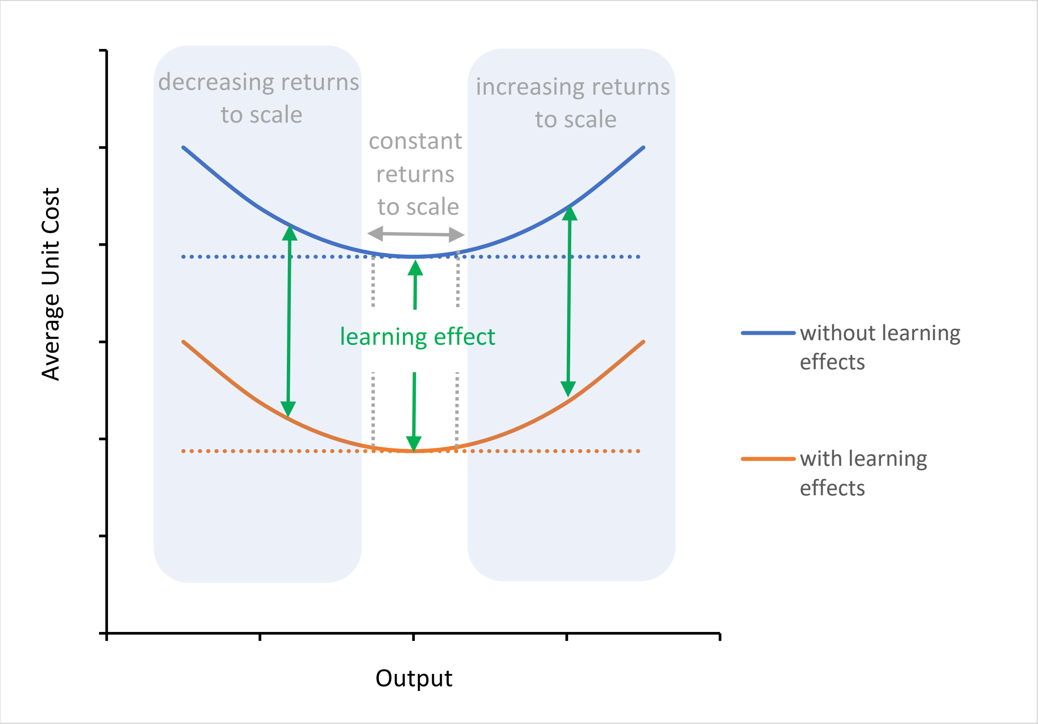

Figure 3.1. Cost-scale curve with learning effects

Consequently, the existence of experience curve is worth understanding even in its very basic form since it may affect the decision and behavior of agents in favor of high capacity production at early stages to be able to accumulate the required learning that will decrease their cost subsequently as soon as possible (Berndt, 1991; Dutton & Thomas, 1984; Nemet, 2006; Rout et al., 2009). Thus, while firms can determine their price strategy accordingly by sacrificing their profits even with selling prices under cost in pursuit of increasing their shipments (Berndt, 1991; Dutton & Thomas, 1984; Nemet, 2006); policy makers can design and evaluate the support programs by considering the social returns of higher capacity investment strategies (Berndt, 1991; Nemet, 2006; Rout et al., 2009).

3.1.2. Derivation of Learning Rate Equation

In terms of its mathematical interpretation, learning curve theory depends on the exponential relation between the cumulative capacity and the unit cost. Therefore, to find a cost value that corresponds to a certain cumulative capacity, the term progress ratio (PR) is introduced. Progress ratio defines the new cost as the percentage of the initial cost based on Equation 2 and Equation 3 below:

$$C_x = X^{-b} C_0 \qquad \text{(Equation 2)}$$

$$ln\, C_X = - b\ ln\, X + ln\, C_0 \qquad \text{(Equation 3)}$$

where C_x is the desired unit cost and C_0 is the initial unit cost and X is the cumulative capacity.

If we sketch Equation 3 above as seen in Figure 3.2, the learning factor b is obtained as in Equation 4.

$$-b = \frac{ln\, C_{x_2} - ln\, C_{x_1}}{ln\, X_2 - ln\, X_1} \qquad \text{(Equation 4)}$$

Then after some manipulations depicted in Equation 5 and Equation 6, progress rate in Equation 7 is attained.

$$-b\ (ln\, X_2 - ln\, X_1) = ln\, C_{x_2} - ln\, C_{x_1} \qquad \text{(Equation 5)}$$

$$-\ b\ ln \frac{X_2}{X_1} = ln \frac{C_{x_2}}{C_{x_1}} \qquad \text{(Equation 6)}$$

$$e^{-b\ ln \frac{X_2}{X_1}} = (\ e^{ln \frac{X_2}{X_1}})^{-b} = (\frac{X_2}{X_1})^{-b} = \frac{C_{x_2}}{C_{x_1}} \Rightarrow PR \qquad \text{(Equation 7)}$$

Therefore, if the capacity is doubled which is used as a common measure for progress, the PR takes the form 2^{-b}=PR. In Figure 3.2, the slope "-b" yields a fast result to estimate the progress that a technology follows i.e the new cost in terms of percentage of initial cost each time the total capacity doubled. Additionally, learning rate (LR) which is more practical to use defines at what percentage of the previous price the cost decrease will be and it is obtained by subtracting PR from 1 as in Equation 8.

$$LR=1-PR=1-2^{-b} \qquad \text{(Equation 8)}$$

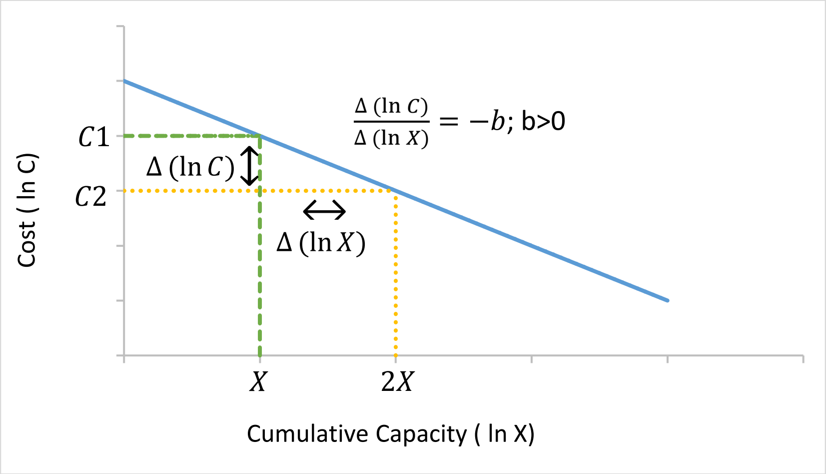

Figure 3.2. A representative learning curve and progress ratio

Though its justification seems to be empirical, there have been attempts to validate learning curve equation through simultaneous solution of the cost function with well-known neoclassical production function i.e Cobb-Douglas (C-D). The final form of cost equation which is attained after some mathematical manipulations and arrangements is extended with incorporation of cumulative output and some knowledge development related parameters which define the unknown technological change coefficient. Thus, the disembodied technology effect in classical notion appears as an endogenous technological improvement parameter in the learning curve inspired cost equation which is called “extended version of the C-D production function” (Antonelli & De Liso, 2005). Still in addition to learning via cumulative production, remaining exogeneous technological factors like spillovers outside the industry, impacts of research and development activities, scale and/or scope economies, other external scientific advances/inventions can be included in the same function as long as their rate of change is assumed constant since otherwise equation becomes too complicated to solve (Nordhaus, 2009). Nevertheless, even if this assumption may sometimes fail to reflect exactly the real conditions, it is far better to perform some trials to understand the detailed reasons of progress or in other words shifts in production function rather than maintaining the black-boxing view of technology.

The very basic form of the extended cost function (Equation 2) that is ultimately utilized to generate learning curve equation (Equation 8) can be obtained as below[54].

$Q = f\left(x_1, x_{2,} \ldots\ldots, x_n; A\right)$ represents the output function that is subject to returns to scale where Q is the output and x_i is the input and A is the state of technological knowledge.

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[54] The paths that were described or given in (Berndt, 1991; Yu et al., 2011) were followed.

$C = g(p_1, p_{2,} \ldots\ldots, p_n; A) = \sum_{i=1}^{n} p_i x_i$ is the cost function which is simply sum of the unit prices of the inputs (p_i) multiplied by the corresponding input amounts (x_i)

The cost is expected to be minimized based upon economic behavior of agents. The minimum ($\mathcal{L}$) is sought for via the Lagrange multiplier λ by writing Equation 9 in the form of inputs and this multiplier.

$$\min_{x_i} \mathcal{L} = \sum_{i=1}^{n} p_i x_i + \lambda \left[Q - f(x_1, x_{2,} \ldots\ldots, x_n; A) \right] \qquad \text{(Equation 9)}$$

Then by taking the partial derivatives of the minimum cost with respect to all inputs and the multiplier and then equalizing them to zero, the sequentially Equation 10, Equation 11, Equation 12 and Equation 13 below are obtained.

$$\frac{\partial \mathcal{L}}{\partial x_1} = p_1 - \lambda f'_1(x_1, x_{2,} \ldots\ldots, x_n; A) = 0 \qquad \text{(Equation 10)}$$

$$\frac{\partial \mathcal{L}}{\partial x_2} = p_2 - \lambda f_2'(x_1, x_{2,} \ldots\ldots, x_n; A) = 0 \qquad \text{(Equation 11)}$$

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$$\frac{\partial \mathcal{L}}{\partial x_n} = p_n - \lambda f_n'(x_1, x_{2,} \ldots\ldots, x_n; A) = 0 \qquad \text{(Equation 12)}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = Q - f(x_1, x_{2,} \ldots\ldots, x_n; A) = 0 \qquad \text{(Equation 13)}$$

Here, the first order partial derivative of the production function f i.e. f'_n with respect to x_n th input, results in marginal product.

The production function written in the form of C-D equation is given in Equation 14:

$$Q = A\, x_1^{\alpha_1} x_2^{\alpha_2} x_3^{\alpha_3} \qquad \text{(Equation 14)}$$

Each x_n can be extracted by simultaneous solution of the partial derivatives above and then eliminating the Lagrange multiplier λ via further mathematical manipulations. In the end, they are expressed as functions of output (Q), prices of each input (p_n) and the other parameters in C-D production function and placed into the cost function in Equation 15:

$$C = p_1x_1 + p_2x_2 + p_3x_3 + \cdots + p_nx_n \qquad \text{(Equation 15)}$$

As a result, C-D based cost function basically takes the form given by Equation 16:

$$C = Z\,(Q)^{1/r}\,(p_1)^{\alpha_1/r}\,(p_2)^{\alpha_2/r}\,(p_3)^{\alpha_2/r} \qquad \text{(Equation 16)}$$

The open form of the constants Z and r shown in Equation 17 and Equation 18.

$$Z= (\alpha_1 + \alpha_2 + \alpha_3)\,(A\ \alpha_1{}^{\alpha_1}\,\alpha_2{}^{\alpha_2}\,\alpha_3{}^{\alpha_3})^{-1/(\alpha_1+\alpha_2+\alpha_3)} = r\,(A\ \alpha_1{}^{\alpha_1}\,\alpha_2{}^{\alpha_2}\,\alpha_3{}^{\alpha_3})^{-1/r} \qquad \text{(Equation 17)}$$

$$r=(\alpha_1 + \alpha_2 + \alpha_3) \qquad \text{(Equation 18)}$$

After further simplifications, the final constants obtained are given by Equation 19 and Equation 20:

$$Z=(A^{-1/r})\,r\,(\alpha_1{}^{\alpha_1}\,\alpha_2{}^{\alpha_2}\,\alpha_3{}^{\alpha_3})^{-1/r} = \left(A^{-1/r}\right) k \qquad \text{(Equation 19)}$$

$$k= r\,(\alpha_1{}^{\alpha_1}\,\alpha_2{}^{\alpha_2}\,\alpha_3{}^{\alpha_3})^{-1/r} \qquad \text{(Equation 20)}$$

To attain the unit cost, total cost C is divided by the output (Q) and finally the cost equation is obtained as in Equation 21:

$$C_{unit}=\left(A^{-1/r}\right) k\,(Q)^{1-r/r}\,(p_1)^{\alpha_1/r}\,(p_2)^{\alpha_2/r}\,(p_3)^{\alpha_3/r} = k\left(A^{-1/r}\right)(Q)^{1-r/r}\prod_{1=1}^{n} p_i^{\alpha_i/r} \qquad \text{(Equation 21)}$$

Regarding the components of Equation 21, there are a few common assumptions explicitly articulated or directly adopted in the RE LC estimations. The first one is assuming returns to scale, which is represented by a constant denoted with r in the cost function, to be equal to 1 as it is often mentioned in the literature (Berndt, 1991; Yu et al., 2011). Hence, the Q term in the unit cost equation which stands for the output is dropped. Therefore, for the estimations which still assume constant returns to scale with a value different than 1 and include the scale effect, authors should be careful in the interpretation of the coefficient due to its complex structure as well as be aware that the term A which is expected to capture the technological change through learning or other ways is under effect of this constant as well.

The second common assumption is related to changes in input prices. For sake of linearity when we take the logarithm of Equation 21 and drop the scale parameter as mentioned in the previous paragraph, the final form includes the constant k, technology or knowledge term A and the input prices. But when the unit cost as the dependent variable is corrected for inflation, the two sides of the equation is divided by the Gross Domestic Product (GDP) deflator and hence the equation becomes robust the changes in the unit prices of the inputs (Berndt, 1991; Yu et al., 2011). However, it should be noted that it is assumed that the change in the input prices is ideally aligned with the material prices considered in the GDP deflator calculations.

Moreover, though the output (Q) is defined as a function of Capital (K) and Labor (L) in its basic form, in some studies “Materials” (M) is also suggested to be included as a factor in the production function. The spot or contractual price of some fundamental raw materials was examined in some studies (de La Tour et al., 2013; Gan & Li, 2015; Pillai, 2015; Trappey et al., 2016; Yu et al., 2011). The parameters that were found to have been exploited in the literature as well as the ways of their use will be discussed in section 3.3.2.4.

In learning curves, the endogenous technological change term A takes different forms according to the interpretation of the authors. However, there are two most common versions. The first one is utilized to constitute the basic one factor learning curve (OFLC) that is given in Equation 22. The second one seen in Equation 23 is the two-factor learning curve (TFLC) that separates the knowledge stock (KS) arisen from intentional research efforts (R&D) from the learning that comes out as a result of accumulation of spontaneous experience i.e. learning by doing. The representative form of OFLC and TFLC versions of technological change parameter are shown below where the cumulative output is abbreviated as CC and knowledge stock is denoted by KS.

$$A=CC^{-b} \tag{Equation 22}$$

$$A=CC^{-b}\ KS^{-\delta} \tag{Equation 23}$$

More parameters to investigate the impact of technological change on unit cost decline rooted from endogenous and external factors can be included in the function. This may differ according to the theoretical and practical justifications of the authors. Yu et al. (2011) defines the technology or knowledge black box parameter A as an aggregate input that can be customized according to the perception of the technological change (Yu et al., 2011). In can simply be written as in Equation 24 where ρ stands for any component that somehow contributes to learning and μ denotes the elasticity coefficient.

$$\mathrm{A}=\prod_{1=1}^{n}(\rho_i^{\mu_i}) \tag{Equation 24}$$

Thus, the equations which employ more than one or two factors are called as multi factor learning curves (MFLC). The final form of a representative MFLC equation can be seen in Equation 25.

$$C_{unit} = \prod_{1=1}^{n}(\rho_i^{\mu_i})\ CC^{-b}C_0 \tag{Equation 25}$$

3.2. Use of LCs in RE Technologies

Learning curves for RE technologies have found application in large-scale energy-economic models (Leonidas et al., 2017). These models consider macroeconomic and technology specific factors under regulatory and resource constraints and simulate various carbon mitigation or climate change policy scenarios for a certain energy mix (Nakata, 2004). Thus, they can be utilized in policy decisions that are required to achieve the environmental targets under defined economic context. Beyond energy-economic models, learning curves have also been used independently to determine the political and industrial strategies (IEA, 2000; Wiesenthal et al., 2012).

In exogenous use of technology cost in large-scale energy-economic models, the cost and other relevant attributes of technology are taken as given; usually a constant rate of cost decline is determined by the modeler which can sometimes depend on expert elicitation (Rubin et al., 2015). Therefore, leaving aside the reliability of estimation; this approach does not enlighten the mechanisms behind the technological change but only requires waiting the time to pass until the cost decreases down to a competitive level or a technological improvement happens (Rubin et al., 2015). Alternatively in endogenous approach (Leonidas et al., 2017; Rout et al., 2009), learning curves of relevant technologies are incorporated into the equations by defining their relation with cumulative output or with other factors (Rubin et al., 2015). The distinctive outcomes of these two different methods manifests as either the decision of early entrance to the market to exploit the advantage of decreasing costs enabled by the accumulated experience or refraining to enter until a breakthrough occasion that reduces the cost, occurs (Rout et al., 2009; Rubin et al., 2015). In sum, while the exogeneous approach treats technological change as a full stochastic process, learning curves entail proactive behaving and at least try to open the “black box” of innovation. But still in what extent they can achieve it, is an issue of discussion too. Therefore, a comprehensive discussion on the efforts that have been given to improve the existing learning curve approaches is made under the subsections of section 3.3.

On the other hand, while endogenous technological change in LCs can find support in the Schumpeterian economics where the seeds of the evolutionary view were first planted, technological change and the innovations that lead it are accepted uncertain due to their path dependent and disequilibria features under bounded rationality of agents (Carlsson, 2007; Dosi & Nelson, 2010; Fagerberg, 2009; Lundvall et al., 2002).

This may seem like the dilemma of evolutionary approach; but while characterizing innovation or technological change as an uncertain and path dependent process, change is described as an outcome of both stochastic events and intentional efforts which can lead to innovation as their variety or volume increases (Carlsson, 2007; Dosi & Nelson, 2010).[55] In that sense, innovation process is neither totally "blind" nor "random" (Dosi & Nelson, 2010). Therefore, evolutionary approach deals with increasing the opportunities for innovation by taking care of the complex context it is embedded in i.e. opening the black box rather than being bounded by certain equilibrium conditions (Dosi & Nelson, 2010; Kline, 1986). The very basic learning curve approach perceives cumulative capacity as the driver of knowledge creation that causes technological advance and thus does not separate technological change from internal context. Consequently, the simulations and/or the optimizations carried out based on endogenous approach, by not considering the sufficiency of cumulative output in terms of capturing all learning effects, yield more sound results to rely on thereby inspiring policy makers or entrepreneurs to take proper actions or decisions.

Though learning curve approach has been utilized to estimate the cost decline in different electricity technologies (Neij, 2008; Rout et al., 2009; Rubin et al., 2015; Samadi, 2018), the studies were mainly focused on renewable energies and more

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[55] This is similar to notion of biological evolution in which variety increases with combination of different factors and the possibility of attaining something increases with the number of trials (Dosi & Nelson, 2010). Similarly, according to Mark I statement of the leading innovation economist Schumpeter, the number i.e variety of entrepreneurs is the fuel of innovation, while the main source of innovation in Mark II is the accumulation of knowledge stock in large scale R&D performers. These are called creative destruction and creative accumulation respectively (Malerba, 2007).

specifically wind and PV (Candelise et al., 2013; de La Tour et al., 2013; Elshurafa et al., 2018; Gan & Li, 2015; Görig & Breyer, 2016; Ibenholt, 2002; Isoard & Soria, 2001; Junginger et al., 2005; Kim et al., 2017; Kobos et al., 2006; Mauleón, 2016; Papineau, 2006; Pillai, 2015; Reichelstein & Sahoo, 2018; Söderholm & Sundqvist, 2007; Trappey et al., 2016; Watanabe et al., 2000; Wiebe & Lutz, 2016; Yu et al., 2011; Yi Zhou & Gu, 2019) since they have become more prominent as the carbon mitigation policies ramped up. Once endogenous learning is embraced, correct estimation of the LBD rates with the other factors that may also be effective becomes very critical though there are difficulties to identify complete learning effects which inherit complex dimensions (Rout et al., 2009).

The need for more precise estimations and the search for investigation of other explanatory variables led to a variety of studies which resulted in too many variations that ended up with uncertainties. As a result, any deviation from the correct estimation may cause wrong or insufficient actions to be taken (Rout et al., 2009; Rubin et al., 2015). Hence, the high variation among the endogenously estimated learning rates becomes crucial as much as the validity of exogeneous models.

3.3. A Review of PV Learning Curves

As defined before, PV module prices plotted against the cumulative capacity installed or produced are commonly referred as PV learning or PV experience curves and the learning rate is defined as the constant change in unit cost of ($/W) PV modules with respect to each doubling of cumulative PV production. A typical PV learning curve that covers all commercially available technologies is depicted in Figure 3.3 based on the data provided by Paula Mints (Mints, 2022). PV LCs are usually sketched based on cumulative amount at global level of which drawbacks will be discussed in the following subsections.

Furthermore, though technologies are distinguished in some sources, PV LCs based on overall technologies are very common in the literature. This depends on a few reasons. First, the share of c-Si PV compared to the other commercially viable technologies which can be grouped under Thin Film (TF) has always been substantially higher. From 1980 till today, only for 8 years in 1980s, its share had fluctuated between 70-80%; in one third of the remaining years it was between 80-90% and it was above 90% in the rest (Fraunhofer ISE, 2022).

Therefore, the studies that especially focus on the recent years after 2000 correspond to a period when c-Si had >90% and mostly >95% market share. Second, the accessibility of global data with installation and cost breakdown of PV panel technologies is not easy via open sources. Third, even if there are c-Si specific LC plots or available required data (BloombergNEF, 2019; Fraunhofer ISE, 2022; IRENA, 2022b; ITRPV, 2022), either they do not go back more than 10-15 years or the type of technology is not clearly indicated until the late years.

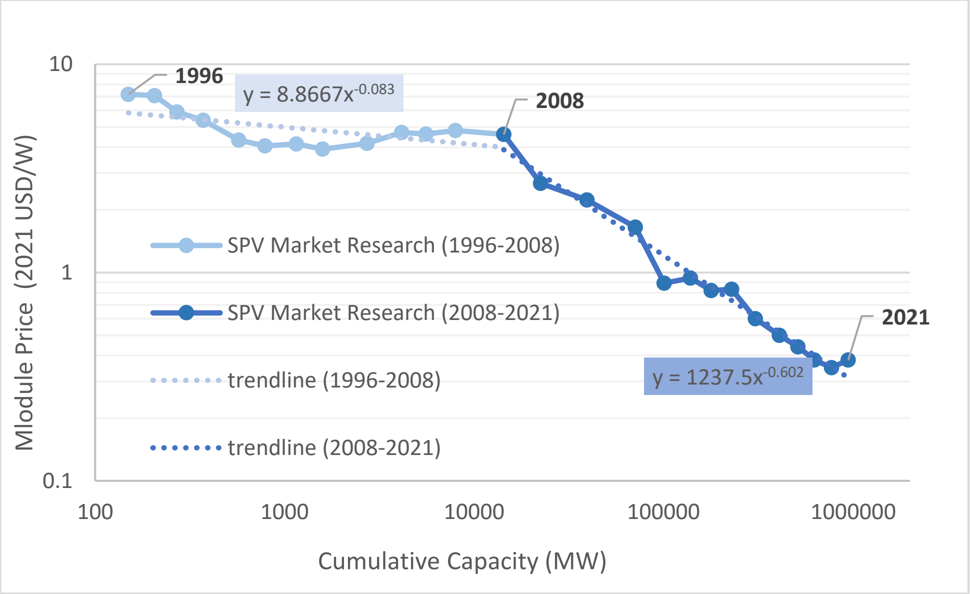

Figure 3.3. A typical PV Learning Curve based on all commercial technologies

In Figure 3.4, c-Si PV specific LC for a wider range of time is plotted[56] (BloombergNEF, 2019). At first sight, though they do not have the same slopes, the two learning curves in Figure 3.3 and Figure 3.4 exhibit a very similar tendency for the corresponding years[57].

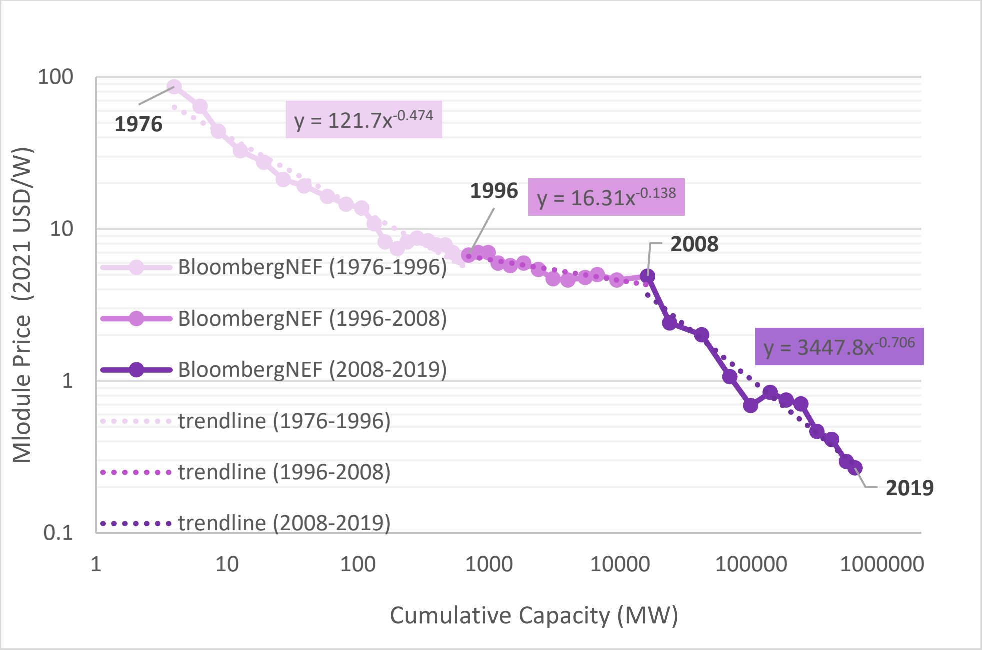

Figure 3.4. PV Learning Curve based on c-Si PV

For the recent times, it is easier to access technology specific prices. In addition, since the market was frequently dominated by c-Si PV with 90-95% share in the last 20

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[56] The graph was formed secondarily from a readily plotted one available in the reference document upon permission of the authors via email since the raw data was not available.

[57] The x-axis in the two graphs which shows the cumulative capacity does not perfectly fit to each other for the same years since while in the second graph, the original capacity data extracted from the readily plotted graph was used, in the first graph, the data regarding the cumulative capacity was not available and therefore relevant data found in a publicly available source (IEA PVPS, 2022c) were referred. Although there was an offset between the capacity values used in the two graphs, they converged much more in the later periods.

years, use of the overall technology data became more eligible for c-Si specific sketches. LC trends specific to c-Si are depicted in Figure 3.5 for the last 12-13 years. The slopes of the two curves which were drawn based on two different available data sources were found almost the same.

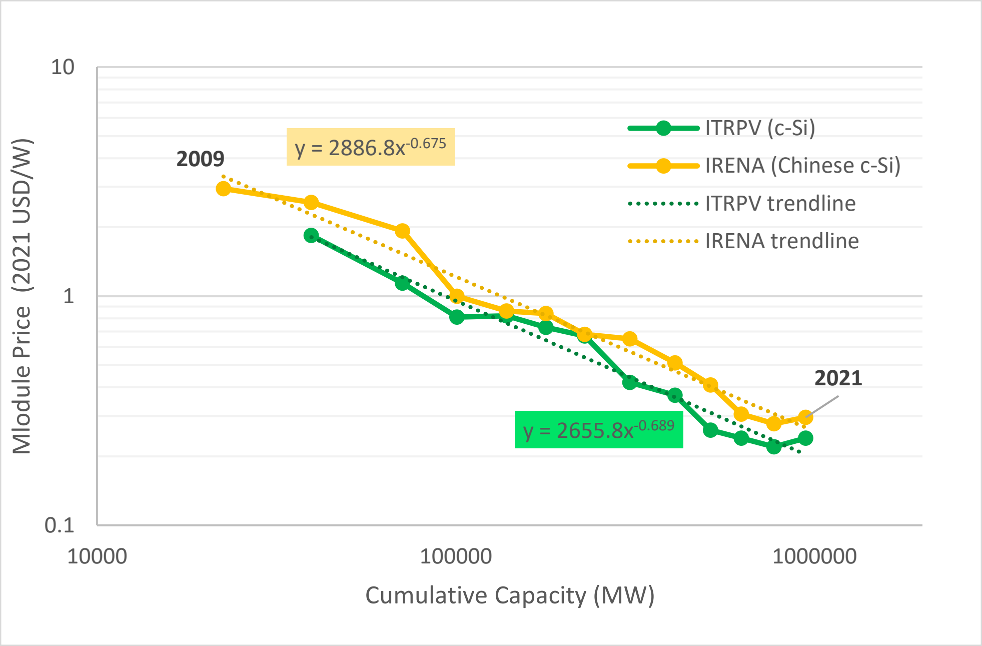

Figure 3.5. Comparison of c-Si PV LC drawn for the recent years based on two different data sources.

To make a better comparison and identify the time dependent and source dependent variation in the LCs graphs above, the learning rates calculated from the coefficients of the slopes in the figures above are presented in the Table 3-1 which also includes the values that were readily provided in some sector reports (BloombergNEF, 2019; Fraunhofer ISE, 2022; IEA PVPS, 2022b; IRENA, 2022b; ITRPV, 2022; Mints, 2022). The periods were chosen first based on the availability, second to make them as comparable as possible, third by considering the industrial stage definitions made in Chapter 2.

The deviation between learning rates may arise from the technology types referred, the differences in data collection and sampling methodologies of the sources as well as the time interval utilized. However, it is clearly seen that this difference is proportionally much higher for the earlier time period while the findings converge in the later period.

It might have arisen from the improvements in the accessibility of data in recent years as well as the increase in the homogeneity of market as a result of Chinese effect which could have decreased the sampling errors, thereby causing the data in different sources to converge. It can also be noticed that the rate of learning got higher from the late maturation stage (near the 2008) till today when compared to the development stage defined in Chapter 2 (1975-1995).

The LR after 2008 was 4-5 times of the value attained for the period from 1996-2008. These studies depend on merely basic learning by doing approach while some of which just indicate that different trends in specific periods can be related to corresponding industrial or technological conditions like polysilicon crisis, economies of scale/mass manufacturing, innovation (BloombergNEF, 2019; IEA PVPS, 2022c; ITRPV, 2022). On the other hand, one of them (ITRPV, 2022) isolates the basic curve from the performance effects only for the later years (2006-2021) by eliminating the impact of extra watts enabled by the efficiency increase on unit price. As a result, the contribution of efficiency was found 7.9% while the merely learning by doing based rate was identified as 17.2%. Since the parameters were evaluated separately, sum of their effect does not correspond to the overall rate found as 39.5% for the same time interval (see Table 3-1).

Table 3-1. PV learning rates in different sectoral reports.

Data Source	**Time interval**	**Technology**	**Origin**	**LR**	**Data collection**
SPV Research (Paula Mints)	1996-2008	all	Overall	5.6%	Values extracted from the data plotted
	2008-2021	all	Overall	34.1%	
	1996-2021	all	Overall	21.2%	
BloombergNEF[58]	1976-1996	c-Si	Overall	39.2%	
	1996-2008	c-Si	Overall	9.1%	
	2008-2019	c-Si	Chinese	38.7%	
	1996-2019	c-Si	Overall	28.2%	
IRENA	2009-2021	c-Si	Chinese	37.4%	
ITRPV	2010-2021	c-Si	Overall	38.0%	
BloombergNEF	1976-2019	c-Si	check[59]	28.5%[60]	Values readily given in relevant reports
Fraunhofer ISE	1980-2021	all	Overall	25.0%	
	2006-2021	c-Si	Overall	31.0%	
IEA PVPS	1992-2002	all	Overall	18.0%	
	2008-2021	all	Overall	41.0%	
	1992-2021	all	Overall	21.0%	
ITRPV[61]	2006-2021	not clear	Overall	39.5%	
	1976-2022	not clear	Overall	24.1%	

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[58] The data is plotted by dividing it into 3 available time periods. First range (1976-1996) almost corresponds to the development stage mentioned in Chapter 3. Second range (1996-2008) correspond to substantial part of the maturation stage and for ease of comparison selected accordingly to be aligned with the time intervals in other sources. Third one (2008-2019) is plotted for the remaining years. Again, to get a comparable value with other sources, the last two ranges are plotted as combined (1996-2019).

[59] Until 2004, the origin of modules is not mentioned therefore assumed to be global as in other sources. Starting with 2004, the origin of modules is indicated as Chinese.

[60] The data plotted above was separated to specific ranges and in one plotting, two ranges were combined. The value regarding the whole range is readily given in the source mentioned as written in the table i.e 28.5%. However, when all range is plotted from the data extracted, it yielded a learning rate around 25%. This slight deviation may arise from data reading by utilizing a graph reading program mentioned.

[61] The type of modules for the data utilized in overall plots is not mentioned.

Beyond the market or industry reports that embrace PV LCs in its very basic form, there have also been many academic efforts performed to enhance the reliability and functionality of the estimations. In the following subsections, first, limitations and uncertainties met in the PV LC literature are discussed and then the studies are classified based on different levels of analysis identified in the literature. While in the former subsection, limitations and uncertainties of the estimated PV LCs are addressed from a general perspective, in the latter where the levels of analysis are classified, details of the limitations and sources of uncertainties are discussed. The vulnerability of technological level to uncertainties, how the spatial domain chosen can limit the estimations and lead to misleading implications, the reasons behind the variations of the results for different time intervals and finally different methodological approaches that are differentiated in terms of the variables and the data structures employed are exhaustively addressed under different levels of analysis.

3.3.1. Uncertainties and Limitations of the Estimations

The review analyses also showed that PV LCs in the academic literature were distributed in a wide range (de La Tour et al., 2013; Elia et al., 2021; Rubin et al., 2015; Samadi, 2018). There might have been many reasons behind the variations of the estimated rates of learning. The most obvious reason is use of different dependent variables. When the cost estimated belong to a broader functional unit, it encompasses many other components which may have different learning rates. Even if the ultimate cost which customers confront is the PV electricity generation cost which is called as the LCOE, it is composed of many cost elements which were mentioned in Chapter 2. Therefore, variation of LRs is an expected outcome depending on the extent of the technological boundaries.

On the other hand, the type of dependent variable matters as well. Use of price as a proxy of cost especially for PV modules is highly frequent in the PV LC estimations as can be seen from the retrospective analyses made in (Elia et al., 2021; Rubin et al., 2015; Samadi, 2018). However, since margins of the price can change based on certain conditions which will be addressed in detail in the following subsections, its use as a dependent variable can cause some uncertainties as well as variations in the estimated LRs based on the sample employed.

On the other hand, independent variables should be determined based on the potential factors that may be effective on cost decline. In OFLC modelling, after eliminating some elements in the Cobb Douglas originated extended cost function based on the widespread assumptions mentioned in the first section of this Chapter, the only parameter that the unit cost is considered to be susceptible is cumulative output or in other words LBD effect. Despite being a basic tool to be adopted in forecasts and simulation models, this approach limits learning to only one dimension and neglects other factors that may be effective. Ignoring other effects and the biased estimation of LBD due to omitted variables may impede allocation of resources properly (Nemet, 2009) as well as attaining certain goals at either technological, national or firm levels. Therefore, learning curve models have evolved within time when authors started to examine the influence of multiple factors through incorporation of multiple learning indicators, control variables and/or others inherited from C-D equation as addressed in the previous section. The variation of LBD rates obtained from different MFLCs is an expected outcome (Rubin et al., 2015) since the explanatory power of the model was distributed over all significant variables in the equation. This discussion will be revisited and discussed thoroughly under “methodological level of analysis” subsection by introducing and evaluating other explanatory variables that were associated with different types of learning and the control variables that were considered to be effective as well. Leaving aside it for now, among the basic LCs that were merely based on “learning by doing”, the learning rates found for LBD were still found to variate.

In a study, the average of previously estimated 18 OFLC based learning rates were found 20.2% for the PV modules with a high deviation from 10 to 26% (de La Tour et al., 2013). In the same study, the average value of the LBD rates attained in other three studies which had employed MFLC based models was 13.7%. The latter finding can be explained by the change in the explanatory power of LBD due to the other variables included as mentioned in the first paragraph. On the other hand, the potential reason of the deviation among the models that utilized same variables was explained with the differentiation in time frames and geographical scopes as well as the data sources (de La Tour et al., 2013). The estimations which employed different years, ceteris paribus, were seen to have had a high variation in learning rates (de La Tour et al., 2013; Rubin et al., 2015; Samadi, 2018). This unveils that temporal effects exist. The same outcome was observed in the studies where the spatial boundary was changed while the rest was fixed (de La Tour et al., 2013; Rubin et al., 2015; Samadi, 2018). In a study (Papineau, 2006), the estimated learning rates for solar PV modules for the same time interval (1992-2000) were found as 15%, 10% and 32% for Germany, Switzerland and the US respectively. Hence, the impact of national factors is revealed as well. Furthermore, even when the time and geographical scope were fixed, the estimated learning rates for same variables were found to change (de La Tour et al., 2013; Rubin et al., 2015) and the difference was found to be as large as 5% absolute [62]. This proves the impact of differentiation in the data sources as well as the reliability of the global or national data in PV.

The reasons behind the variations and the uncertainties of LCs should be understood thoroughly in terms of whether they arise from the flaws in the estimations or due to the nature of the industrial phases and regional effects. Especially implications based on OFLC estimations put too much attention on deployment programs which ultimately have some economic and social burdens (Ferioli et al., 2009; Nemet & Baker, 2009; Rout et al., 2009). A study simulated the distribution of the cost of a subsidy program that “bought-down” the PV modules until the cost reduced to a

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[62] For example, two different estimates for the time interval 1976-2001 in global base are 25 and 20.6% and for a very close time interval 1992-2000 and 1992-2001, the estimated learning rates for Germany are 15 and 10% (de La Tour et al., 2013).

competitive level based on varying LRs from the literature with 15% median value and 4% absolute standard deviation (Nemet, 2009). In sum, based on the industry growth rate assumed and the range of the LRs employed, when the targeted cost level was reached at a breakeven year, the standard deviation of the overall public cost was found 713 b$ for the PV LRs estimated until 2006. Findings from another study which benchmarked 22.5 and 20.2% learning rates for PV revealed that the difference of the public burden for a targeted level of electricity generation cost could be 30 billion $ (Ferioli et al., 2009). Therefore, especially when only LBD effect is taken into account, overestimation of LR may be very harmful for the effective use of public funds while its underestimation may mislead the customer decisions with higher price signals that end up with lower demand and ultimately distortion of price margins (Rout et al., 2009).

The potential causes of variations in LRs of energy technologies which bring along uncertainties in different dimensions were articulated in a relatively structured or discrete way by many authors in the literature (Candelise et al., 2013; de La Tour et al., 2013; Elia et al., 2021; Kahouli Brahmi, 2008; Mauleón, 2016; Nemet, 2009; Rout et al., 2009; Rubin et al., 2015; Samadi, 2018; Söderholm & Sundqvist, 2007; Wiesenthal et al., 2012; Yeh & Rubin, 2012; Yu et al., 2011). For instance, in (Rout et al., 2009) an exhaustive set of factors were listed. They can be summarized as follows: difficulties in accessing correct and sufficient cost and capacity data due to reluctance of companies to disclose their trade information; changing price margins in the data obtained from the technology developers or the distributors; different behavior of learning in different phases of market maturity; use of almost same specific cost/price values for different regional boundaries in lack of data; uncertain outcome of R&D and unclear pattern of public and private R&D; effects of other direct or indirect inputs such as material costs, oil price, etc; variable and fixed costs in plants; economies of scale; forgetting by not doing; reversing previous technological flaws; modifications and upgrades in technology; knowledge development through scientific understanding, skilled labor, market mechanisms and the interactions between them; institutions such as intellectual property, standardization, abatement measures, social acceptance, taxes; oligopolistic pricing; international trade market; macroeconomic conditions such as labor market, demand-supply gap, discount factor; different orientation of policies according to demand pull or technology push approach; clustering and learning by spillover.

However, it is not possible to employ and investigate all effects listed above via quantitative analysis due to characteristics of innovation as well as quantifiability and availability of the data. On the other hand, LCs are practical tools to investigate some learning factors which may have impacts on the apparent cost decline. As a result, being aware of the dimensions that may affect the sensitivity of the results and thereby constructing and interpreting the models accordingly may help to improve the predictions and the conclusions made out of them. In that sense, examining the variations based on level of analyses can enable to understand the causes of uncertainties more easily and may facilitate a clearer pathway to overcome the limitations of LC approach.

3.3.2. Classification of LCs based on Level of Analysis

To understand the variations and the uncertainties they cause in a systematic way may help to improve more robust models. In his review study, Samadi (2018) classified characteristics of LCs of electricity generation technologies under four different domains which are (Samadi, 2018): "methodology; learning system boundary; definition of specific costs (dependent variable) and definition of experience (independent variable)". Some of the domains had same or very similar subcategories. For example, the last two were both categorized with "geographical scope" or "product definition" which required, as expected, selection of corresponding levels for the dependent and independent variables. Same was partially valid for "learning system boundary" since "object of investigation" which was identified as power plant or power plant technology determined the mentioned domains above. On the other hand, another subcategory under it i.e. “level of perspective” that was defined for firm or industry level of analysis was independent from the ones discussed above. Only “methodology” subcategory was totally independent from other domains. It was characterized depending on the number of explanatory variables in the model, use of price or cost, estimating either one continuous LC or many partial LCs for the same sample. In another study, the variation of PV LCs was categorized with differentiation in purpose, data source and methodology but the details were not revealed. (Yu et al., 2011). Also in (Wiesenthal et al., 2012), a stylized question set was listed for implementation of learning rates in energy modelling, which implicitly embodies a kind of classification for LCs. The authors suggested to consider the following dimensions: limits of learning, selection of scenarios, use of price or cost, variation over time, geographical boundaries, system boundaries for technological learning.

To be able to identify the problems that are confronted in the chosen boundaries and evaluate their impacts, the classification units should be more distinctive and have their unique characteristics. Therefore, in this study, the LCs are classified and examined under four different level of analysis defined below.

3.3.2.1. Technological Level of Analysis

One of the clearest reasons behind the variation of PV LCs is use of different dependent variables. While some authors preferred to estimate the price of electricity generated from a RE in USD/kWh, some focused on overall PV system installation costs in USD/W or cost of PV panels in USD/W. The components of these units can be found in Chapter 2 (see section 2.2). It is highly probable that they yield different learning rates due to their structural differences. The reliability of the estimations may be gradual as well. In this thesis, this effect is examined under “technological level of analysis”.

The risk of uncertainty is the highest for unit electricity generation cost as the dependent variable since, first, it is an aggregate indicator of many components which may develop different learning rates (Ferioli et al., 2009; Louwen & Junginger, 2021; Rubin et al., 2015; Yeh & Rubin, 2012) and they may be in different phases of maturity (Yeh & Rubin, 2012); second, they cover “influential but exogenous” (Nemet, 2006) components such as land prices, project expenses, other soft costs as well as natural conditions which are mainly local and limit the sample usually to national level.

Electricity generation and overall system installation costs as mentioned in Chapter 2 embody multiple components of which rates of change may not have an identical trend within and between. Because, each component may have a different learning response. This was called as “component-learning” in (Ferioli et al., 2009). In addition to Ferioli et al., in case of multiple learning factors, all components may not be vulnerable to the same factors. Similarly, Louwen and Junginger addressed this issue as different learning potentials in the functional units which might lead to non-constant learning (Louwen & Junginger, 2021). Thus, they emphasized the importance of selection of “systems boundaries”. In terms of PV electricity generation, soft costs component in overall systems, especially the ones related to permissions and regulatory requirements, can change with a different rate from one country to another as well as from year to year (IEA, 2014; ITRPV, 2019b). Second, the land costs may have a different impact from year to year even within the same country when the weight of locations preferred for PV installations change even the fluctuations in the valuation of the same land are ignored. On the other hand, the amount of electricity generated which determines the unit cost of electricity can change based on the locations chosen for installations due to the latitude based solar radiation. Thus, when the systems are installed in different locations within years, it may affect the amount of electricity generated substantially and thereby the unit cost of electricity. Consequently, these are different factors that do not include direct learning effects[63].

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[63] Maybe, the locations chosen or the required permission and thereby their costs can be affected from better practices. But these require extremely detailed analysis which still cannot capture these effects quantitatively.

The component-based learning may sometimes be additive and intertwined for some systems. It was exemplified with the wind blades which had a higher cost but led to more power output in the end (Ferioli et al., 2009). In this case, if unit electricity generation cost was the focus, while the system price on the nominator increased, simultaneously the electricity obtained would increase as well. Thus, the change in unit cost is determined (i.e. so-called learning effect) based on the composite contribution of the two elements. In PV, as given in Figure 2.5, the efficiency of the device has increased simultaneous to cost decline so far (see Figure 3.4 for cost decline of c-Si). The unit cost of device component in PV is directly related to the unit power that can be obtained from it; indeed, even if its fabrication becomes costlier, in overall, this has not made a visible impact on its unit cost until now. Moreover, it was also shown that when the cost decline was isolated from the efficiency gain, there was still a significant decrease (ITRPV, 2021). It proves that the PV industry maintained its improvements without creating a net burden on costs. As a result, while for certain energy technologies, electricity generation costs as the dependent variable may work better to capture the learning effects, evaluation of learning for each component separately still seems better for PV (Louwen & Junginger, 2021).

To sum up, the unit electricity generation cost as technological level of analysis in PV LCs distinctively suffers the problems arising from the power output but the rest of the handicaps confronted are almost same if the functional unit is chosen as PV systems. Because, the distinguishing elements between these two boundaries (electricity generation vs installed systems) such as operation and maintenance as well as fuel have very minimal or no costs. Hence, they almost have the same components except the final electricity output that affects the unit cost of generation (for details please see subsection 2.2.). As a result, system installation costs as well fail to anticipate the different learning rates arising from different technological components. On the other hand, the electricity price is the easiest one that can be subsidized so that it should be purified from these effects; otherwise the learning rate may be negative and cannot be suitable for comparison of countries or aggregating their data (Ibenholt, 2002).

If PV systems cost is zoomed in, as described in subsection 2.2., it includes project, land and other soft costs as well as cost of BOS which includes the other electrical and mechanical/ structural components and PV modules. The problems that may arise from choosing the aggregate PV system cost can be summarized as follows: First, the land costs which have substantial share in the overall system cost for some regions (ITRPV, 2019b) may change within time and based on the locations chosen in a country as discussed above. This is not related to the learning that happens in PV manufacturing steps. Second, the non-physical components in a PV system cost i.e. can be affected from the magnitude of the capacity allocated per project without any learning effect and the accumulated practice of installations which is a completely different operation than manufacturing and can have a different learning rate. Indeed, these components were observed to have a slower or constant learning rate than the rest (IEA, 2014) which indicates a component based learning. Third, the constituents of BOS which is mainly composed of physical components, should be considered in terms of their utilization in other industries. Especially, learning mechanisms or other cost dynamics regarding the units used in construction and cabling which are mainly made of steel and copper may not be specific to PV industry. As a result, to be able to capture the learning mechanisms behind the cost decline in PV as much as accurately, choosing PV modules as the technological level of analysis in PV LCs seems more effective.

Finally, even if the unit of analysis is PV panels, it may require a certain level of decomposition, too. PV panels variate according to the substrate of the device (i.e. the base material). The main types used in terrestrial installation are *"crystalline silicon"* and *"thin film"* technologies. As mentioned in previous chapters, c-Si technology is far dominant than the latter. Therefore, the substantial amount of the LCs met in the literature are either focused on c-Si or overall PV technologies (see Table 3-1) since the effect of other products in overall is minimal. However, the industrial dynamics of each technology can be very different since they do not depend on same fabrication steps and raw materials as well as do not have the same integration structure.

Therefore, it is crucial to be very careful while using composite data in terms of reliability and accuracy of the estimations, especially if industry specific learning factors are examined in addition to LBD. There are subcategories under c-Si module types as well. The c-Si PV modules can differentiate according to the crystal structure, dopant type in the base material, design properties and end use purposes such as multi or mono crystal, n or p type doped, mono- or bi-facial modules, aluminum framed or frameless glass-glass modules, etc. However, though their decomposition may require different type or amount of sub-materials with small changes in sub processes, in the end, they belong to the same industrial segment which employs very similar fabrication steps compared to other technologies. Therefore, they can be influenced by the same learning factors similarly.

Consequently, PV module price seems to be the most suitable unit for technological level of analysis in LC estimations. Also, it is a good candidate since it constitutes the dominant share in the total system costs[64] alone (ITRPV, 2019b; Nemet, 2006, 2009). But ultimately, learning rates of modules remains as an indirect way to plan the deployment of solar energy. The final cost to consumer can be found only by incorporating it to the LCOE equation and assuming other factors remain same. Still, it can be helpful in other ways like orienting the industrial strategies correctly in the pursuit of decreasing the costs and securing the supply chain.

3.3.2.2. Spatial Level of Analysis

Another important variation source is the spatial boundary of learning. Spatial boundaries though their choice seems more intentional, are limited by the availability of the data as well. The most common boundary encountered in the literature for RE experience curves as well as specifically for PV is global aggregate data. Though it was articulated that there might have been regional differences, due to unavailability

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[64] Please see subsection 1.4 and 2.3.1.

of data, authors usually preferred to use the global costs (i.e. prices as proxy) especially for PV modules and wind turbines -which were at least more isolated from the local effects than the system prices (Neij, 2008) as mentioned in the previous subsection. The high frequency of use of global data can be found in the review studies (Elia et al., 2021; Samadi, 2018).

Global aggregate data as the spatial level is the easiest one to access for a large time period. As mentioned in Chapter 2, PV market was infinitesimal before 1995 until the deployment support programs were commenced by one by one in the leading countries. Immediately after, the production started to ramp up and rocketed by 2000 which can be seen from Figure 2.8. There might have been some international trade especially in the upstream value chain products before this date but it has clearly become more intense afterwards. The clear-cut change in the balances between installation and production at certain regions during the ramp-up period can be seen in Figure 3.5[65]. Then, as exhaustively discussed in Chapter 2, the international market started to become more dependent on China. At the end of this 10-year period, market was substantially dominated by China of which share has fluctuated between 70-80% in the relatively recent years as seen in Figure 2.11. Therefore, since the market was more local before 2000 and a relatively decentralized industry was observed between 2000 and 2010 with significant international trade indications, country level analysis could provide more information about national learning for early times. But for the relatively recent time period, reliable and consistent data regarding locally manufactured modules are not easily accessible at least via the public sources since domestic shipments and prices reported there do not represent merely local manufactured modules and cover all shipments within the current country due to potential imports. For more detailed information please see[66]. On the other hand, since

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[65] These graphs are based on same data employed in Figure 2.3 (IRENA, 2022a) and Figure 2.9 (Mints, 2011).

the market has been significantly steered by China afterwards, national level disaggregation of the industry to understand the learning factors became unmeaningful. Either because of unavailability of decomposed data at national/regional level or since regionally distributed industry almost disappeared, still use of globally aggregated values for a long term especially in the OFLC estimations should be handled very carefully. Generalization of their implications may suffer biasedness due to ignoring other factors that might have local roots and may cause the industrial strategies and the relevant policies fail in the end.

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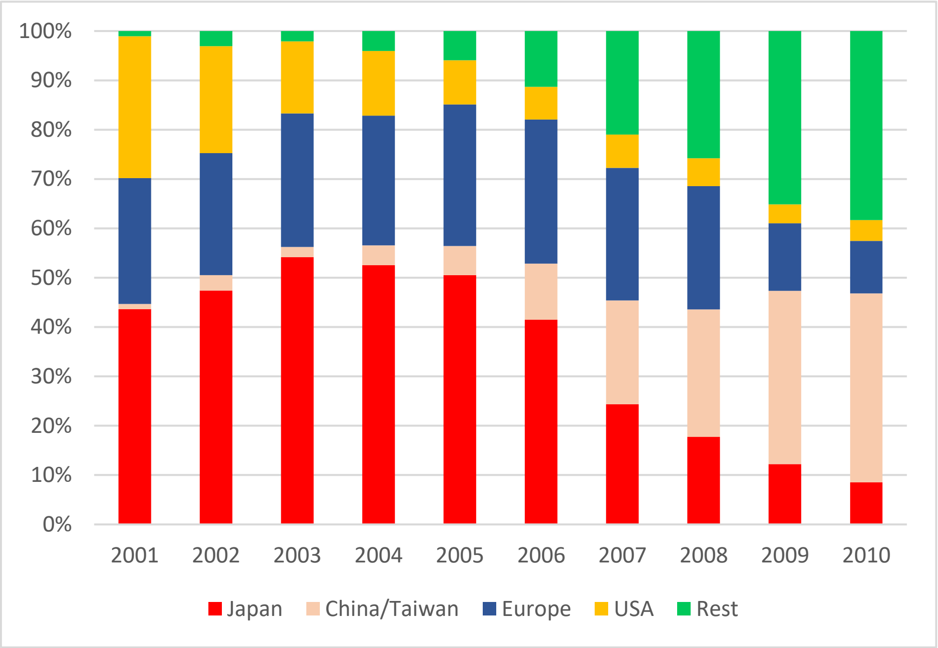
[66] Though some shipment and price values are available in some national and international sources and even if they are reliable in terms of the accuracy of the data, their use may not be eligible and therefore estimations based on them may not be reliable due to the following reasons. First, usually the values shared as public in the official databases do not distinguish the price/cost for domestically manufactured modules from the imported ones. For instance, in the U.S. Energy Information Administration (EIA) database, from 1980s till now, PV shipments as well as the module prices in the USA are accessible via (U.S. Energy Information Administration (EIA), 2022b, 2022a). In addition, for other IEA countries including USA, module prices are provided in the National Survey Reports prepared for IEA PVPS (IEA PVPS, 2022a) but either without any clarification about their origin (excluding a few countries for a certain time period) or mostly it was clearly indicated that the prices were given as average or a range for the all modules available in the national market including imports. Second, a clear distinction cannot be made about the average value of the prices based on market segments and usually a range of prices are given or as in the case of Japan, the values shared are the end-user prices of residential modules (not wholesale). In sum, even if it was easier to access local manufacturing data from international or national sources, public sources do not provide reliable and consistent data about domestically manufactured module prices/costs for a wide and continuous time period that can be exploited in LC estimations.



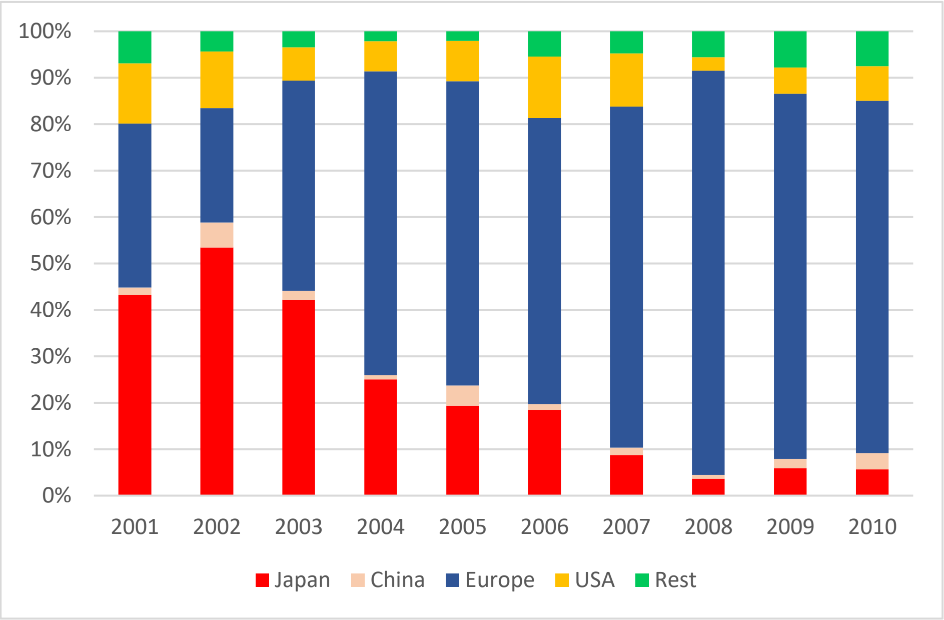


Figure 3.6. Comparison of global PV manufacturing (above) and installation (below) breakdown in between 2001-2010

Because of the handicaps regarding data as well as the status of the industry, PV LC research remained mainly at global level. Only a few studies were found that somehow conducted country level PV LC analysis. Some studies were listed in the LC review articles investigated discrete PV LCs for specific countries such as Japan, USA, Germany which were the first league players of the PV industry till the beginning of last decade (de La Tour et al., 2013; Rubin et al., 2015; Samadi, 2018). Based on the secondary information collected from the referred sources (since these studies were not accessible), it was seen that their observations were extending at latest until 2002 with varying ranges which corresponded to a time period before the ramp-up of the industry. In sum, country analyses mentioned above were based on short term data and were just able to provide an idea about the current country dynamics when the industry were relatively distributed though the overall production was still not too much. Therefore, the findings could only be indicative for the short-term period examined and the current country investigated since a global industry did not exist yet at this time.

It is also very hard to find any PV LC studies that allowed comparison of different regions through simultaneous estimations or that investigated the cost decline for a data set in which multiple spatial domains were clustered with their own representative data for each year (i.e. which is basically panel data estimation[67]). In one of the exceptional studies found in the literature, Papineau (2006) investigated the LRs for PV modules in Germany, Switzerland and the USA first separately and then with panel estimation by clustering the country level data. However, the duration she employed was too short and belonged to a term (1992-2000) (Papineau, 2006) when the LR had shown the slowest trend (see Figure *3.4*) and was again before the industry ramp up. Furthermore, as it was articulated by other authors (de La Tour et al., 2013), she had employed national installation data instead of local manufacturing output which hindered the reliability of estimations due to the biasedness caused by the possibility of imported modules. Same concern about the use of cumulative installations within

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[67] For more details about panel data estimations, please see Chapter 4.

the country rather than the production output as independent variable in wind turbine LCs estimated at national levels was addressed in (Junginger et al., 2005).

There is another study that conducted panel data estimations for PV system installation costs in IEA PVPS countries from 1992 to 2007 (Kim et al., 2017). Due to data availability, unbalanced panel data with time gaps yielded 105 observations. Since estimation was carried out on installation costs rather than the cost of PV modules, not the production amount but the cumulative installation was utilized instead as the capacity amount accumulated within the corresponding countries. Seven out of ten variables were found significant[68]. Nevertheless, the results should be interpreted carefully because as well as the drawbacks regarding the use of installation costs that were already addressed in subsection 3.3.2.1, there are a few more risks when country wise estimations which were carried out on system costs were being compared. First, the tax measures applied against Chinese origin PV modules in certain countries/regions of which implementations had started by 2012 as i.e. anti-dumping precautions (European Commission, 2016; U.S. Department of Commerce, 2012), can manipulate the findings since they can variate for certain countries and regions. Second, the system costs might have been affected from the freight costs of the physical compounds which could have been much higher for certain countries as well as the local project and labor costs. Third, since the distribution of segments such as residential rooftop or utility scale ground mounted installations may differ in each country/region and their prices are not same (IEA PVPS, 2022b), estimations based on systems rather than PV modules at country level -if they are not controlled for certain effects- cannot escape from suffering biasedness problem.

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[68] As a result, 7 out of 10 variables investigated in the same model, ‘LBD effect’, ‘domestic knowledge stock’ that represented accumulated relevant patents, ‘obligations regarding renewables’ such as portfolio standards or quotas on electricity suppliers, ‘public investments’ in the form of public procurement or direct subsidies for PV systems/installations in the country, ‘environmental taxes’ and some control variables i.e. ‘price of pSi’ as the raw material and ‘GDP’ were found significant; while ‘tariff incentives’ that stood for electricity purchase guarantees, ‘overseas knowledge stock’ and ‘absorption capacity’ that represented the ratio of domestic knowledge stock to overall knowledge stock in the cross sectional sample were not.

In sum, LC based quantitative inspection of local learning processes which might have been effective at national/regional level and were suppressed by the global estimates, did not become possible so far due to various handicaps such as availability of data or modelling problems arising from other levels of analysis like the technological level selected without sufficient controls or sufficiency and accuracy of the time level of analysis to yield satisfactory findings. Hence, alternative studies were emerged in the literature. Some authors who were either focused on only China or conducted a relatively comparative analysis, utilized descriptive statistics and bibliometric research based quantitative analyses (Gandenberger, 2018; Zou et al., 2017); while some supported the methods mentioned with qualitative evaluations inferred from expert interviews as well (Huang et al., 2016; Lee, 2011).

Beyond the country or regional level of analysis as an alternative to global aggregate data, it is also possible to focus on firm level where the reliability of data can be stronger in case of being accessible. Also, it may allow investigation of further factors which are not observable in other levels or cannot be exploited due to lack of data as well as estimation restrictions. Global data allows low number observations since the time interval for PV is the short. On the other hand, country level suffers the same problem. Although it is possible to increase the overall data size through panel data estimations which include time series and the countries as the cross-sectional dimension, the number of countries involved in PV at comparable level is very limited for the long term. Therefore, both levels can only include a certain number of observations which is hard to exceed 50 currently. As a result of limited number of observations, investigation of additional effects other than LBD is not so easy due to lower degrees of freedom which ultimately affect the significance of the variables estimated.

There were a very old and a relatively recent study which employed annual company data in PV LC estimations (Pillai, 2015; Watanabe et al., 2000). Pillai (2015) utilized unbalanced panel data estimation to examine the change in unit module costs in 15 PV

PV firms from 2005 to 2012 against cumulative capacity (learning effect), plant size (scale effect), silicon (main raw material) price and usage, China dummy, current and initial product efficiency of the firms, annual industry investment and the firm investment (Pillai, 2015). In the old dated study, decline of solar cell prices in Japan in 19 years between 1976 and 1995 were estimated for 6 Japanese firms separately and in a pooled way without considering the individual heterogeneity (i.e. in aggregate form of all firms) (Watanabe et al., 2000). The cost estimations were carried out in two models. In the first one, the authors investigated the impact of learning effects together with the scale, while the second model was built on energy prices and R&D based knowledge which investigated learning by researching (LBR) rather than LBD. A more detailed discussion about these studies will be carried out in the methodological level of analysis subsection.

3.3.2.3. Time Level of Analysis

The time intervals of the PV LC studies were usually chosen as long as possible according to availability of the data when the relevant studies were conducted. Still, since the past of renewable energies which have attracted the highest attention i.e. wind and solar PV does not exceed 40-50 years commercially, the estimations found were usually based on very small number of observations which were much below the given duration. It is hard to extend the observations to very old time spans due to accessibility of raw data which is mainly found in the plotted form in the literature. Moreover, in case that some part is accessible, the technologies are usually not distinguishable. Almost a full list PV LC studies that were carried out until now and the ranges utilized can be found in the recent review studies on PV learning curves (Elia et al., 2021; Samadi, 2018). As discussed in the beginning of this subsection, different time intervals could yield changing learning rates even when the other analysis parameters remained same, which indicated that the rate was not linear or in other words it was changing for specific time periods. Some specific reasons of this discontinuity can be summarized in four main steps.

The first potential reason of varying PV LRs within time is use of unit price instead of unit cost. The type of dependent variable which at first sight may sound to be an issue of methodological level of analysis, explains one of the potential reasons behind the varying learning rates within time. Therefore, it is addressed here under time level of analysis subsection first. Use of unit price is very common in estimation of RE learning curves since it is not easy to access the unit costs (Ferioli et al., 2009; Junginger et al., 2005; Rubin et al., 2015). It was usually underpinned by the exhaustive studies of BCG on experience curves where unit price rather than the unit cost or labor productivity had been employed with respect to cumulative output (Dutton & Thomas, 1984; Junginger et al., 2005; Neij, 2008; Yeh & Rubin, 2012). In a retrospective analysis, it was revealed that 23 out of 28 PV LC studies conducted until now were based on unit price rather than the unit cost and there was only one study among the cost based ones that utilized modules as technological level of analysis (Samadi, 2018).

Since price is susceptible to many other internal and external parameters such as marketing strategy, demand trends, industrial structure, subsidies etc., normally, it is an imperfect measure of cost decline (Candelise et al., 2013; Junginger et al., 2005; Rubin et al., 2015). However, the simultaneous trends in cost and price in different market phases, under the assumption of learning exists, were described by Boston Consulting and the illustration that was reproduced from the relevant figures in (Junginger et al., 2005; Neij, 2008) to describe this relation is given in Figure 3.7. The market phases seen in there should not be confused with the ones defined in Chapter 2 though there may be partially corresponding periods. As can be seen, though the price may follow a parallel path with the cost in the mature phase, until a shake-out emanates, it does not decrease in accordance with the cost. In the so-called development phase, which seems to have been used to define the early market phase, the supplier intentionally determines a lower price than the cost for the sake of increasing the demand and creating the required mass for learning that emanates from the accumulated output. In the price umbrella stage, the costs decline as expected and the learning supplier exploits the advantage of development phase strategy while other suppliers are attracted to the market. Thereafter, the following shake-out distorts the existing market advantages of the first runners due to competition and decrease of price becomes aligned with the cost in the mature market phase (Ferioli et al., 2009; Junginger et al., 2005). As a result, within this market scenario, even the cost has a persistent and stable cost decline, the price may follow unstable patterns according to the stage and this may lead to a different rate of learning for price except the competitive market phase.

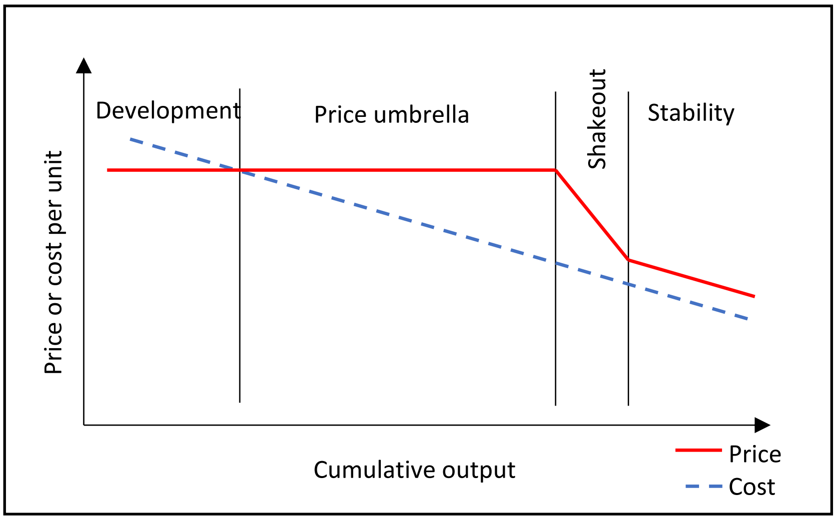

Figure 3.7. The simultaneous change in price and cost in different phases of market

Second, even if cost is the dependent variable, its rate may still not follow a continuous linear pattern. Behavior of varying unit cost decline rates can be seen in Figure 3.8 which was reproduced from the illustrations in (Ferioli et al., 2009). The phases defined there again do totally correspond to neither the ones in Figure 3.7 nor defined in Chapter 2. According to Ferioli et al., the linear rate is specific to the early phase where speed of learning is faster (Ferioli et al., 2009). Then, in the maturity phase it exhibits a slow down as non-learning components such as cost of raw materials become more dominant and, in the end, this slow down ends up with a stable cost that is not sensitive to cumulative experience. This assumption anticipates a diminishing return of learning since at some point it is surpassed by emergence of market constraints and natural resource limitations. But the author adds that the learning may continue only if radical changes occur. Therefore, without the exception of radical changes, experience curves that use unit cost as the dependent variable can only attain reliable results as far as they are limited to linear phase where innovative component is the largest contributor in the cost decomposition.

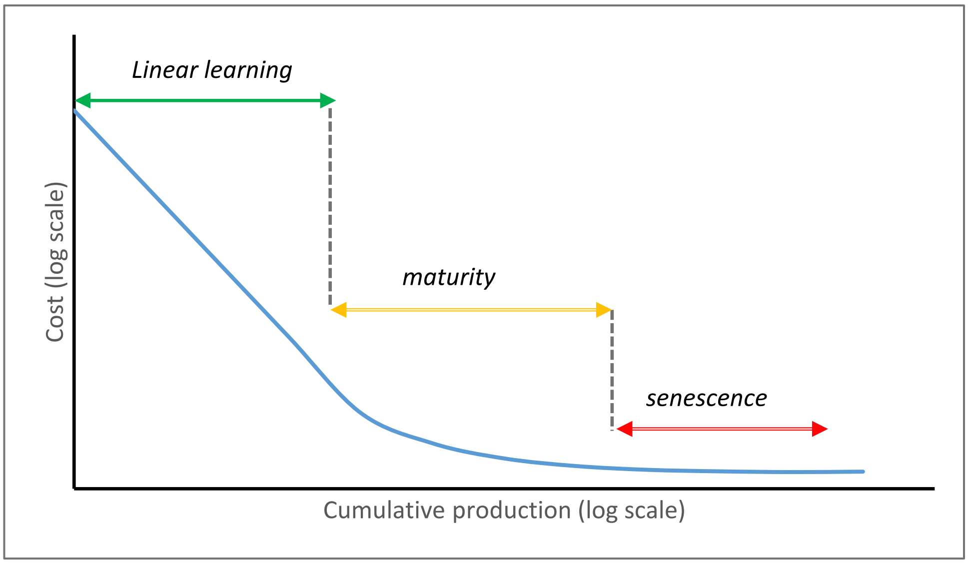

Figure 3.8. Learning cycle for unit cost

The third cause of non-constant PV LRs within time can be explained with the significant technological changes that occurs within time. In a broader context, it may arise from any interactions or disturbances arising from social, political or institutional dimensions in a path dependent way which is one of main characteristics of innovation from evolutionary perspective (Fagerberg, 2003). In two bottom up models (Kavlak et al., 2018; Nemet, 2006) which were proposed as alternative methods to PV LCs, the influence of different factors on cost decline of PV were investigated for discrete time periods. In these studies, the analyses were separated into periods where the weights of cost components change. Authors made ex-ante or ex-post identification of these periods based on some occasions occurred within the time intervals examined such as: terrestrial use of PV that surpasses space applications after 25 years; boost in global PV R&D expenses; emergence of governmental supports to commercial applications after research oriented focus (Nemet, 2006); technological improvements that led to substantial material reduction and performance increase enabled by public R&D expenses; economies of scale gained through market stimulating policies (Kavlak et al., 2018). In that sense, though the ranges selected may be characterized differently when evaluated today, among these definitions, shifts or changes both in terms of technological paradigm and trajectory can be diagnosed.

Technological paradigms which were introduced to the literature by Kuhn (Kuhn, 1962) and interpreted by Dosi in terms of technological change economics (Dosi, 1982) are set of laws, common scientific perceptions that are usually dedicated to the same purpose and orient the current research heuristics (Dosi, 1982; Dosi & Nelson, 2010). They do not change unless a revolution that disturbs them happens. It can also be a crisis that triggers the change. On the other hand, trajectory term is used to define the different paths within a paradigm to fulfill the same purpose in a common context (Dosi, 1982; Dosi & Nelson, 2010).

The disturbance created by the oil crisis corresponded to the start of the first time period employed in (Nemet, 2006). The attention of policy makers was oriented to PV in the first half of 1970s and since then the governments started to commence actions to exploit solar PV as a conventional power technology and allocated large funds to the improvement of this technology. In that sense, terrestrial use of PV as an alternative power source can be seen as indication of a paradigm shift although it was bounced back when the concerns related to oil crisis were mitigated.

On the other hand, the change in public policies in favor of large-scale deployment in the mid-1990s as mentioned in Chapter 2 and the technological improvements identified in (Kavlak et al., 2018) caused significant cost decline in a later term. Therefore, the research paths dedicated to decrease the cost of a specific technology can be identified as different trajectories. It can also be adapted to industrial strategies such as supply chain characteristics or concentration trends. The distinctive properties of certain periods were already discussed in Chapter 2.

Here, it is revisited to reveal how these can be interpreted from the paradigm and trajectory change perspective and can be associated with time level of analyses. As a result, different time periods may yield different LRs which was already observed in the bottom up cost models as well as in the LC studies. The phases of changing LRs can be identified with paradigm and trajectory shifts as well as temporary or permanent occasions like small scale production, pSi crisis, mass production, supply chain disruptions as employed in (IEA PVPS, 2022b). The historical phases of PV industry defined in Chapter 2 is a combination of both where the main phases started with either paradigm shifts (i.e. from space to terrestrial applications and the first appearance of governmental supports which have industrial/commercial aspects) or trajectory changes (i.e. from research and industry oriented policies to deployment policies, from small scale to utility scale projects, from a relatively globally distributed manufacturing to a highly integrated monopolistic industry) and included some specific occasions which created sub-disturbances such as mitigation of oil crisis, polysilicon crisis, etc.

Fourth, forgetting may occur as well if the knowledge attained is depreciated or lost by disappearance of influencing factors that inherit learning such as fast turnover of labor, shut down of plants for a while due to macroeconomic or political instability, etc. These may be another cause of stagnancy and change in rate of learning (Yeh & Rubin, 2012).

Consequently, either arising from the data and modelling problems or the reality that can be explained theoretically, the changing LRs in PV is an observed fact. To overcome the problems arising from the LR variations within time, researchers included critical variables that may have created temporary effects and thus handled discontinuity (de La Tour et al., 2013) and/or conducted discrete LC estimations for different time periods (Gan & Li, 2015; Kavlak et al., 2018; Yu et al., 2011). As another solution when such effects are not considered and LR is used as the input in the energy modelling studies, employing a sensible range for the LR is suggested (Samadi, 2018). Finally, as indicated in literature, once the number of firms stabilize the rate can remain constant for 30-40 years (Yeh & Rubin, 2012).

3.3.2.4. Methodological Level of Analysis

The drawbacks and the limitations of PV LC estimations mentioned in the subsections above are more or the less related to the definition of the boundaries at different levels, and selection of sampling accordingly as far as data were available. But even if they are solved, there are still uncertainties arising from the limitations of the current methodologies. These problems can be overcome via different solutions addressed in the literature such as: incorporating other variables into the LC equation to prevent omitted variable bias (Candelise et al., 2013; de La Tour et al., 2013; Gan & Li, 2015; Samadi, 2018; Trappey et al., 2016; Wiebe & Lutz, 2016; Yu et al., 2011) and to unveil other key factors which are masked with basic learning curve function (Candelise et al., 2013; Mauleón, 2016; Pillai, 2015; Wiesenthal et al., 2012); using component based bottom up cost models (Candelise et al., 2013; Kavlak et al., 2018; Nemet, 2006, 2009); improving the estimations via expert elicitations (Neij, 2008; Nemet, 2009).

Before starting to discuss the paths to clear the uncertainties and enhance the predictive power of estimations, the dependent variable issue is revisited shortly. As mentioned in the previous subsection, price is often accepted as a proxy of cost in experience curves since it is not easy to access cost values due to data availability and confidentiality (Candelise et al., 2013; Junginger et al., 2005; Rubin et al., 2015). It was discussed in time level of analysis subsection exhaustively that if the market is mature and the component is still subject to innovation, then price may be a proper indicator of cost decline since the margins will sustain and they will show a parallel pattern if short term fluctuations are ignored. Therefore, if otherwise not indicated, they are usually used interchangeably in LC estimations. On the other hand, in a firm level study, it was found that the margin was not constant and even could be negative for shorter time intervals i.e. quarterly data (Reichelstein & Sahoo, 2018). Additionally in a component based study (i.e. bottom up cost decomposition) carried out based on global data until 2001, it was corroborated that margins were not stable but rather decreased and even converged to zero as market became mature, thereby causing learning rates for earlier time span to be overestimated (Nemet, 2006). Around 2005, the c-Si PV module prices increased suddenly due to the shortage of silicon which was triggered by the unexpected demand increase in solar PV (Gan & Li, 2015; Mauleón, 2016) (also see Figure 2.10 and the discussion made in subsection 2.3.2). But then the market was recovered and stabilized after 2008.

In sum, for the emerging or developing market phases which are characterized by continuous technological improvements, enlarging market and unsettled industrial structure, if price is used in the absence of cost data, variables that can capture the market dynamics such as industry concentration index, supply demand gap, structural breaks etc. can be added to the model to enhance the predictive power of the estimation (Candelise et al., 2013; Nemet, 2006).

The very basic form of learning curves which was derived in subsection 3.2.1., depends on one factor i.e. LBD. It has been the most preferred version due to ease of its estimation and utilization in simulation studies. However, there are also some other reasons that might have limited the improvement of LCs and prevented them to go beyond being based on one factor.

First, as discussed in the "time level of analysis" subsection, the estimations were usually conducted based on small observation sets at any level because of the available time span for PV data. It limits including many variables because of lower degrees of freedom which prevents to attain higher significance of variables. Second, even if the largest time interval is available, nevertheless, the availability of data for the selected predictors and their quantification may not be so easy (Kahouli Brahmi, 2008; Wiesenthal et al., 2012). Third, when the previous challenge is tackled, the correlation between independent variables i.e. multicollinearity problem is frequently confronted (de La Tour et al., 2013; Samadi, 2018; Yi Zhou & Gu, 2019). Since it affects the variance of estimators, they become less efficient. As a result, it becomes harder to reveal the partial effects of collinear variables and relying on their predicted values(Wooldridge, 2009). In sum, larger observations, availability of relevant data and robustness of multiple predictors to various modelling handicaps ultimately confine the methodological scope and determine the potential scenarios that can be studied quantitatively.

On the other hand, refraining from including more variables, least but not last may decrease the explanatory power of the model and yield biased LR values due to the omitted variables. Beyond it, one factor model does not go beyond telling how much capacity increase is required for the target cost and attribute all efforts on demand side policies such as deployment subsidies in the form of electricity purchase guarantees. It does not allow to find out other underlying mechanisms either they are exogeneous or endogenous and to enlighten the cost reduction process thoroughly (Candelise et al., 2013; Mauleón, 2016; Pillai, 2015). Therefore, despite all challenges, authors either implemented or suggested a variety of models built on miscellaneous variables to investigate the further drivers of cost reduction in PV modules.

The potential factors can be measured by a set of explanatory variables that can be employed in PV LC estimations. These will be addressed soon with the relevant data problems and modelling drawbacks confronted in case of their incorporation to LC equations. But primarily, the conceptual background that underpins the requirement for investigation of further factors will be founded.

There are many potential endogenous factors as well as exogeneous effects which can improve the models and estimation results. However, they may inherit some handicaps as well. Though the historical progress steps and the industry structure mentioned in Chapter 2 may underpin the requirement for controlling or investigating the effects of some factors, a more comprehensive discussion around learning concepts is needed to enhance the analytical frame.

In OFLC estimations, learning is confined to only one dimension i.e. learning by doing though there are other types of learning defined in the literature. Indeed, technological innovation is an ultimate outcome of distinct learning patterns which sometimes overlap or feed each other (Rosenberg, 1982). These different patterns of learning can be enabled by the endogenous efforts which are stimulated by the external effects and as the stimuli evolve, learning can be maintained (Arrow, 1962).

On the other hand, the interactive nature of innovation somehow relates learning to innovation competences. It is possible to say that external effects can be endogenized through actors' capabilities and certain learning patterns together. Nevertheless, it is a virtuous cycle rather than a one-way relation. While the activities carried out during learning process can reinforce these capabilities (Nielsen & Lundvall, 2003; Zahra & George, 2002), their existence and extent can facilitate learning (Teece & Pisano, 1994; Wang & Ahmed, 2007). It was mentioned in section 3.2 that innovation is an uncertain and complicated process due to its path dependent and disequilibria features. Similarly, in (Rout et al., 2009) learning was characterized as an uncertain and complex process which was contributed by other factors through two way feedback mechanisms. In that context, learning can be perceived as an interplay between the internal efforts, capabilities and exogenous factors.

However, it is not an easy task to measure either learning or the capabilities it is intertwined with. Therefore, kind of derivatives of learning activities are employed as their common indicators, which in turn makes distinguishing learning and capability concepts harder. More clearly, while various measures regarding existence, absolute amount, degree, or intensity of the activities that follow “learning by” expression identify certain learning patterns, they may also be the signs of certain innovation capabilities which are assumed to be improved through these activities. On the other hand, though the theoretical discussions in the innovation economics describe an exhaustive conceptual frame for the capabilities that can cause innovation and provide some clues to figure out them (Wang & Ahmed, 2007; Zahra & George, 2002), their exact diagnosis substantially requires qualitative research and analyses. As a result, the activities that belong to certain learning patterns can also be used as the key factors that improve and thereby can ultimately indicate the presence of these capabilities.

Although many different types can be met in the literature, the most widely articulated learning types in LC literature are learning by researching/searching, learning by using and learning by interacting in addition to learning by using (de La Tour et al., 2013; Elia et al., 2021; Kahouli Brahmi, 2008; Mauleón, 2016; Rout et al., 2009; Samadi, 2018; Wiebe & Lutz, 2016; Yu et al., 2011). These concepts which were already introduced by different authors in the past can be described as follows:

Learning by doing (LBD) was known to be mentioned in (Arrow, 1962) first. It comes out upon accumulation of experience formed by carrying out a repetitive activity. As more is done, more occasions are confronted and the ability to make better is developed while trying to solve the problems. As addressed in subsection 3.1.1, exhaustively, the effect of this type of learning on cost reduction has been usually measured by cumulative output since it was first observed by (Wright, 1936). It was then further developed through more observations and relevant discussions made upon.

According to Arrow (1962), since it tends to equilibrium after a certain level, the conditions that stimulate learning should be evolving to maintain its effect (Arrow, 1962; Thompson, 2010). However, when the rate of output remained same (Alchian, 1949; Berndt, 1991) or there were no new investments (Arrow, 1962; Dutton & Thomas, 1984; Thompson, 2010), learning was still observed. Therefore, learning effect can take place independent from the returns to scale or in other words economies of scale (Yu et al., 2011). Improvements through LBD can be at both manufacturing and organization levels (Samadi, 2018) upon development of labor and management knowledge (Elia et al., 2021). But, in the most common used global aggregate approach in LCs, learning is measured by the world average prices/costs against global output and LBD is no longer an individual firm feature. Rather, a strong assumption is made about homogeneous knowledge spillover which allows all firms benefit from it equally (Nemet, 2006; Samadi, 2018) and presence of a weighted impact is ignored.

Learning by researching (LBR) can be traced back to the well-known study of Cohen and Levinthal (Cohen & Levinthal, 1989b). They introduced the learning dimension of R&D and defined it as absorptive capacity. Aligned with the definition of these authors, R&D activity itself is a learning process since in addition to the first role attributed to it i.e. creation of new knowledge, it improves the agent's ability to understand the existing knowledge base, distinguish the useful information among and find the proper ways to exploit it. As a result, by means of the internal efforts dedicated to research activity, how to assimilate external knowledge is learned. The concept of absorptive capacity will be discussed in the next subsection more in detail. LBR is the second most common investigated type of learning in energy technology LCs after LBD (Elia et al., 2021; Rubin et al., 2015; Samadi, 2018; Wiesenthal et al., 2012) despite still being rare. The models that include it are widely known as TFLC.

The indicators that were used as proxy of LBR in the PV LC literature are mainly as follows: knowledge stock which is calculated by adding cumulative research expenditures to the current year's R&D expenditure by taking care of a certain time lag and depreciation factors (Kobos et al., 2006; Watanabe et al., 2000; Yi Zhou & Gu, 2019), cumulative R&D expenditure with a certain lag (Wiebe & Lutz, 2016), cumulative patents (de La Tour et al., 2013), power conversion efficiency of PV modules (Pillai, 2015). The last two are controversial in terms of their ability to capture the whole effect of LBR since all R&D efforts that lead to improvements may not end up with patents and research contributions are not only related to efficiency. The study that investigated the effects of cumulative patents with a depreciation coefficient did not find any significant results for LBR (de La Tour et al., 2013). On the other hand, the impact of power conversion efficiency of firms on unit cost was found significant in a firm level panel data study (Pillai, 2015). Though it is a good measure of performance and can be strongly related with the firms' research activities, it is still not an adequate parameter to capture all LBR effect alone. Moreover, employing firms' own efficiency values is somewhat trivial since its effect on unit cost through the denominator (i.e. power value) is certain.

On the other hand, there are studies that utilized knowledge stock or cumulative R&D with a certain time lag as LBR indicators. In (Watanabe et al., 2000) where unit costs of 6 Japanese PV firms were examined as pooled data and also individually at solar cell level, knowledge stock and the energy prices employed as control were found significant for many of the firms. However, the LBD effect was not included in these models. In (Wiebe & Lutz, 2016) where both global module and system prices were estimated in different models, LBR was not found significant for any of the trials regarding PV modules; but it was only significant for the system costs estimated for Germany. In (Kobos et al., 2006), TFLC estimations were carried out for global PV module prices and after many trials with changing lags and depreciation durations, LBR was found significant for 3 years lag and 10 years depreciation. In another study, global system prices in the US were examined with TFLC for different plant scales i.e. residential and utility scale PV systems and LBR rate was found extremely high with a value of around 75 and 65% (Yi Zhou & Gu, 2019)[69]. The multicollinearity problem

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[69] In (Kobos et al., 2006; Yi Zhou & Gu, 2019), the variance inflation factors (VIF) was controlled for multicollinearity and in (Kobos et al., 2006) the depreciation and lag were selected based on the criterion that VIF was <10. However, in both studies where only LBD and knowledge stock were employed as explanatory variables, VIFs were very close to 10 which still indicated a high level of multicollinearity.

between the potential learning variables is one of the greatest risks (de La Tour et al., 2013; Samadi, 2018) that can yield insignificant coefficients or cause the estimated coefficients to be misleading. Therefore, though LBR is seen as an interchangeable and important contributor for the energy technology LCs (Rout et al., 2009; Rubin et al., 2015), due to availability of consistent global data (Gan & Li, 2015; Wiesenthal et al., 2012; Yu et al., 2011) or multicollinearity (de La Tour et al., 2013) concerns, its effect is usually ignored in many of the models in the literature. The cumulative value of R&D carries the risk of capturing some part of the LBD effect which is measured by cumulative output and when the effect of research on cost reduction becomes increasingly difficult by time, LBR may be overestimated with cumulative R&D expenditure-based indicators (Wiesenthal et al., 2012). On the other hand, using R&D intensity instead can mitigate these problems (Wiesenthal et al., 2012).

Learning by using (LBU) term was introduced in (Rosenberg, 1982). According to Rosenberg, especially for complex technologies, learning can be a function of its utilization by the final users. In the general description, LBU is an understanding process regarding the performance and limitations from the perspective of users and making required modifications or suggesting them to the manufacturer (Kahouli Brahmi, 2008). When observations arising from exploitation of a technology are fed to the producer, variety of perspectives can open new paths for improvement as well as existing flaws can be noticed.

Rosenberg separated LBU into two forms as embodied and disembodied (Rosenberg, 1982). The first one, embodied LBU, happens at the earlier development stage where the systems may require design modifications due to the performance observed in the field and they are made iteratively until reaching an optimal design, since there may be some difficulties brought along by further adjustments or trade-offs between the previous performance characteristics. In this version, relevant industries are a part of learning process since modifications may require innovations in other fields as well. Rosenberg explained it with the need of improvements in metallurgical solutions and electronic components in the pursuit of optimal design of aircrafts. On the other hand, the disembodied version is more like development of new practices in operation and maintenance and usually requires none or less hardware modifications. However, in the long term they are intertwined and may both end up with improvements in design.

Since performance of complex systems which have long lifetimes have an intrinsic uncertainty, prolonged experience is an undeniable requirement for reliability especially for high technology industries as well as an optimal design, which is exemplified by communication and software technologies in (Rosenberg, 1982). He emphasized the potential contribution of this type of learning pattern to productivity which ultimately would affect the costs, and found its empirical investigation in different industries worth. However, it should be carefully handled when the effect of LBU on costs is examined. Since its effect may remain at operational level, it can be easier to observe this effect when the dependent variable is the cost of electricity generation rather than the PV modules. Even in case there is a product modification, the better performance may be regarding the reliability within the lifecycle and hence contribution may be in the form of long-term cost reduction again rather than the product cost. Moreover, in global aggregate data, it is hard to distinguish LBU effect from LBD since doing and using are almost equal in overall. As a result, investigation of LBU in PV LCs has not been met. In the LBU pattern that focuses on user-producer interaction, it is the end user that is usually mentioned. On the other hand, the interactions may be at different levels.

Learning by interacting (LBI) was first introduced and discussed exhaustively in (Lundvall, 1988). For a successful innovation, knowing the needs of users is as crucial as introducing new technological opportunities and it entails intra-organizational interactions and knowledge sharing between the individuals and different departments within the same organization (Lundvall, 1988).

In transaction cost approach from neoclassical point of view, firms tend to be vertically integrated and create a hierarchy when markets are small, uncertain, limitedly rational and are not willing to take risks; therefore, process improvements are expected to be dominant against exceptional product innovations (Lundvall, 1988). However, as mentioned in (Lundvall, 1988) even in the old times when neoclassical view was dominant, it was observed that more than half of the innovations in the post second world war era was rooted from outside. He also mentioned that product innovations were as important as process innovations based on the R&D data of OECD countries. Contemporary data supported it by finding these two complementary, based on the observation that the most innovative industries in terms of business processes were also ranked at the highest levels for their product innovations (OECD, 2022). Therefore, since product innovations are more frequent than assumed and they may be fueled by other actors in the market, "organized market" concept where formally independent units interact in the form of qualitative information flows or direct cooperation was introduced as an alternative to "pure market" or "pure organization" approach (Lundvall, 1988). Rather, by "pure market", it is assumed that the interaction between producers and users are not intentional and the substantial feedback depends on quantitative data regarding volume and price.

Though it is possible that a hierarchy may appear due to financial or scientific superiorities of the parties, common codes and trust may decrease the uncertainty and make the innovation process more efficient (Lundvall, 1988). Moreover, in the process of LBD, seeking solutions to new problems confronted may trigger different patterns of learning and hence entail interacting with several actors (Nielsen & Lundvall, 2003). LBI may be reinforced with respect to time and geographical proximity (Lundvall, 1988). It is resistant to time since once the trust and channels of information are constructed, they sustain unless the cost of relationship does not become a burden. When the technology is complex and continuously changing, common codes of conduct and cultural background can facilitate and speed up the knowledge exchange.

In terms of vertical integration, LBI may be hampered due isolation of integrated actors from the external knowledge exchange (Lundvall, 1988). Lundvall described it as follows: producers may hesitate to interact since they may be afraid that their know-how can be embodied by the vertically integrated competitor in the later stages while users may refrain to be in relation since they may be provided inferior products compared to the integrated counterpart which is their competitor at the same time. The trade-off between the lack of benefits arising from external interactions and advantages of transaction costs may be specific to industry (Lundvall, 1988).

Though Lundvall extended the LBI beyond classical user-producer relations it is a much wider concept which is enabled by knowledge exchange through informal relations, networking or collaborative activities between various stakeholders such as producers, suppliers, users, research institutes, policy makers (Kahouli Brahmi, 2008; Mauleón, 2016; Rout et al., 2009; Yu et al., 2011). Moreover, LBI is the dynamic dimension of agglomeration or in other words clustering effect which can appear in time upon interactions and cooperation between firms, policy actors and research bodies (Noteboom, 2007). The feedback mechanisms upon interaction between the agents from different domains can unveil the handicaps confronted or enable to notice the solutions that can be created at other levels. But also, contacts in between lateral stakeholders in an innovation system can create a positive impact as well through variety of individual perspectives that every party brings along.

Elia et al. made the distinction as “industrial” and “geographical” LBIs. Knowledge exchange through benchmarking among actors in a technology value chain was categorized under the former and joint ventures between players in different geographies were covered by the latter (Elia et al., 2021). They also included knowledge spillover from other industries as industrial LBI. In any case, diversity based on differentiation of knowledge and skills in various actors is the key aspect for LBI since the interaction with the actors outside the organizations may beat the internal myopia when the cognitive distance of interacting agents is bigger (Noteboom, 2007).

As defined by Noteboom, cognitions developed under different circumstances such as “national, regional and organizational culture, customs/habits, social norms/values, education, technologies, markets” create a distance between the actors and while it can be fruitful in terms of creating novelties since it affects mutual understanding negatively, an optimal point should be attained (Noteboom, 2007). Industrial networks, social networks, sectoral unions, clustering, scientific or sectoral conferences, international/national collaborations between or within agents in university, government, industry dimensions, labor mobility, student exchange as well as producer-user relations may channel LBI. Any studies that investigated the quantitative impact of LBI directly or indirectly has not been found in the PV LC literature.

Overall evaluation of different learning factors and other factors utilized in LCs

As mentioned above, the learning types that were frequently addressed in PV LCs are LBD and LBR. The relevant variables used as their indicators were addressed before. There are other internal or external parameters that were employed in PV LCs. One of the common problems that may affect the significance of these variables is multicollinearity which is inevitable for some variables. Since cumulative output as the proxy of LBD is a generated value obtained by summing up annual outputs retrospectively, it definitely increases. Therefore, other potential variables like R&D expenditures, plant scale which certainly increases as well, can easily show an aligned trend with LBD in a continuously growing industry (de La Tour et al., 2013). Pertinence of measuring some impacts with globally aggregated values is another handicap that may preclude the investigation of the impacts accurately. Lack of worldwide PV R&D data[70] or data that only cover governmental expenditures seems to have caused deliberate ignorance of learning by (re)searching effect (Gan & Li,

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[70] The PV oriented R&D expenditures are only available for certain countries. For more details, please see the data source utilized in Figure 2.7.

2015; Yu et al., 2011). But even if it was included, due its aggregate feature, global data could not reveal whether all research efforts were identically effective or the impact was arising from a certain region.

Economies of scale is one of the parameters that was found worth investigating in the LC estimations. As mentioned in subsection 3.1.2, indeed it was naturally a part of the C-D originated cost function which was evolved to fundamental LC equation in the end. However, when returns to scale parameter was assumed constant with a value of 1, the output term was dropped. Nevertheless, there have been some trials by different authors to test the validity of this assumption for the PV industry. Yu et al. found average industry plant size significant in the model where the unit cost of PV modules was estimated for the time interval 1976-2006 with global aggregate data based on LBD, scale effect and cost of other input variables, and returns to scale was calculated as 1.07 (Yu et al., 2011). Estimation of unit PV module costs in between years 1976 and 1994 against cumulative PV installations and scale in (Isoard & Soria, 2001) resulted in returns to scale as 1 when it was assumed constant and in case the model was arranged according to flexible economies of scale it deviated between 0.70-0.97. Same authors concluded that still in the long run it would converge to 1 making its effect smaller compared to LBD due to reaching optimum production scale. In another study carried out for the time interval 1990-2011 with the global data, when scale effect was included in different model variations composed of cumulative output, some input costs, LBR indicator, it was found insignificant (de La Tour et al., 2013).

The findings above show that there are increasing, decreasing and constant returns to scale in PV as well as insignificant results though all depends on PV module costs and global aggregate data. As it was already mentioned in the previous paragraph, de la Tour et al. articulated that since scale was highly correlated with experience, the accuracy of the models that included both were not reliable (de La Tour et al., 2013). Another concern about the use of scale may be related to the data structure. Though it was remained ambiguous in some studies, some of the authors who investigated effect of this parameter in econometric estimations or bottom up models, explained the relevant data they utilized as the current year's representative industrial value for the plant scale. Global average of the production scale, average scale of certain number of firms or values reported by a few well known manufacturing firms were the most common data sources utilized for this purpose (Kavlak et al., 2018; Nemet, 2006; Yu et al., 2011). Thus, in aggregate form, it is generalized without knowing how widely this scale is adopted among the sample. In that sense, validity of employing a representative value (which entails capital investment) as a common variable and relying on its effect and relevant implications made from should be handled carefully.

On the other hand, in (Pillai, 2015) where firm level panel data for the years 2005-2012 were utilized, average plant size of each firm was employed as the scale parameter and it was found insignificant when it was investigated together with the other factors like LBD, LBR, feedstock parameters and some industrial factors. However, when it was introduced into the model alone, it was significant with a negative sign and yielded very similar result with LBD effect. Although cumulative industry output was used as the LBD parameter rather than the cumulative output of individual firms, the author indicated that they behaved very similar. He added that it was same when the firms' annual output was utilized as the scale parameter rather than the average plant size of the firms[71]. Beyond similarity of the results for the different proxies used for LBD and scale, these two factors, as mentioned above, yielded very identical results in terms of sign, coefficient, significance level and predictive power of the model (i.e. R square) when they were included in the model alone but they both became insignificant jointly. It is noteworthy that for firm level data if the output of individual firm is utilized as the scale, it becomes structurally an obvious part of the cumulative output and correlation between these two independent variables is

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[71] Since the firms in the sample are mainly big players of PV industry, they embody more than one plant in their organizations. Therefore, it is not possible to identify one unique plant size for one firm. Probably thereof, the author employs the average size of the plants for each firm.

inevitable. Furthermore, it is hard to find a representative value of scale for these firms due to the reasons addressed in the footnote 73 below. The problems regarding the model and data as well as the similarity of the effects of these two variables, require LBD and scale parameters to be handled very carefully and their contribution to the model should be decided based on their meaning as well as statistical behavior.

Other factors that were incorporated in PV cost estimations can be categorized under ***input prices***. Though they were dropped from the model when the prices were corrected with the GDP deflator as discussed in subsection 3.1.2., extreme fluctuations in especially the prices of feedstock i.e. polysilicon (or shortly silicon) required the models to be controlled for its effect. The polysilicon crisis of which traces became visible near 2006 and was mitigated by 2009 after making peak in 2008 was examined in detail in subsection 2.3.3. As a result of the unexpected demand increase in solar PV, prices had suddenly increased due to the shortage of silicon. Therefore, many of the authors included relevant parameters in their models. The impact of polysilicon price ($/kg) on global PV module costs was investigated together with LBD and some additional variables such as scale and miscellaneous control variables in (de La Tour et al., 2013; Gan & Li, 2015; Yu et al., 2011). As a result, it was found significant with a positive sign for changing time intervals utilized in the relevant articles between the years 1976-2011. Wiebe and Lutz, included a dummy that represented the period for the “silicon bubble” (2005-2008) in addition to LBD effect and so-called overcapacity year dummies and found the silicon effect on PV module costs positive and significant (Wiebe & Lutz, 2016). Pillai included the polysilicon amount used in addition to the polysilicon prices in the firm level panel data estimations carried out for the years between 2005-2012 and the coefficient of both variables were positive and significant in all model variations he tried with changing factors including LBD, LBR, scale, industrial and firm level investments and dummy for China etc. (Pillai, 2015).

Mauleon made a joint estimation of global PV module costs based on LBD for the years 1993-2013 by regressing polysilicon prices on energy prices and the cumulative capacity (Mauleón, 2016). He concluded that energy prices had positively significant effect on PV module costs through polysilicon prices but the polysilicon prices were also affected by the demand at certain time interval. On the contrary, in (Trappey et al., 2016), where the PV systems cost in Taiwan in 2001-2010 was utilized as the dependent variable, the effect of prices of oil and steel which were evaluated as other inputs yielded insignificant coefficients while LBD and silicon price were found similar to other studies. Indeed, it is obvious that silicon as the raw material is an important contributor alone in the PV module costs. As can be seen in Figure 2.12, its share can change in between 12% to 44% in the long run. Therefore, since the costs are certainly affected by this variable which can also be confirmed by the bottom-up cost analyses, the way how it is related to learning factors may be more critical than revealing its contribution to costs. In addition, continuous reduction in unit amount of polysilicon used upon technological improvements is also a relevant and important parameter to be considered when the price of polysilicon is investigated. There is only one study found in the literature that considered the unit amount of polysilicon used and found it significant (Pillai, 2015).

The parameters mentioned up to now were seen as a remedy to omitted variable bias and aimed at investigating other learning effects partially. However, for a reliable estimation, structural changes in the market, technological breakthroughs and spillover effects may be as crucial as others (Candelise et al., 2013). Rubin et al. suggested underlying mechanisms and technological change process to be understood and handled more carefully since the overall evaluation of LBD in global data did not necessarily indicate a causal relation despite proven correlation that had been provided with exhaustive research (Rubin et al., 2015). As a result, the variables should be able to unravel the ***external effects*** as well in addition to internal factors.

In (Wiebe & Lutz, 2016), it was claimed that PV module supply was globally higher than the demand in the years 2011 and 2012 within the time interval examined i.e. 1992 and 2012. To control this effect, an overcapacity dummy was introduced for these

2 years and its effect on module costs was found negative and significant. However, this may be a misinterpretation based on the data source; since as seen in Figure 2.10, difference in supply and demand was not specific to those years. Still, near these years can be seen as a structural breakthrough time when dominance of China on all value steps of PV value chain is considered (please see Figure 2.11). Similarly, Gan and Li (Gan & Li, 2015) in their study where they examine the global PV module costs for the years between 1988-2006 introduced a parameter called the supply-demand gap as a control variable in addition to LBD and silicon price but it did not yield a significant result. In the same paper, authors also aimed at investigating the effect of Chinese share in PV production. But for the time interval examined, it did not result in a significant coefficient either. Also, in (Pillai, 2015) for the estimations carried out for 2005-2012 with firm panel data, China dummy which was included in case the models were not estimated with fixed effects, was found significant.

Finally, LBD effect in the LCs was suggested to be controlled for the ***time trend*** that was expected to capture exogenous factors that were said to be unrelated to learning like spillovers from outside the industry, the returns to research and development, economies of scale and scope, as well as exogenous fundamental inventions (Nordhaus, 2009). However, this is not different than creating a new black box and putting inside all changes that accumulated within time. In addition, this approach that isolates external effects as totally exogeneous and ignoring their relation to learning, is not aligned with the interactive approach of innovation and the innovation capabilities which will be mentioned in the following subsection. Yeh and Rubin criticized the approach that perceived learning merely as an outcome of growth and external progress that was a function of time, since learning was made an ambiguous aggregate concept again that embodied every improvement (Yeh & Rubin, 2012).

It is also highly problematic in terms of econometric issues since mathematically, time trend is not a different thing than accumulated static output in terms of slope. Therefore, correlation between LBD and a basic time trend variable is inevitable which ultimately decreases the accuracy of estimations. In two studies which investigated PV module costs from 1993 to 2012 and 1987 to 2000, time trend was tested for alternative models and respectively was either found insignificant in all models (Mauleón, 2016) or captured some of the LBD effect in one model while causing its insignificance in another (Papineau, 2006). Also, in (Pillai, 2015), where a firm level panel data analysis was carried out for the years between 2005-2012, while effect of time on cost decline of PV modules was significant with a negative sign, it lost its significance when it was in included in the model with plant size and cumulative industry output. Hence, all of these were omitted from the models and the following models were investigated based on combination of annual firm, annual industry and cumulative industry investments as well as polysilicon parameters and product efficiency which were discussed in the previous paragraph. As a result, in addition to the input and product performance parameters, only annual industry investment was found significant with a negative sign which was explained by the authors as contribution of economies of scale in capital equipment due to industrial investment volume. However, it might also have been a sign of spillover as the new equipment was introduced into the overall market.

As a result, any learning that might have occurred in the last 20 years and ended up with the outstanding consequences regarding the product performance and costs mentioned in the last paragraph of sub section 2.3.3 could not have merely arisen from an aggregate parameter like global cumulative capacity employed in basic learning curve estimations. In that sense, many of the variables mentioned above may worth investigating in PV LC estimations. But by global data, although it is possible to decompose the cost decrease to more than one parameter, their contributions remain ambiguous in the aggregate form.

On the other hand, as described in section 2.3, starting from the mid of maturation stage of the PV industry (i.e. 2003) till today, China became a noticeable actor and stayed as the dominant player of the PV industry thereafter. Hence, incorporation of the factors that allow investigation of the dynamics within the firms and the industrial trends in China as well as the global improvements may be more effective to enlighten the learning mechanisms that have driven the substantial cost decline of PV module in the almost 20 years.

Furthermore, there are also alternative methods developed by some authors to estimate the cost of PV technology. In this bottom up method or so-called component-based model, the cost is decomposed to different factors that can affect it. In the end, weights of different components in cost decrease are revealed (Kavlak et al., 2018; Nemet, 2006). But at the end of the day, they are composed of very explicit parameters such as material cost, material amount, product performance and scale effect. In that sense, they somehow remain exogenous and fail to say anything about the direct effect of the efforts regarding R&D, industrial or firm structure beyond the technical details as well as how these were functionalized through agent's capabilities. Since the underlying mechanisms behind these improvements or their interaction between internal factors are not revealed, they cannot contribute to the decisions directly. Candelise et al., criticized both bottom up models and the LC estimations for being focused on long term factors rather than more immediate and local factors (like scale effects, market dynamics, industrial re-organization) which triggered the innovation in the energy system and led the dramatic change in PV costs and prices in the maturation stage. (Candelise et al., 2013). They concluded that diversity of the learning effects and their potential interaction with policy should have been considered in that scope. Consequently, a middle way should be found between valid and reliable cost estimations and identification of factors behind of which interpretation will be functional.

3.4. Relation of Learning Concepts to Innovation Capabilities

As addressed in the subsection 3.3.2.4, learning patterns are strongly related to improvement of endogenous competences which ultimately contribute to innovation and provide competitive advantage to economic agents (Teece & Pisano, 1994).

Inspired from the resource-based strategy, dynamic capabilities approach defines the abilities of firms to adapt, integrate, reconfigure their assets. In a wider context, it is comprised of the distinctive resources, processes, organizational skills and functional competences in the economic agents under changing technological conditions (Teece et al., 1997; Teece & Pisano, 1994; Wang & Ahmed, 2007). However, while resource based perspective focuses on distinguishing and embodying the resource combinations appeared outside, dynamic capabilities require creating new combinations from them (Pavlou & Sawy, 2011). In that sense, these capabilities of economic agents are idiosyncratic and have a certain barrier to imitation (Teece et al., 1997). The role of learning in shaping these capabilities lies in their determinants. Based on (Teece & Pisano, 1994), they can be shortly described as follows:

- *Organizational and Managerial Processes:*
    - *Integration:* This defines the coordination ability of firms based on either they have a vertical integration internally or externally through strategic alliances and sourcing. The existing coherence and complementarity between processes determine if the new technologies can be adapted easily. Therefore, how effectively new routines are integrated into the existing organization and coordinated determines the dynamic capability of a firm at this level.

    - *Learning:* It is defined as a process that happens through repetitive practices as well as experimentation and enable to make better and faster as well to identify the new opportunities around. In organizational dimension, it requires interactions in the pursuit of successful solutions to existing problems. As a result, dynamic capabilities are seen a door that open the door for organizational learning. In that sense, relations with different stakeholders and collaborations can channel it and help firms to identify their routines that do not function well and prevent corporate blindness.

  - *Reconfiguration and Transformation:* This behavior requires sensing the need for change, distinguishing the external improvements that are useful to adopt by following and evaluating environment i.e. the markets, technologies and competitors. Ultimately it is related to willingness to transform. The firms that are successful at these tasks are characterized with high flexibility. Benchmarking, decentralization and local autonomy may contribute to these processes.

- *Positions*
  - *Technological Assets:* They are shortly firm's know-how either it is protected with intellectual property rights or not.
  - *Complementary Assets:* They are related assets that complement the firm's own activities and enable production and delivery of new products or services. They are usually found in the downstream steps.
  - *Financial Assets:* It is basically the situation of cash within a firm. The firm's ability to access the finance can be related to providing sufficient information to the investors.
  - *Locational Assets:* That is related to critical geographical positioning. Some issues like ease of transport, cost of land or environmental restrictions can provide advantages or disadvantages to firms.

- *Paths*
  - *Path Dependencies:* As one of the key attributes of innovation, path dependency defines irreversibility in an innovation process of which evolution is shaped by the history i.e. the previous activities of the firm and its routines and the occasions confronted on the path upon trial, feedback and evaluation mechanisms. To keep the learning process healthy, there should be enough space to make experiments and develop cognitive abilities upon. Therefore, multidimensional rapid changes may deteriorate the learning process.

- *Technological Opportunities:* It defines the speed and extent of an industrial progress depending on externally existing knowledge base and existence of breakthroughs in technology and science at one side and the firm's ability to recognize them through its internal research efforts.

In the dimensions above which determine the dynamic capabilities, it is easy to find traces of different learning patterns defined in subsection 3.3.2.4. First, the learning concept defined as the component of managerial and organization processes above (Teece & Pisano, 1994) indeed corresponds to LBI. The ability of building external relations and the effectiveness of interaction can be seen as a dynamic capability which in the end improves organizational learning.

In "reconfiguration and transformation process" defined (Teece & Pisano, 1994), the sensing and responding ability to the advances in the environment can be easily associated with absorptive capacity which was described as the capability to recognize and assimilate the new and external knowledge through R&D intensity of firms in (Cohen & Levinthal, 1990). However, more contemporary approaches in the literature extended the enablers of absorptive capacity to other factors such as technological information, R&D staff, R&D department activities, technical and professional staff, staff training, scientific outputs and patents, machinery i.e. new knowledge embodied in capital investments, networks i.e. partnerships/affiliates, attending events, research alliances, organizational structure and conditions in the surrounding environment (Ayala et al., 2015).

Due to the possibility of recognition of potential transformation opportunities through networks and other kind of relations, a certain level of LBI can help to improve this absorptive capacity based dynamic capability in addition to learning by researching. It makes sense since capturing external knowledge in the industry may require being in coordination with other stakeholders as well. Moreover, the cumulative investment was discussed to be the real reason behind the LBD effect (Arrow, 1962; Thompson, 2010). It can improve the capabilities of firms by stimulating reconfiguration and transformation of the activities in a dynamic environment. Thus, it can enhance the absorptive capacity. Also, through it, new routines can be created, tried and utilized in operations. Thus, transformation and utilization capabilities are mobilized. In sum, “reconfiguration and transformation process” as a determinant of dynamic capability requires a certain level of absorptive capacity which can be improved by LBD, LBR and LBI as discussed above.

In the path definitions (Teece & Pisano, 1994), path dependency includes cumulativeness of firm’s activities and gradual adaptation to changes. In that sense, it can be related to LBD. Firms can learn and develop dynamic capabilities through their routines and the trials that accompany them on their path. The contribution of technological opportunities to dynamic capabilities is again strongly related to absorptive capacity of a firm. As it was articulated by its definition above, research efforts and staff i.e. LBR may play an important role here in terms of recognition and assimilation of the improvements outside, while LBD can act effectively in transformation and exploitation of them. On the other hand, LBR and LBD can function synergistically in creating new routines as a part of transformation activities. Moreover, networking activities i.e. attending events, partnerships and alliances and acquisition of new technology through machinery and equipment can contribute to firms' adaptation to changes and determine its path as well.

Finally, regarding the integration process examined under organizational and managerial processes (Teece & Pisano, 1994) which may be a barrier for dynamic capabilities, as discussed in sub section 3.3.2.4 under LBI, despite transaction advantages, vertical integration may hamper the learning process by limiting interactions and the knowledge that can flow from outside. As mentioned in (Fagerberg, 2009), organizational structure within a firm evolves according to the best practices in time. However, these routines that are based on daily internal communications and interactions may preclude firm from absorbing the new knowledge outside especially if the existing knowledge base is challenged (Fagerberg, 2009).

The intertwined structure of absorptive capacity and the dynamic capabilities makes it hard to make clear distinction between them. According to Wang and Ahmed, as the absorptive capability of a firm is demonstrated, the firm becomes more competent in dynamic capabilities (Wang & Ahmed, 2007). In (Zahra & George, 2002), the absorptive capacity which was recognized as a dynamic capability was reconceptualized with four capability dimensions i.e. acquisition, assimilation, transformation and exploitation which were together determined the firm's existing and potential competitive advantage. The new knowledge outside is gained and converted to a functional form by combining it with the internal knowledge through these capabilities (Zahra & George, 2002). Acquisition explains the ability to distinguish and identify the external knowledge which is analyzed, understood and interpreted by the assimilation capability; then by means of transformation ability the knowledge assimilated is refined and new routines are developed by combining the existing and external knowledge; finally exploitation requires incorporation of the new knowledge created through its implementation and utilization in operations (Zahra & George, 2002). Based on the descriptions and discussions above, absorptive capacity which shortly enables to identify, understand, transform and create knowledge and the dynamic capabilities affected from this ability of firm can be related to four types of learning i.e. LBI, LBR, LBD and LBU in different dimensions. Therefore, the learning patterns that contribute to improvement of absorptive capacity can be seen as precursor of dynamic capabilities.

On the other hand, as defined in (Wang & Ahmed, 2007), firms that have higher absorptive capability exhibit stronger learning patterns and as mentioned by Teece et al., dynamic capabilities enable organizational learning (Teece et al., 1997). As a result, once these competences are built, they may ease the further learning processes themselves.

3.5. Understanding Learning Through Innovation Systems Perspective

This subsection aims at introducing the main types innovation systems (IS) to construct the foundation of functional dynamics approach, which was utilized in the evaluation of the qualitative research carried out in the thesis study. Each analysis has its own evaluation methodology; but ultimately, they all serve functioning of a PV Technological Innovation System (TIS). Use of TIS approach in evaluation of renewable energy technologies is traced back to the beginning of 2000s (Jacobsson & Bergek, 2004). There are studies that examined the PV industry with TIS perspective, more specifically with the functional dynamics view (Gandenberger, 2018; Huang et al., 2016; Jacobsson et al., 2004; Zou et al., 2017). They mainly utilized qualitative and quantitative desk research based on literature review, bibliometric and descriptive analyses (Gandenberger, 2018; Zou et al., 2017) or a combination of these as well as expert elicitations (Huang et al., 2016).

In this section, the theoretical foundation of the functional dynamics analysis carried out based on expert interviews in Chapter 5 is underpinned. In this thesis, the expert elicitations primarily aimed at supporting the quantitative study by enlightening the reasons behind but also unveiling the other factors of which effects that could not be measured through the econometric estimations. The interviews were not intentionally designed to understand the functions of the PV TIS. However, in the end, some issues pointed out by the experts in the semi structured survey allowed the elicitations of the experts to be evaluated with a functional dynamics analysis.

In sum, rather than carrying out an exhaustive PV TIS analysis, a complementary view about the blocking and inducement mechanisms that were found to have been effective in PV TIS based on the expert interviews was provided. Hence, during the discussions in the qualitative part, all functions will not be addressed comprehensively with all dimensions described here. Nevertheless, the findings may inspire further research that either focus on TIS analysis or learning mechanisms with LC approach. Therefore, in the following sections, functional dynamics approach will be described by providing sufficient information about its domains which are utilized to evaluate the findings in Chapter 5 from this perspective.

3.5.1. A Brief Introduction to Innovation Systems

Innovation is uncertain by its nature (Kline, 1986) since it is path dependent, and may not come to or stay at equilibrium for longer durations (Dosi & Nelson, 2010). It occurs in collaboration and interdependence between the components of a system (Edquist, 2005). Previous to emanation of innovation systems concept, innovation was first accepted as linear from either technology-push or market-pull perspective until a chain linked model was proposed (Kline, 1986). In the chain linked model which was a more improved version, all domains in the market and the knowledge base that feed innovation were assumed to be interacting in a continuous feedback loop without a deterministic approach as seen in the preliminary models. But still it was not sufficient enough to solve the complex features of innovation by isolating it from the context it is embedded and the components that formed it.

From innovation systems point of view, knowledge is created and diffused through market and non-market interactions between firms and non-firm organizations, which are shaped by institutions (Carlsson, 2007; Malerba, 2005). When innovation systems view was first introduced by Chris Freeman in 1980s, endogenous growth theory had just started to appear in the literature (Carlsson, 2007). However, innovation systems approach provides a deeper perspective and focuses on understanding the mechanisms that link knowledge formation to economic growth as well as identifying the components that affect this process rather than leaving it as a black box as in endogenous growth theory (Carlsson, 2007). The concept started to diffuse more rapidly after it was called as “National Systems of Innovation” or “National Innovation Systems” (NIS) though the Innovation Systems concept had been articulated long before (Lundvall et al., 2002). As pointed out in (Lundvall et al., 2002), the need for understanding the differentiation between the development of national economies and the international competitiveness as well as controlling them might have triggered the fast diffusion of these concepts by the beginning of 2000s. Later on, other versions were started to be generated as its function and power in explaining the technological change and the possible root causes of differentiation in rate of change were understood. Whatever the boundaries are, innovation systems aim at enlightening the backyards of a “learning economy” where the organizations and individuals which learn rapidly and develop new competences upon the problems they confront are selected in competition (Nielsen & Lundvall, 2003).

All types of ISs have common constituents which can be summarized as actors, institutions and interactions (Edquist, 2005). Actors are the players that exist within the defined boundary which may be territorial or conceptual such as individuals, firms, governmental entities, trade chambers, suppliers, customers, researchers in a country, region, sector (Edquist, 2005). Institutions such as legislations, laws, norms, routines, standards, trust relations, habits, codes of conduct officially or informally regulate, enable, arrange, punish or standardize the activities of these actors and the relations among them (Edquist, 2005; Lundvall et al., 2002). Finally, interactions can be formal, informal, contractual or personal, network, market and non-market type (Carlsson et al., 2002; Edquist, 2005). Thus, understanding an innovation system requires to identify the type, quality, quantity, effect, mechanisms and many other features of its constituents or the factors that affect its constituents (Carlsson et al., 2002).

On the other hand, the general characteristics of an innovation system can be summarized based on (Lundvall, 2007) as follows. First one is the level of difference in specialization of production, trade and knowledge from the ones outside the borders. Second one is the difficulties in knowledge flows outside or ease in transfer of knowledge within the border. It should be noted that the definition of knowledge here differs from information which can be transferred easily while knowledge entails effort due to its tacit dimension (Foray, 2004). The third one is related to the understanding why and how knowledge is in embodied in routines of firms and interactions between individuals and organizations besides minds and bodies of agents. Thus, the system itself is endowed with a function. The fourth one is the importance of relations and interactions. While the former transfers the knowledge, the latter channels its creation.

According to the definition of the system boundary, ISs differentiate as National, Regional, Sectoral and Technological Innovation Systems (Carlsson et al., 2002; Lundvall et al., 2002). National Innovation Systems (NIS) is the easiest one to distinguish due to legally defined territories that are more or the less distinguished by regulatory system and common language, macroeconomic constraints, educational systems, etc. On the other hand, Regional Innovation Systems (RIS) exploit the advantages of geographical proximity that enables easier knowledge flows, shared endowments such as supply chain, labor market and common habits/understanding (Cooke, 2001; Cooke & Schienstock, 2000; Edquist, 2005). The sectoral innovation system (SIS) and technological innovation system (TIS) differentiate from the others slightly by embodying a common knowledge base component (Malerba, 2005). Though they seem to correspond to each other, the sectoral innovation systems (SIS) includes an industry that covers all sets of technologies such as energy systems of innovation while technological innovation systems (TIS) remain more focused such as photovoltaic technological innovation system or in a similar way like aerospace industry SIS and unmanned air vehicle TIS. Despite the ISs are categorized under the mentioned types, they cannot be evaluated as totally isolated since for a well-functioning system, a certain level of interplay between them is required. ISs are at some point bounded by the higher level of IS which they are in interaction with.

3.5.2. Functional Dynamics Approach for Analysis of Technological Innovation Systems

The components of a TIS are summarized as shown in Table 3-2 which is reproduced from (Wieczorek & Hekkert, 2012). Though the boundary is defined based on the activity realm, to sustain and improve, TISs inevitably have to have frequent and close relations with the remaining world outside their borders. The necessity of these interactions is conceptualized under contextual discussion in (Bergek et al., 2015). As the first context, they shall be in contact with their surroundings. They can either be a subsystem of NIS and RIS or be totally independent from geographical borders as long as they have a shared knowledge base (Malerba & Mani, 2009). But usually they are defined together with a geographical boundary such as European Thin film PV TIS, German PV TIS (Bergek et al., 2015). Moreover, any contacts in between different TISs at vertical (complementary) or horizontal (competitive) level make them learn from each other (Bergek et al., 2015).

Table 3-2. Structural dimensions of a TIS

Structural dimensions	Subcategories
Actors	• Civil society • Companies: start-ups, SMEs, large firms, multinational companies • Knowledge institutes: universities, technology institutes, research centers, schools • Government • NGOs • Other parties: legal organizations, financial organizations/banks, intermediaries, knowledge brokers, consultants
Institutions	• Hard: rules, laws, regulations, instructions • Soft: customs, common habits, routines, established practices, traditions, ways of conduct, norms, expectations
Interactions	• At level of Networks • At level of individual contacts
Infrastructure	• Physical: artifacts, instruments, machines, roads, buildings, networks, bridges, harbors • Knowledge: knowledge, expertise, know-how, strategic information • Financial: subsidies, financial programs, grants etc.

Understanding the complex mechanisms of a TIS in a systematic way is crucial to be able to anticipate its innovative potentials. To meet this need, researchers improved an upgraded version of TIS concept and called it as functional dynamics approach (Bergek et al., 2008). It basically defines and elaborates seven functions that can be utilized to evaluate the performance of a TIS for sake of improving more effective policy tools. These seven dynamic functions are identified via the indicators attributed to each function. The description of these functions and their corresponding indicators are refined from (Bergek et al., 2008; Wieczorek et al., 2013) and given in Table 3-3. Each function gains different weights and role in *formative*, *growth* and *matur*e phases of TIS throughout its lifecycle (Bergek et al., 2008; Markard, 2018). In the end, these functions are utilized to map a TIS and identify the mechanisms that induce and block it as described in (Bergek et al., 2008).

Table 3-3.Description of seven functions with their relevant representative indicators

Function	Description	Indicator
Knowledge development	Mechanisms of learning are at the heart of any innovation process, where knowledge is a fundamental resource. Type: Scientific, technological (e.g. system integration), production, market, logistics, application specific, design. etc. Source: R&D, learning from applications, imitation, import, etc.	Bibliometrics; R&D projects; Patents; Assessments by managers and others; learning curves
Guidance of search/direction of search	Processes that lead to a clear development goal for the new technology. Factors that may influence the direction: Visions; expectations; belief in growth potential (incentives arising from changing factors, growth in other SISs in other countries, changes in demographic trends, climate debate); actors' perceptions about the relevance of other knowledge sources; regulations; policy; articulation of demand from leading customers; technical bottlenecks; crises in current business.	Belief in potential growth (source: interview); Incentives from factor/product prices, e.g. taxes and prices in the sector
Resource mobilization	The financial (seed, VC, others), human (educated in specific technology and science fields, entrepreneurs, managers, finance professionals) and physical resources (complementary products, services, network infrastructures) are necessary basic inputs for all activities in an IS. Without these resources, other processes are hampered.	Volume of capital; volume of VC; Volume and quality of HR, Complementary assets (source: interviews, trade journals)

Table 3-3 (continued)

Function	**Description**	**Indicator**
Entrepreneurial experimentation	Entrepreneurs are essential for a well-functioning IS. Their role is to turn the potential of new knowledge, networks, and markets into concrete actions to generate and take advantage of new business opportunities.	Number of entrepreneurial experiments, i.e., no. of new entrants and diversifying established firms; variety i.e. no. of different types of applications, the breadth of the technology used and the character of complementary technologies.
Market formation	This process refers to the creation of markets for the new technology. In early phases, markets can be small and niche but later a larger market is needed to facilitate the cost reduction and encourage entrepreneurs to move in.	Market size; Customer groups; qualitative data on actors‟ strategies, the role of standards, purchasing processes and lead users (source: interview, industry analyses)
Creation of legitimacy	Innovation is uncertain by definition. A certain level of legitimacy is required for actors to commit to the new technology with investment, adoption decisions, etc.	The strength of the legitimacy for the SIS; What or who influences it and how; how it influences demands, legislation and firm behavior (source: questionnaire, interview, secondary data)
Knowledge Exchange/ Network externalities	Relevant knowledge exchange between actors and knowledge spillovers through networks in the system supports learning.	Networks; conferences/ seminars/ workshops, collaborations; cluster formation.

Finally, some diagnostic questions that can be utilized to identify the inducement and blocking mechanisms in each function that were gathered from (Bergek et al., 2005; Wieczorek et al., 2013; Wieczorek & Hekkert, 2012) are provided in Table 3-4. Thus, it can be possible to evaluate the well-functioning and problematic parts of a TIS through the systematic information provided in Table 3-3 and Table 3-4 which would be so complicated without the help of such a guide.

Table 3-4. List of diagnostic questions associated with seven functions of a TIS

Functions	Diagnostic Questions
Knowledge development	• Are there enough actors contributing to knowledge base and are they competent? (publications, citations, journal impacts) • Are there any finances that support knowledge development and are they sufficient? (R&D support, R&D intensity per sales or labor or researcher) • Does it allow technological development? (patents) • Does the knowledge satisfy needs of actors in the market or do they remain at academic/individual level or unexploited? (advances in product performance, new product types) • Is whole value chain involved in knowledge development? (patents or publication in different steps of value chain or # of new product in different steps in case of vertical integration) • Does it allow variety creation in products or is it focused on one type? (different product types manufactured; patents on differentiated product or same type of product?
Guidance of search/ direction of search	• Is the belief in sectoral growth articulated by different actors? • Are there any clear investment targets by suppliers/customers/public organizations? (installation targets, manufacturing targets, tech roadmaps, deployment programs) • Do regulations seem to support growth? (feed in tariff, tax incentives, externalities of environmental targets/commitments etc) • Are there any interactive customer-supplier relations that stimulate search?
Resource mobilization	• What is the availability of financial resources? (Manufacturing, installation funding, credit or any privilege by government? VC?) • What is the availability and competence of human resources? (# of labors, skilled labor with educational levels) • Is the physical infrastructure convenient and sufficient? (natural conditions, endowment of specific sources and their extraction, transportation channels for international trade)

Table 3-4 (continued)

Functions	Diagnostic Questions
Entrepreneurial experimentation	• Are there sufficient number of new entrants or the satisfying number of established firms? (industrial concentration: Herfindahl Hirschman Index (HHI)) • What is the extent of entrepreneurial experiments? (involvement in different steps value chain) • In which steps of value chain do entrepreneurs have activities? Are they diversified? (involvement in steps value chain; capacity share/market share in different value chain steps) • How difficult is it to enter the market? (mono/oligopolistic structure HHI, knowledge base in focused or relevant industry (patents, publications), any subsidies or public intervention, dumping, anti-dumping measures) • Are there entrepreneurs leaving the system? (change in number of firms by year)
Market formation	• What is the phase of the market? (Nursing, bridging, mature) (existing manufacturing capacity, retrospective sales, export volume) • Who are the potential users/customers and what is their capacity of demand and is it enough to encourage innovation? (export import volumes and directions; share of internal demand for domestically manufactured products) • Are there any risks that orient the market to a certain direction? Or uncertainties that hinder growth? (Regulations, roadmaps, change in critical material price) • Is there any international market potential arising from geographical or value chain advantages? (closeness to high demand countries for relevant technology or share of same language, reciprocal trade among different steps of value chain?) • Do institutions support market formation? (policy tool evaluation) • Are there any monopolistic/ oligopolistic formations? (industrial concentration, no of firms) • What is the rate of market growth?

Table 3-4 (continued)

Functions	Diagnostic Questions
Creation of legitimacy	• Is there any explicit resistance from public authorities/other industries/counter lobbies? (strikes, acts, etc) • Are there any promoting activities of public institutes, NGOs, universities? (conferences/exhibitions on relevant technology) • Are there any sector focused platforms? (chambers, associations, etc) • Is there alignment between the SIS and current legislation? (technology focused regulations or privileges to certain technologies) • What kind of impressions are gained from the statements of actors about the sector? (belief to development and deployment) • Are the news about the sector observable in mainstream and other
Knowledge Diffusion/Network externalities	• Are there any networks that promote knowledge exchange between actors? (manufacturing or R&D facilities outside, co-authorship in publications with other countries) • Are there any sector specific conferences/seminars/workshops?

3.5.3. Use of Innovation Systems Approach in PV Technology/Industry Analysis

TIS was already utilized in renewable energy analyses (Geels et al., 2008; Jacobsson & Bergek, 2004) with its first plain version before Bergek’s contributions mentioned in previous part did not be popular (Bergek et al., 2005). However, after it was introduced to the literature and evolved with further studies, researchers started to use it by defining TISs for different technologies and geographical boundaries under renewable energy. Among these, wind (Wieczorek et al., 2013, 2015) and solar photovoltaic (Gandenberger, 2018; Huang et al., 2016; Jacobsson et al., 2010; Strupeit, 2017; Zou et al., 2017) were the ones which have been examined widely. Strupeit analyzed soft cost reductions in photovoltaics in Germany without defining any specific TIS and approaching photovoltaic as a general sectoral innovation system (Strupeit & Neij, 2017).

Beyond enabling examination of a TIS with its cycles and identifying the blocking and inducement mechanisms in it, functional dynamics is also a suitable methodology to compare the performance of the countries for a specific technology or sector (Bergek et al., 2005). Jacobsson et al. examined the solar cell TIS in Germany by utilizing functional dynamics approach before the well-structured methodologies described in Table 3-3 and Table 3-4 were not developed (Jacobsson et al., 2010). In another study the overall energy innovation systems for some countries were compared with functional dynamics approach (Borup et al., 2016). To implement the comparison, countries were ranked according to the points they take from the indicators and thus their positions were determined based on the strength of their functions.

Recently, upon the rapid and vast growth of Chinese photovoltaic industry, some researchers utilized innovation systems perspective to define and examine Chinese PV TIS (Gandenberger, 2018; Huang et al., 2016; Zou et al., 2017). The variations between TIS definitions arise from the perspectives of the studies but also from the blurred boundaries of TIS which is different from other well defined IS concepts (Bergek et al., 2015). In that sense, in a study, the degree of intersection areas between Chinese PV TIS and NIS as well as Chinese PV TIS and Global PV TIS were examined for each phase of technology by considering the external context (i.e. global effects, international factors, etc.) that affected both (Huang et al., 2016).

3.6. Concluding Remarks

In this chapter, first the foundation of learning curve approach was provided with its empirical and theoretical backgrounds. Then its implementations from the literature were examined with a critical view and classified in a systematic way. Thus, the selection of the sample frame and the variables investigated in the quantitative analysis were justified from technological, spatial, time and methodological levels of analysis. Then dynamic capabilities and how they can be related with different learning patterns are investigated. Finally, the theoretical frame for functional dynamics technique which was utilized for examination of technological innovation systems is drawn.

The implications from this theoretical investigation can be summarized as follows:

- The technological level of analysis should be selected by considering the different learning rates that its components may have. Therefore, rather than PV systems or PV electricity generation costs, PV module is a better candidate for the unit of technology. As the final end product of the PV module manufacturing value chain, it is much more homogeneous in terms of the industrial dynamics while others include components from different industries or manufacturing sectors.

- The use of globally aggregate data due to availability of reliable data problems suppresses variation of findings for national or firm levels which may not be homogenous for all. Moreover, it does not allow investigation of firm or country specific effects. Another problem is the number of observations which is limited by the years that global PV data is available since the only dimension is time. Therefore, use of firm level panel data which allows investigation of micro effects and extending the sample to both cross section and time dimensions is favored. Though there are a few studies found to have employed annual firm level panel data for PV module cost estimations, one of them dates back to 20 years ago; while the other is limited in terms of the variables investigated. Moreover, despite being more recent, its time interval was not covering the years that the PV industry had recorded a significant progress in the last 10 years.

- The PV LRs in the literature are found to have varied too much based on the two levels mentioned above and the variables utilized in the models as well. However, LRs change for the different time intervals as well. The theoretical reasons that may cause a non-constant LR are discussed. Shortly, use of price as a proxy of cost which is very often met in the LC estimations can be justified based on the constant margins in a mature market but it should be decided carefully since based on the periods employed margins can change and the rate can be affected. Furthermore, as the technology becomes mature, learning itself can naturally have a changing rate. This also requires a delicate selection of the level of analysis or control of some factors. Similarly, some structural breaks that can cause a changing rate should be considered. Finally, forgetting effect which is a kind of depreciation may work on the contrary of learning.

- The variables used and the modelling problems that arise from them are examined under methodological level of analysis. Use of cumulative output as the one factor causes it to gather all effects and creates a black box itself while intending to open it. Moreover, due to the omitted variable effect, the estimation results become biased and do not yield reliable estimations. On the other hand, investigation of different effects is limited by the data available and the number of observations due to degrees of freedom of the model. Another drawback is the multicollinearity problem that the most prominent factors examined in the PV LCs suffer. Cumulative R&D expenditures, scale effects, the raw material (polysilicon) prices, time trend to capture the external progress are the most utilized parameters. However, the first two and the time trend are usually collinear with the LBD effect. In addition, some control variables like other input prices, dummies that correspond to an industrial situation are tried, as well. Except LBD and polysilicon effect, it is hard to imply a common conclusion from the estimations made though most of them utilize global data which more or the determines the variables that can be employed as well. As a result, understanding the occurrences happened in the time frame examined and the factors that might be effective on cost decline for the spatial level analyzed as well as their relation with each other is crucial in selection of the variables.

- Dynamic capabilities are basically a set of abilities of an economic agent to sense, distinguish the new knowledge outside the boundaries and then adopt them to be utilized in the routines after transforming accordingly. They are idiosyncratic and robust to imitation. The efforts dedicated to learning and the absorptive capacities developed upon enhance the dynamic capabilities within firms which ultimately leads to innovation. The potential instruments that can improve absorptive capacity can be listed as: R&D intensity, technological information, R&D staff, R&D department activities, technical and professional staff, staff training, scientific outputs and patents, machinery i.e. new knowledge embodied in capital investments, networks i.e. partnerships/affiliates, attending events, research alliances, organizational structure and conditions in the surrounding environment. The factors above require researching, interacting, implementing. In that sense, they are all relevant to LBD, LBR and LBI at a certain extent. Moreover, some hints are inferred from the requirements of dynamic capabilities. In contrast to transaction cost approach, the vertical integration may create a resistance to external knowledge flows when the complementarity in internal routines and communication is challenged and for the firms which are not open to interactions can improve myopia. Upgrading is an important source of knowledge flows and allows creation of new routines. However, the tradeoff between developing a learning effect through repeating actions and the stimuli for change should be considered. Absorption of technological opportunities and developments in the science base is a measure of the dedication of the firm to research through its internal efforts. The technology, finance, complementary and locational assets can also determine the level of the capabilities that the firm can have. Therefore, the knowledge embedded in its own boundaries; the availability of financial resources and the ability of the firm to access and receive them; relations with the other actors in the value chain; the overall medium that the firm is located are important factors to support and nurture its dynamic capabilities.

- Finally, the seven functions in a TIS are introduced. They are defined in detail with diagnosis questions which ultimately allow to identify the blocking and inducement mechanisms in the TIS: They can be summarized as follows: knowledge development through various sources resource mobilization in financial, labor and infrastructural dimensions; guidance of search by the government of the top down agent; knowledge exchange and network externalities for dissemination of the knowledge embedded in the TIS actors; entrepreneurial experimentation that increases the number and variety of enterprises within the defined boundary; market formation of new technologies and creation of legitimacy which determines the attitude against the technology on focus for its faster adoption and diffusion.

The implications above which draws the analytical framework of the study are utilized in the design, implementation and evaluation of the analyses that follows this chapter.

CHAPTER 4

A MULTI FACTOR LEARNING CURVE APPROACH FOR COST DECLINE OF c-Si PV MODULES

> *The rate of development of science is not the rate at which you make observations alone but, much more important, the rate at which you create new things to test.*
>
> Richard Feynman
> The Meaning of it All, 1998

4.1. Introduction

Starting from the mid of the maturation stage of the PV industry, China has become a noticeable actor and the dominant player of the PV industry thereafter. This period which is seen to have started by 2003 in Figure 2.9 and Figure 2.10, is characterized with more than two orders of magnitude increase in PV module manufacturing triggered by the boosted installation demand (please see Figure 2.2) as well as the rapid increase in product performance (module power conversion efficiency) and dramatic reduction in PV module costs. The average efficiency of commercial PV modules in 2003-2004 was around 12% and has increased to 21% recently (please see Figure 2.5) while it was 9% in 1980 (ITRPV, 2022), and by 2021 the unit cost of PV modules (2021 USD/Watt) declined to almost 5% of the value in the beginning of this phase (please see Figure 3.4). As a result, the costs decreased much more than enabled by the performance increase which at first sight might have been considered to have emanated from the substantial amount of public R&D expenses of the developed countries oriented to PV (please see Figure 2.6).

In this time interval, China has been the leader of the industry in every step of PV module manufacturing value chain by far despite not having had a corresponding internal demand for years (please see Figure 2.11) and overcame the pSi crisis which appeared in the first few years of the Chinese takeoff. Any learning and knowledge created that resulted in the outcomes mentioned above could not merely have arisen from an aggregate parameter like global cumulative capacity employed in basic learning curve estimations or R&D efforts recorded worldwide. Even if they have been effective, the capabilities of Chinese firms that enabled to them to identify and understand the external knowledge, convert it into a new form in combination with their existing knowledge, adapt their production routines accordingly and utilize in their operations deserve attention.

On the other hand, according to the national/regional strategies regarding energy transition which were affected by the problems confronted in the Global Value Chains (GVC) during the Covid-19 pandemics, the intentions seem to be in favor of localization of the PV industry in the near future (European Commission, 2022b; U.S. Department of Energy, 2021). Therefore, investigation of the Chinese firms can be meaningful in terms of understanding the learning mechanisms that have been effective in the past 20 years and their relation to innovation capabilities. It can be guiding for survival of the companies and the countries which intend to (re)enter the PV market that is currently under control of China by providing clues for design of proper policy tools that will keep the pace in cost reduction or at least maintain the level reached. In addition, the implications made can be useful for improvements in other technology areas.

This chapter aims at investigating the drivers which have potentially contributed to the cost decline of PV modules through panel data econometric estimations. For this purpose, the joint effects of some internal dynamics within 11 PV firms -that were associated with certain learning patterns and innovation capabilities- and the industrial trends were examined for the years between 2003 and 2019.

As a result, this study contributed to the literature by being much more guiding than the estimations that utilized global aggregate data which inherit a certain level of ambiguity due to generalization of the learning patterns and the capabilities that they may be related to. Moreover, distinguishing the learning patterns through internal firm dynamics and the evaluating them together with the external conditions that had stimulated or affected the learning process, can be enlightening in terms of understanding the capabilities that may bring along competitive advantage to the firms or can be inspiring for the other industries as well.

After this introduction, in the following section, the basics of panel data econometric estimation as the quantitative method utilized are mentioned and the details of the model construction are described. Thereafter, in subsection 4.3., the justifications of sample selection, the way that the data were collected and summary statistics of the sample are provided. Following, the estimation results and discussion of the findings are addressed. Finally, the chapter is concluded with the summary of findings and the contributions made.

4.2. Methodology: Panel Data Econometric Analysis

As exhaustively discussed in the previous chapters, using global aggregate data is a common approach in the LC estimations. However, it only allows one dimensional data and thus limits the observations to the time interval that the data is available for a technology. Since the history of terrestrial PV is less than 50 years and the industry has commercially become significant in the last 20 years within this interval, except a few variables, it is not easy to extend the data available for long terms. Therefore, estimations can be built on basic learning curve for the sake of exploitation of the years broadly by taking the risk of omitted variable bias or can be made for a shorter time period which increases the possibility of including a diverse set of variables. But due to the reduced the amount of observations, the latter leads lower degrees of freedom which increases the possibility of econometrically insignificant estimates. As a remedy, panel data can solve not only the problem of limited number of observations but also allows investigation of different effects which cannot be found out by aggregate values.

4.2.1. Estimation Issues and Modelling Techniques

Panel data[72] is a combination of cross-sectional and time-series dimensions where the total number of observations corresponds to the product of number of samples in each dimension. The panel dimension is represented by the cross-section samples which can be at different levels such as country, region, firm, sector, etc. Time dimension defines the time frame that each cross-sectional sample is available for. If the length of time is same for all panels, then it is called balanced panel data and otherwise unbalanced.

The general equation that represents a basic panel data model can be expressed by Equation 26 and Equation 27 (Baltagi, 2008):

$$y_{it} = \alpha + \beta X_{it} + \omega_{it} \qquad \text{(Equation 26)}$$

$$\omega_{it} = u_i + v_{it} \qquad \text{(Equation 27)}$$

The dependent variable y_{it} is predicted by the constant term α, the independent variable is defined by X_{it} and its coefficient β and the error term as overall residual is depicted by ω_{it} which is the sum of panel specific error term u_{it} and the remained disturbance term v_{it} . Since in panel data the impact of variations is not one dimensional anymore, the variables are labelled with double subscripts where i denotes the panel dimension and t denotes time.

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[72] The term “panel” here should not be confused with PV panels which is the end product of PV manufacturing. Throughout the text, to prevent this confusion and since it is possible to call c-Si PV panels as PV modules, the former term is preferred in the technical definitions and the latter in econometric discussions.

Panel data can be modelled in different forms. This basic form shown above, depends on the assumption that there is no difference between panels i.e. the samples are randomly selected and their distribution is identical for each period they are collected. Thus, they can be pooled as individual observations. However, this is usually a rare case and they do not identically vary across time; at specific years or in all years examined there may be certain external occasions that affect the variables observed (Wooldridge, 2009). In addition, the unobserved time invariant attributes regarding each individual may not be random and may have an explanatory power on the dependent variable as well as effect on other independent variables (Wooldridge, 2009). Ignorance of them causes omitted variables bias which leads the coefficients estimated without these variables excluded to be biased (i.e. deflated or inflated) and prevents to rely on the test results of the hypotheses since the standard errors of the coefficients and the test statistics are not valid anymore (Dougherty, 2007).

The effect of time on independent variables can be eliminated by including time dummies and allowing the intercept term change accordingly. However, it does not solve the problems that may arise when the assumption that panels are identical is not valid. In this case, the model should be controlled for the panel entities to get rid of potential endogeneity problem arising from the omitted variable bias. Otherwise, correlation of the error term i.e. residuals with these unobserved effects is inevitable which in the end leads to biased and inconsistent estimators and makes the coefficient values and their significance unreliable (Dougherty, 2007).

Differencing method is sometimes utilized as a solution to get rid of the unobserved effects arising from the panel specific attributes as well as the unit root problem that can emerge in case the time series dimension is conserved (which is eliminated when time dummies for the whole series is used) (Wooldridge, 2009). Estimation based on the first difference model (i.e. the model based on the first lag of the dependent and explanatory variables is subtracted from the model which is based on the current values of the variables) satisfies the condition of being strictly exogenous since both the panel specific time invariant factors and first-degree autocorrelation that may emanate from other external conditions are eliminated (Wooldridge, 2009). However, despite providing a certain reliability, it is not free from handicaps. First, the available number of observations is decreased. Second, it risks the significance of the coefficients if the rate of change in independent variables is constant. Third the effect of certain occasions at specific years i.e. impact of structural breaks as well as the panel specific time invariant variables remains unknown.

The problems mentioned above indicate a common issue which is called endogeneity. In general, it describes the situation when an explanatory variable is correlated with the error term thereby indicating an unobserved effect that is ignored in the model (Hill et al., 2021). The practical outcome it causes is the bias arising from the omitted variables or simultaneity as well as measurement flaws or sample selection faults (Hill et al., 2021; Ullah et al., 2018). Measurement flaws and sample selection require some careful handling of data and sampling. Systematic error behavior with respect to explanatory or dependent variables can indicate measurement errors which can be originated from design of surveys/selection of variables while wrong selection of the overall sample may hinder observation of equally representative portion of population and can be endogenous to selection criteria (Hill et al., 2021). Therefore, first of all, selection of the sample and the variables should be carefully justified ex-ante and a careful ex-post examination of the error terms is required. On the other hand, similar to omitted variable bias which is described above, simultaneity problem which is also called reverse causality arises when one or more explanatory variables are determined by the lagged values of the dependent variable and it should be treated accordingly as well (Leszczensky & Wolbring, 2022). Indeed, it is almost never possible to find variables that are strictly exogeneous which prevents to ensure that the statistical estimations are totally free from endogeneity problem (Ullah et al., 2018).

There are some modelling strategies like (I) first differencing (FD) which is mentioned above; (II) its more advanced version which eliminates further causes of endogeneity by replacing the first difference of the explanatory variable on the right side with its lagged first difference (LFD); (III) dynamic models which include the lag of dependent variable on the right side of the original model; (IV) first difference based dynamic models i.e. Generalized Method of Moments (GMM) which includes the lag of dependent and independent variables on the left and right sides respectively similar to FD models but including the first difference of the dependent variable on the right side too as a kind of dynamic model and utilize the lags of dependent variable as instruments; (V) crossed lagged structural equation models (SEM) which include lags of both dependent and independent variables on the right side by keeping the rest of the model standard without differencing anything and estimate the equation with maximum likelihood (Leszczensky & Wolbring, 2022).

However, all of these modelling techniques bring along their own limitations and potential estimation bias in case all mandatory assumptions are not satisfied. The potential drawbacks based on the modelling technique can be listed as: eliminating only previous years effects; limiting correlations to the defined lag year of which diagnosis may be complicated and hard i.e. timing of causality; multicollinearity between lagged variables when no difference is taken; estimations that are only sensitive to differences i.e. rates; loss of degrees of freedom and significance levels due to using too many lagged variables or other instruments thereby requiring large number of sample units; handicaps in correct identification of independent instruments and weak instrument problems which hamper causal inference. More detailed discussions about how these modelling techniques address endogeneity and their flaws can be found in (Leszczensky & Wolbring, 2022).

Some of the methods mentioned above can solve the unit root problem too. It is a time series originated problem and can appear when any unobserved disturbance at a time causes a persistent change in the estimated value which can exhibit a trend that is either deterministic (i.e. a constant slope with time trend) or stochastic (i.e. random and varies over time)(Stock & Watson, 2020). In other words, unit root is a special case of autocorrelation which causes the contemporary value of errors terms to be explained by the previous values i.e. lags. The model is accepted as non-stationary only if the absolute value of β is >1 in Equation 28 below, otherwise it can be autocorrelated but its effect is expected to be mitigated within time rather than being persistent (Stock & Watson, 2020; Wooldridge, 2009). The form shown in Equation 28 is the most basic one and shows a random walk when the change persists in time. More complicated cases are explained in two different forms (Stock & Watson, 2020; Wooldridge, 2009). When a stochastic disturbance at a time that causes a permanent one-time change occurs, it is captured by a constant term and called as random walk with drift. The representative equation is shown in Equation 29. If there exists a deterministic trend as mentioned above, the effect is captured by the coefficient i.e. the slope of the time trend variable as given in Equation 30. As mentioned above, first differencing is one of the solutions that is used to eliminate unobserved unit roots.

$$y_{it} = \beta\, y_{it-1} + z_{it} \qquad \text{(Equation 28)}$$

$$y_{it} = \alpha + \beta\, y_{it-1} + z_{it} \qquad \text{(Equation 29)}$$

$$y_{it} = \alpha + \beta\, y_{it-1} + \delta\, t + z_{it} \qquad \text{(Equation 30)}$$

The y_{it} is the dependent variable in the original equation, y_{it-1} is its first lag with a coefficient of β, α is the constant term that collects the drift effect, z_{it} is the overall disturbance, t is the time trend and δ is its constant slope value.

If there is a suspect for endogeneity (residuals have a clear correlation with the explanatory variables and there are indications of unit root i.e. non-stationarity; instead of suffering the drawbacks of the complicated methods mentioned above, the part originated from the panel attributes can be eliminated by controlling the model under their existence (by adding each panel specific factors to the model). Other unobserved effects should still be cared by adding the structural breaks, time trend or other time variant variables if it is possible to find out the reason of the disturbances and any other omitted effects. When the omitted variable is strongly correlated with one of the independent variables but not with the error term, then it means it has an impact through this explanatory variable rather than being an independent variable with individual effect on the dependent variable. These variables are called instruments and should be incorporated into the model by defining their relation to the relevant variable. However, identifying instruments that are strictly exogenous and are strongly correlated with only the relevant independent variable is really a hard task (Ullah et al., 2018). In case it has an individual effect as well, it should be added separately to the model.

Moreover, reverse causality as a source of endogeneity other than omitted variables, measurement and sample selection errors requires elimination of this effect through following the LFD, advanced dynamic models like GMM or SEM based on maximum likelihood and while it can be solved by these modelling techniques, it has to suffer their drawbacks as well (Leszczensky & Wolbring, 2022). Granger causality allows to understand if there is a causal relationship in either way between variables (here, the technical causality is addressed not the causality in terms of meaning) in a time series data which is valid for panel data as well. It can be tested by estimating the dependent variable based on its and independent variables’ previous values. If the coefficients of all lags of independent variables are not jointly insignificant in the presence of dependent variables’ lags in the same model as well, then we can mention a causal relation in the direction from the explanatory variable to the dependent variable (Lopez & Weber, 2017). Otherwise, the independent variable cannot be utilized as a predictor. If the dependent variable predicts the independent variable in one-way, there is reverse causality and when it is a reciprocal relation, there exists simultaneity, both of which is problematic as well. The representative estimation to test Granger causality and the zero hypothesis is given in Equation 31 and Equation 32, respectively (Lopez & Weber, 2017). It can be reversed to measure the causality from the other side.

$$y_{i,t} = \alpha + \sum_{k=1}^{K} \gamma_{ik}\, y_{i,t-k} + \sum_{k=1}^{K} \beta_{ik}\, x_{i,t-k} + \omega_{it} \qquad \text{(Equation 31)}$$

$$Ho{:}\, \beta_1 = \beta_1 = \ldots = \beta_K = 0 \qquad \text{(Equation 32)}$$

In Equation 26, the fundamental panel data model was shown. When change with respect to two dimensions are considered i.e. time and cross section, then they should have separate effects. As mentioned before, a practical way of mitigating the unobserved heterogeneity arising from the non-identical panels is controlling the model for the attributes of each panel. However, since it is not easy to anticipate and include every panel specific variable that has an effect on the dependent variable, dummies for each panel are utilized to eliminate the impact of unobserved variables that characterize each panel. This is called “fixed effect estimation”. The estimation is isolated from any panel specific effects and coefficients become independent from unobserved panel heterogeneity since the time averages of each panel entity are subtracted from each longitudinal observation (i.e. time-demeaned data) with inclusion of panel dummies through which the panel effects are absorbed by the constant term (Wooldridge, 2009). Thus, in fixed effect estimation, the residuals arising from the panel characteristics can be correlated with any of the independent variables and still it does not contradict the unbiasedness of estimators due to the treatment of variables accordingly as mentioned above. In addition it considers the panel effects in overall not only the ones that can be eliminated by the difference from the previous years and does not cause loss of observations as in differencing (Leszczensky & Wolbring, 2022). The only drawback of fixed effect estimation is that the time invariant variables are no longer applicable; since only the within effect is observed, the effect of any variable that remains constant along all available time frame cannot be measured. A typical fixed effect model is shown in Equation 33 (Baltagi, 2008; Stock & Watson, 2020).

$$y_{it} = \alpha + \beta\, X_{it} + \sum_{i=1}^{N} u_i D_i + v_{it} \qquad \text{(Equation 33)}$$

The dependent variable y_{it} is predicted by the constant term α, the independent variable X_{it} with coefficient β, panel dummies D_i with coefficient of each panel u_i as well as the overall residual v_{it}, where for all i denotes the panel dimension and t denotes time.

The predictions that utilize time-demeaned data and consider the change in time within each cross-section is also called "within effect" as well as "fixed effect". On the other hand, the predictions that can only capture the difference among panels is called "between effect" and when they are made by Ordinary Least Square (OLS) estimation based on the time mean of observations available for each panel entity thereby reducing the dimension to only cross section (Wooldridge, 2009). However, since the panel effects still remain correlated with the error term and the model is not treated to eliminate this effect exactly, the between estimations based on the technique above become biased in contrary to within/fixed effect estimations (Wooldridge, 2009).

If the effects of panel specific characteristics are desired to be observed, then "random effect estimation" should be utilized. Since it assumes the unobserved panel effects i.e. u_i to be uncorrelated with other independent variables, it allows to measure any time invariant variables that might have an explanatory power on the model. The general equation that it is represented by is given in Equation 34. The estimation method utilized in random effect estimations is based on Generalized Least Squares (GLS) and is much more complicated is as well as the properties of the estimators are ambiguous when the number of longitudinal data is small and the time dimension is large (Wooldridge, 2009). Since it is more common that unobserved panel effects to be correlated with the other explanatory variables, usually the panel data is estimated with the fixed effects. More details can be found in (Wooldridge, 2009).

$$y_{it} = \alpha + \beta\, X_{it} + u_i \ + v_{it} \qquad \text{(Equation 34)}$$

In this thesis, panel data estimations were made based on fixed effect models by utilizing the statistical software package program Stata 17[73]. The potential model and variable related problems discussed above as well as the other fundamental requirements for validity and reliability of the estimations were addressed by following some ex-ante adjustments or post model treatments which can be summarized as follows:

- Since the firm characteristics are expected to have an effect on the other explanatory variables employed, the fixed effect model was utilized. The validity of employing fixed effect instead of random effects is checked by Hausman test and the F test with the hypotheses i.e. Ho: unobserved residuals are jointly zero.

- The normality of the residuals and zero expectation of their mean were controlled with relevant graphs.

- Independency i.e. serial correlation and homoscedasticity of the error terms were tested by relevant commands in Stata as well as scatter plots of residuals against variables. This also allowed to observe if there existed any systematic pattern in residuals which can be a sign of endogeneity, unit root, heteroskedasticity and autocorrelation. The models were corrected with available commands for the sake of robust standard errors in case the last two problems mentioned were detected.

- The validity of estimation was observed via plotting observed versus predicted dependent variable.

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[73] StataCorp. 2021. Stata: Release 17. Statistical Software. College Station, TX: StataCorp LLC

- Degree of multicollinearity of the potential independent variables was checked based on the pairwise correlation tables as well as the variance inflation factors (VIF).

- The potential unit root i.e. persistent non-stationarity of the model was controlled with available ready to use test procedures in Stata as well as by checking the value of coefficients in the diagnosis estimations described above. The hypothesis tested by the available commands was Ho: that all panels have unit root. As an additional precaution, time variant factors such as time trend or time dummies that might capture the external effects and would otherwise be stored in the disturbance term and ultimately affect the sensitivity of other variables were included in the model.

- Granger causality as well as reverse causality was examined by employing the equation mentioned above which was defined for the causality test. Alternative variable is presented accordingly.

- Finally, different kind of sensitivity of analyses were carried out step by step for the reliability of the estimations. Various variables that might have a substituting effect were tried in the preliminary studies. A lagged variable (R&D employment) was utilized after checking for its different lags. An explanatory variable (polysilicon sensitivity) was controlled with a relevant structural break time dummy that could capture its effect. Some alternative variables for external effects including the time trend were tried. Different time frames were employed for the industrial trend parameter (after 2011 dummy). Finally, the estimation results of the finally selected models were compared with the ones that were conducted by omitting the outliers and imputing the missing values.

4.2.2. Model and Data

In the subsections below, model construction, selection criteria of the sample frame, definition of the dependent and independent variables and their description with summary statistics are provided.

4.2.2.1. Model Construction

A typical formula of MFLC was derived in subsection 3.1.2 and given in Equation 25. The model variations utilized in this thesis were generated based on this fundamental MFLC equation. When natural logarithm based transformation is made for sake of linearity, the following equation is obtained:

$$ln\, C_{unit} = \alpha + \beta\ ln\, CC + \mu_1\ ln\, \rho_1 + \mu_2\ ln\, \rho_2 + ... + \mu_n\ ln\, \rho_n + u_i + v_{it} \quad \text{(Equation 35)}$$

Where C_{unit} is the constant unit cost (USD/Watt) corrected with GDP deflator; α is the constant term, CC is the cumulative module output in power units (Watt) which is utilized as the proxy of LBD effect; β is the estimator of its coefficient; ρ_n stands for any component that somehow contributes to learning, μ_n denotes their elasticity coefficient, u_i is the panel specific error term which is captured by the fixed effects and v_{it} is the remaining residuals. In the estimated models, as mentioned in the previous subsection, some time-variant and firm invariant variables were utilized for control of external effects. They were included in the model in standard form without taking natural logarithm-based transformations as made for other explanatory variables shown in the representative equation above.

The internal variables employed in successive and alternative models were chosen based on their relation to certain learning mechanisms or the innovation competences i.e. absorptive and dynamic capabilities which were sometimes used interchangeably. The external variables were selected according to the possibility that they might have been a stimulus on these internal factors. The descriptive statistics results and the historical analysis of the PV industry carried out in previous chapters were utilized to identify these factors that could be related to a structural break, technological progress or an industrial stimulus.

4.2.2.2. Sample Selection and Data Collection

The annual reports of the firms that are listed in the Stock Markets are very reliable data sources for a quantitative analysis. It is possible to access very detailed financial data like net sales, cost of goods sold, R&D expenditures, unit price values as well as the information regarding qualitative and quantitative structure of the firms' activities such as value chain steps involved in, manufacturing amount i.e. output with segment breakdown, technology types utilized, labor distribution. The type and extent of reported values may be different based on the accounting procedures in other markets but except the differentiation in some details revealed, the financial and other information are almost identical for the firms that are listed in the same stock exchange[74].

In this study, annual reports of 11 PV manufacturing firms that were listed in the US Stock Exchange[75] in between 2003 and 2019[76] were utilized as the major data source. The data regarding each firm starts with the first year that they reported module outputs and lasts until the end of the time period indicated as far as the firms continued to be

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[74] The firms that were not listed in the US Stock Exchange were kept out of the scope of this study though there were some firms of which annual reports were accessible in English. Because, the differences in their financial reporting format could cause problems in the availability of the suitable data or variation in the extent of the data which ultimately could lead to bias and inconsistency in the estimated results.

[75] Annual reports were accessible through the company filings on (U.S. Securities and Exchange Commission, 2021).

[76] There were only two firms that were listed after 2018 and one firm before 2004 and some of the data regarding these years were omitted from the final sample upon lack of sufficient data regarding all variables or for being outliers.

listed in the US Stock Market and maintained their module manufacturing activities. The data is unbalanced since all of the firms did not have activities in the same time periods. There were also some variables utilized in the model as controls or general industrial indicators which were common for the cross section but varied only with time. The source of non-firm specific variables is mentioned in the sub section 4.3.3 under each variable.

Crystalline silicon is by far the dominant PV technology as explained in sub-section in 1.4. The industrial structure as well as the cost elements are different for different PV technologies. Therefore, as the sample of this study, only the firms that were based c-Si PV technology were selected. All firms were totally or partially vertically integrated at certain times. The firms that had activities in different fields under large corporations were excluded since their financial data were consolidated with the other segments than PV manufacturing and the required values that would be utilized in the estimations were missing.

In addition, although some companies were only specialized in PV and seemed to have reported their financial values along the different steps of PV value chain, during detailed examination of their documents it was seen that some of them had consolidated their relevant data regarding the downstream products which were out of PV module manufacturing such as PV systems or PV kits with the module segment. It was also observed that sometimes they merged the data of excess upstream products that did not end up with PV modules but rather were sold outside with the modules. As a result, unless their data were not identical with the rest of the sample set, these firms were not included. The firms that constituted the sample and the years when observations were available are provided in Table 4-1.

Table 4-1. Sample summary

		Year		
	Company	**Min**	**Max**	**Number of observations**
1	CSUN	2007	2015	9
2	Canadian	2004	2019	16
3	Hanwha	2005	2017	13
4	JA	2007	2017	11
5	Jinko	2009	2019	11
6	LDK Solar	2009	2014	6
7	Renesola	2010	2016	7
8	Shunfeng	2012	2018	7
9	Suntec	2003	2011	9
10	Trina	2004	2015	12
11	Yingli	2005	2018	14
	Overall	2003	2019	115

The firms that were listed in Table 4-1 had 22.3 ± 12.9 % of the global PV module production on average within the time frame employed. Their current shares in China and in the world can be seen in Figure 4.1. On the other, it should be noted that 9 out of 11 companies in the sample frame were registered in the stock exchange as Chinese, 1 firm was defined as Canadian and 1 other was registered as Chinese or Korean for certain years. However, all carried out substantial part of their production activities mainly in the China located facilities[77]. Including only China located firms can cause selection bias. But when it is considered that 70% of PV production was in China for more than half of the time frame (please see Figure 2.11 in section 2.3), the sample selection bias becomes less meaningful in terms of country and the results indicative for the overall industry in the years examined. However, in this case, the interpretation

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[77] The origin of manufacturing facilities could be an important factor to be examined. However, it was too complicated to obtain a meaningful data since there was no identical reporting between firms i.e. while some of them provided all facility details, some of them just mentioned the existence of new facilities in other countries. Moreover, the breakdown of production was sometimes too distributed among different steps of value chain such as all PV modules were produced in China while activities in upstream may shift to other countries partially. In the end, they were mainly registered as Chinese companies and started and maintained their activities in China though some of them had additional facilities in other Asian countries.

of the analysis results should be made carefully in terms of generalizing the findings without disregarding the potential national effects.

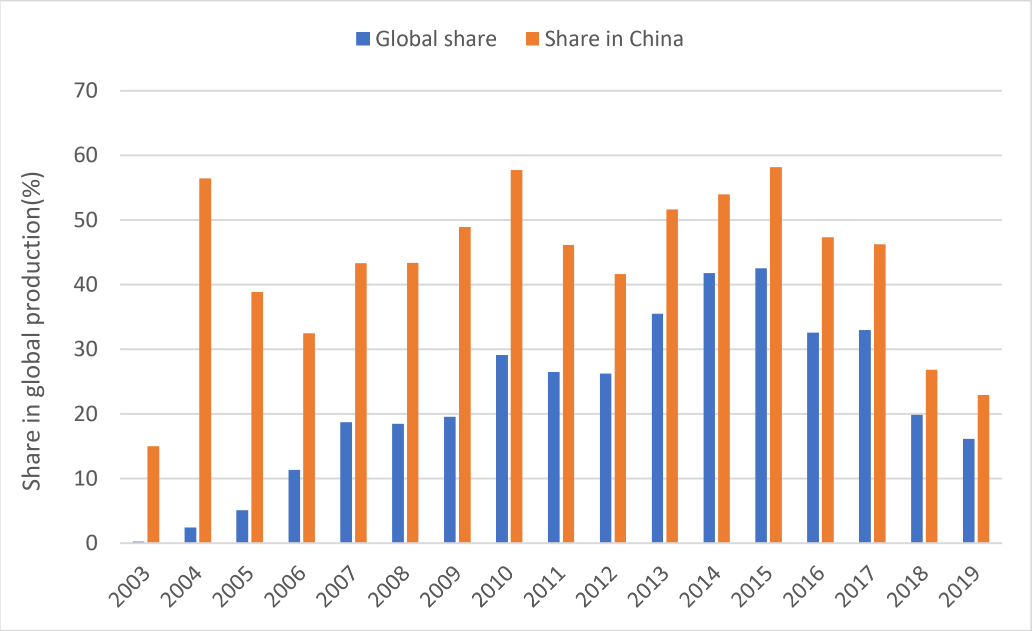

Figure 4.1. Share of sample frame in PV module production

4.2.3. Description of the Variables

The variables employed in the presented estimations are listed in Table 4-2. Time dimension of the panel data is represented by the variable ‘Year’ since the frequency of the observations was annual. Cross-sectional dimension is represented by the variable ‘firmID’ which is the level utilized in the panel data.

The preliminary arrangements of the data i.e. monetary conversions based on the currency exchanges[78] and inflation rates were carried out in Excel. Exchange rates and

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[78] Some values were reported in RMB were converted to USD first.

US deflators based on the year 2015 were extracted from the World Bank database[79]. Except the arrangements mentioned above, while some variables were available in the annual reports as they are seen in Table 4-2, some were generated from the underpinning data collected. Therefore, the variables listed were not all directly used in the estimations but utilized secondarily to obtain other variables. For linearization purpose and sake of normal distribution, logarithmic transformations were made to all firm specific non-dummy variables. Then, they were employed as proxy of different learning factors, indicators of innovation capabilities or as control variables.

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[79] World Development Indicators (The World Bank, 2021)

Table 4-2. List of variables utilized in the estimations

NAME	LABEL
Year	Year
firmID	Company
Financial	
ASP_r	Average Selling Price real (2015 US$/W)
UMCcalc_r	Calculated Unit Module Cost real (2015 US$/W)
NetModSales_r	Net Module Sales real (K 2015 US$)
CoModSold_r	Cost of Modules Sold real (K 2015 US$)
TotNetSales_r	Total Net Sales real (K 2015 US$)
Production	
ModShip	Module Shipment (MW)
CumModShip	Cumulative Module Shipment (MW)
ModCap	Module Production Capacity (MW)
CellCap	Cell Production Capacity (MW)
IngotCap	Ingot Production Capacity (MW)
WaferCap	Wafer Production Capacity (MW)
fullintegrated	involvement in all value chain i.e. ingot/wafer/cell/module (1/0)
Research	
RDExp_r	R&D Expenditure real (K 2015 US$)
RDEmp	R&D Labor (#)
RDint	R&D intensity (RDExp/TotNetSales_r)
Value Chain	
fullintegrated	involvement in all value chain i.e. ingot/wafer/cell/module (1/0)
Industrial Values	
pSicost	Polysilicon cost per Watt (2015 US$/W)
after2011	Years after 2011 i.e. China dominated PV industry (1/0)
eff	Industry average of c-Si PV module efficiency (%)
Interaction Variable	
polySisensitivity	pSicost x fullintegrated (2015 US$/W)[80]
Time Controls	
y_2008	Dummy for the year 2008 i.e. pSi spot price peak year (1/0)
timetrend	Cumulative number of years from 2003 to 2019

In the subsections below, the type and structure of the dependent and independent variables are discussed more in detail.

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[80] This is an interaction variable based on an overall industrial parameter and a firm specificvariable (i.e. being fully integrated).

4.2.3.1. Dependent Variable

The annual average unit price of PV modules (2015 USD/Watt) in each firm in the sample was employed as the dependent variable. The underpinning discussion for use of price as a proxy of cost was provided in subsection 3.3.2. Therefore, PV LCs are usually estimated based on global aggregate price of PV modules. Indeed, the main reason behind is that companies do not report their costs due to confidentiality issues (Candelise et al., 2013; Junginger et al., 2005; Rubin et al., 2015). In stock listed companies, it seems possible to access the cost values reported as Cost of Goods Sold (COGS) in the financial tables. There are two studies found in the literature (Pillai, 2015; Reichelstein & Sahoo, 2018) that employed unit module costs in their firm level PV LC analysis. However, there are some handicaps to get unit cost of PV modules from the company filings accurately. Assumptions made and the details overlooked may bias the results worse than using price as a proxy of cost. These are shortly mentioned below.

In the balance sheets of stock listed PV companies, the net sales were mainly provided separately for each activity segment. To obtain the average selling price (ASP) of PV modules in USD/Watt which is the unit price indeed, the net sales can be divided by the modules sold (in Watts). They were both available in substantial part of the reports overviewed. On the other hand, the average selling price of PV modules is mostly provided in the key financial tables or within the text part of the reports as a readily calculated variable. In a case that it is not, the ASP can be calculated by dividing the net revenue from the module sales to the overall module amount sold in power units i.e. Watt. As to costs, the unit cost of PV modules was not provided readily like ASP and in overall, the cost data regarding only PV modules were not separately available. Rather, for most of the companies, they were consolidated under the costs of goods sold (COGS) with other segments. Therefore, it was not possible to access the costs regarding only PV modules. But still it was available for almost half of the observations in the sample[81].

In a panel data study that was based on the years between 2005-2012 and 14 PV firms which had the China, the US and Europe origins, the author employed the unit cost of PV modules as the dependent variable for PV module cost estimations (Pillai, 2015). Due to the unbalanced structure of data, the maximum number of observations employed in the estimations was 99. The unit cost of PV modules was told to have been calculated by dividing COGS that was reported specifically for the PV modules to the annual module shipments. Half of the sample i.e. 7 firms was common with this thesis study and 5 out of 7 remaining companies were not listed in the US Stock Exchange. As indicated by the author himself, the reporting format of the European origin companies and the extent of their financial data were different and the COGS for PV modules could be obtained indirectly after making some accounting calculations. In addition, after careful examination of the annual report texts of the other 2 US Stock Market listed companies (i.e. Sunpower and Evergreen) which were utilized in the paper mentioned but not in this thesis, it was found that the annual module shipments as well as any financial data labelled as PV modules were consolidated with other downstream segments like PV systems, solar kits or upstream products i.e. solar cells though they were sometimes reported under the general title of PV modules in the key tables. This was also valid for 2 out of the 5 European companies (SolarWorld and REC) of which reports were examined within the scope of this study as well[82]. Since the breakdown of the costs and the shipments may be different, dividing the aggregate cost values to the aggregate shipments of different segments can be misleading. In such a case, since the cost data does not exactly belong

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[81] For three firms (Jinko, Shunfeng and CSUN), the cost of modules sold was not reported; for three firms it was limited to a few years (Trina, Hanwha, Canadian) and for the rest (JA, LDK, Suntech, Renesola, Yingli), it was available in all years.

[82] The rest three firms which had German origin and utilized in the mentioned paper were not investigated in the scope of this thesis study.

to module manufacturing, it is not accurate to use it in unit module cost calculations and the estimation results based upon cannot be reliable. Moreover, similar to costs, other values required to calculate ASP or annual cumulative output were suspicious for being associated to specifically to the PV modules as well. Therefore, none of these companies which had an ambiguity in cost or other relevant data breakdown were not included in this thesis.

In another company level panel data study (Reichelstein & Sahoo, 2018) which made PV LC estimations based on unit costs, probably for similar reasons addressed recently, only observations from the firms that were utilized in this thesis except one were employed. The other firms listed in other markets or the ones that had ambiguity in the breakdown of data were not included. In that paper quarterly data of ten companies were examined for the years between 2008-2013. As discussed above, the COGS for PV modules was not available for all firms within all time frame. Therefore, the authors made some assumptions to get the cost. Since these companies were mostly vertically integrated, even if downstream application segments out of manufacturing value chain were separated, overall COGS could include some upstream products that were not converted to modules and sold as semi-products to outside. Thus, their costs were included in the COGS as an additional component. However, even if they are all expressed in the same unit, they cannot be summed basically since there will be some losses in the following stages. In (Reichelstein & Sahoo, 2018), the unit module cost was obtained by dividing the COGS to the overall shipment which was adjusted for the weights of each components. The authors developed a calculation method for converting the shipment amount of these intermediary products to module power. They multiplied additional output of each which was not converted to modules with a coefficient that was the ratio of their ASP to module ASP. Thus, a weighted output which was thought to have been expressed in module watts was used to get unit module costs by dividing COGS with it. Assuming that the ratio of the prices could reveal the potential conversion of the semi-products to PV modules in power units does not sound realistic. The ASPs are susceptible to margins which can be assumed constant for the products at the mature market stage (please see subsection 3.3.2.1.), but it does not mean that it can be same for the products manufactured in different steps of value chain. Furthermore, price also cover the losses both emanating from process yield and technical performance. But it is hard to say that the ratio of prices for successive products in the value chain can capture their conversion. Therefore, while exploiting unit costs by considering that the price margins were not stable in years and advocating that the estimations based on price and cost differ, other assumptions made to obtain the cost values raised the risk of yielding biased the results themselves.

As a result, since reliable cost data do not provide a satisfactory amount of observations and based on the justifications discussed before, in this study the ASP is employed as a proxy of cost as it has been done in almost all of the studies in the PV LC literature. Still, the available and reliable cost data was utilized to underpin this choice.

Average Selling Price versus Unit Module Cost

Even though using average module selling price instead of unit module cost as the dependent variable was theoretically underpinned by the relevant literature, the relation between them was examined empirically for half of the observations of which module specific cost data were available. The correlation between two, upon regression of average selling price (ASP) on unit module cost (UMC), can be seen in Figure 4.2. Since the natural logarithmic forms of the variables were employed in the both sides of the model, the estimations showed the percentage change in the ASP with respect to percentage change in the UMC. The correlation between these two parameters had a slope value of near 1 which proved their rate of change was almost identical. Hence, based on half of the sample group, it was shown that use of price as a proxy of cost for the current dataset was empirically sound as well.

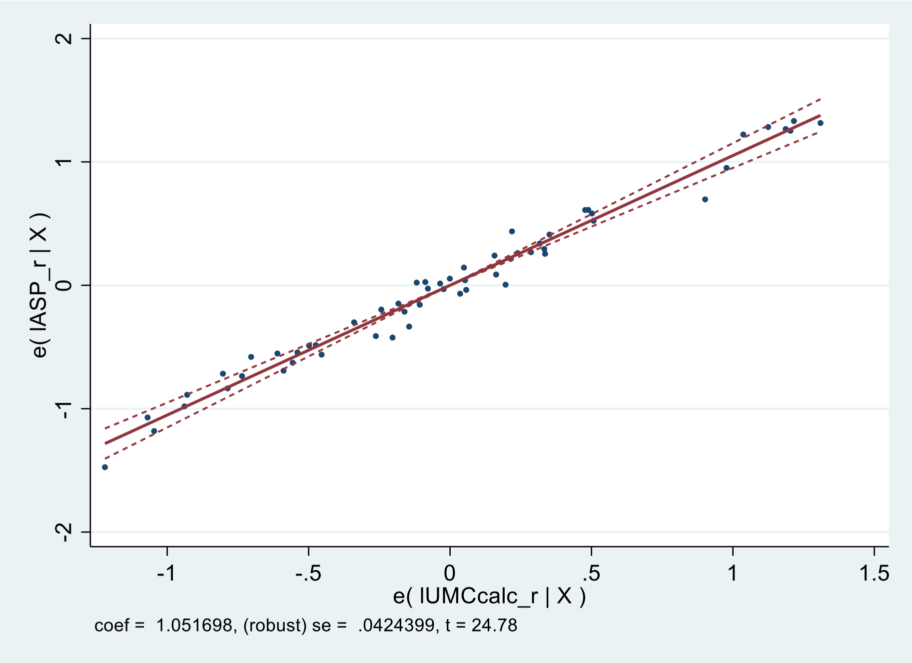

Figure 4.2. The predicted Average Selling Price (ASP) upon its regression on Unit Module Cost (UMC)

4.2.3.2. Independent Variables

As exhaustively discussed under subsection 3.3.2, though there have been some attempts to capture different learning effects and some external factors by means of different variables, investigations at global aggregate level as well as availability of data do not allow including too many variables in conventional PV LC models. The mostly used variables were cumulative capacity; knowledge stock calculated based on accumulated R&D expenditures or patent data with an assumed lag and depreciation; polysilicon prices; plant scale and some market dynamics in a few cases. The detailed findings of the studies which investigated the effects of these factors were discussed in methodological level of analysis (subsection 3.3.2.4). Except cumulative capacity associated with the LBD effect and polysilicon prices, others were found to have often yielded insignificant results. However, the multicollinearity problem and the ambiguity in contribution of composed variables make these results controversial. A comprehensive list of PV LC studies and the variables employed can be found in some review studies (Elia et al., 2021; Rubin et al., 2015; Samadi, 2018).

Description of the independent variables that were directly or indirectly utilized in the alternative estimations carried out in the scope of this thesis study to explain the cost decline of PV modules are summarized in Table 4-3. Based on the analytical framework provided in Chapter 3, they were associated with certain learning patterns and innovation capabilities. Further discussions on their relevance, the hypotheses established and thereby the direction of their effects (i.e. sign of their coefficients) are provided in the following subsections.

Table 4-3. Description of the independent variables utilized in the estimations.

V#	**Name**	**Symbol**	**Functional form & data type**	**Categorial definition**	**Primary & supporting learning patterns**	**relevant innovation capabilities**
1	Cumulative Module Shipment	CumModShip	log - continuous	internal effort	LBD LBR/LBI	transformation/ exploitation
2	R&D intensity	RDint	log - continuous	internal effort	LBR	acquisition/ assimilation/ transformation
3	R&D employment	RDEmp	log - discrete-lag2	internal effort	LBI/LBR LBD	acquisition/ assimilation/ transformation/ exploitation
4	Vertical integration	fullintegrated	dummy	internal effort	LBI LBD	acquisition/ transformation/ exploitation
5	Polysilicon cost	pSicost	continuous	market dynamics& external technological progress	-	external stimulus & knowledge
6	Polysilicon sensitivity	polySisensitivity	Interaction (V4xV5)	mixed	LBI LBD	capabilities in V4 stimulated by V5
7	Year 2008	y_2008	dummy	structural break	-	external stimulus
8	After 2011	after2011	dummy	industrial dynamics	LBI LBR/LBD	acquisition/ transformation/ exploitation
9	Module efficiency	eff	continuous-lag1	external technological progress	LBI LBR/LBD	acquisition/ assimilation/ transformation
10	Time trend	timetrend	discrete	any kind of external progress	LBI LBR/LBD	acquisition/ assimilation/ transformation/ exploitation

a. Cumulative Module Shipment

Cumulative output was calculated by adding annual module shipments for each company[83]. It was used as indicator of LBD of which background was comprehensively addressed in Chapter 3. In sum, as the firms accumulated output either it was static or increasing, they were expected to learn from their repeating routines and refine them as they confronted new occasions. Moreover, capacity additions which required new investments were anticipated as stimulation for new knowledge as well. Therefore, the sign of the coefficient of LBD parameter was expected to be negative.

In most of the years for substantial part of the companies, the amount of shipments was continuously increasing due to new capacity additions. This gradual growth prevented firms to have a static output and caused the cumulative capacity to have a non-constant and increasing slope. It was addressed in subsection 3.1.1 that some authors found continuous investment was worth considering as the real source of learning since repeating the same action would have a decreasing return after a certain duration, while the stimuli provided by the new machinery would bring along some new knowledge (Arrow, 1962; Thompson, 2010). New investment may not necessarily cause capacity increase but if the capacity increases, there is probably a novel technique or technology embedded in the new equipment or systems purchased unless the upstream machinery industry is not fully identical and has a persistent non-improving character. The situation in the PV industry will be revisited in Chapter 5. At this stage, it can be assumed that the LBD variable employed in this sample did not only capture the learning formed by means of repetitive actions but also through the new infrastructure adopted.

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[83] It was mentioned in the previous sub section that some of the firms could have excess output in the upstream steps. These semi-products were reported as extra sales other than module shipments by the companies. In the dataset, only the module shipments were considered.

Investing can also be seen as a channel to improve the absorptive capacity of firms which in the end leads to innovation. As addressed in section 3.4, the activities of the firms can be reconfigured and transformed as a result of their dynamic capabilities which are enabled by a certain level of absorptive capacity (Teece & Pisano, 1994). Transformation and exploitation dimensions of absorptive capacity require the new knowledge gained to be refined, combined with the existing knowledge to create new routines and incorporation and implementation of them in(to) the operations (Zahra & George, 2002). New knowledge embedded in capital investments under continuous capacity increase can mobilize these abilities since new machinery which is seen as an instrument for absorptive capacity (Ayala et al., 2015) can force firms to reconfigure and transform their activities in a dynamic environment and utilize the new routines improved in their operations.

Indeed, LBD can also be associated with the path dependency which was defined as one of the determinants of dynamic capabilities (Teece & Pisano, 1994) and is one of the important characteristics of an innovation activity (Dosi & Nelson, 2010). In the path definitions it was mentioned that path dependency was related to accumulated activities of firms and their gradual adaptation to changes (Teece & Pisano, 1994). This can be enabled by LBD. Firms can learn and develop dynamic capabilities through their routines and the trials that accompany them. In that sense, the external knowledge of which acquisition and assimilation were enabled through research activities, new machinery and interactions with the stakeholders can be transformed and exploited by trials and repeating activities within firm. In that sense, both new investments as addressed in the previous paragraph and the repeating activities itself can improve transformation and exploitation levels of absorptive capacity. Thus, LBD can be seen as a complementary part of learning activities which all together improve the dynamic capabilities of firms. For more details about the underpinning literature, please see section 3.4. Indeed, this is what differentiates LBD from a scale effect which is addressed in the next paragraph.

On the other hand, it was also underlined that so-called LBD effect had still been observable under static output which proved its impact regardless of the scale (Alchian, 1949; Arrow, 1962; Berndt, 1991). Therefore, scale can be an important parameter to be examined in LCs. However, since it was found insignificant when incorporated into the models together with the LBD effect (de La Tour et al., 2013; Pillai, 2015), it is not so common (Samadi, 2018) to see it in the final PV LC models.

The multicollinearity problem arising from the correlation of the scale with the cumulative output and the assumption about the validity of average industrial plant scale for the whole dataset were discussed under methodological level of analysis in sub section 3.3.2. In (Yu et al., 2011), the PV LC estimations resulted in returns to scale with a value of 1.07. In (Isoard & Soria, 2001) the returns to scale was found 1 when it was assumed constant and in case the model was arranged according to flexible economies of scale it deviated between 0.70-0.97. In the first case, it causes the scale parameter to be dropped from the C-D production function originated LC as shown in subsection 3.1.2. Moreover, the authors concluded that in the long run, returns to scale would converge to 1 even if it was not in the whole lifetime and its effect would get smaller compared to LBD due to reaching optimum production scale.

For the sample utilized in this study and the similar studies that was based on firm level data as well, though the scale value seems to be specific to firms, it is still a little tricky. PV factories have a modular structure and new lines at certain capacities are added when any expansion is required or planned. But, since the companies in the sample became too large after a certain point, it was observed that they opened new factories rather than adding new lines which could be because the advantages to exploit from the plant scale might have become stagnant or mitigated. Though it was still expected to observe the LBD effect that arose from overall capacities accumulated under same corporation, the effect of scale could not be measured since there was no one plant size. Taking their average could be an approach as it was done in (Pillai, 2015) and in all global level estimations or bottom up cost models[84] that employed

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scale effect (Kavlak et al., 2018; Nemet, 2006; Yu et al., 2011). However, it would make the boundaries which determined the behavior of the scale effect unclear. Probably depending on the problems discussed above, except the two studies mentioned above (Isoard & Soria, 2001; Yu et al., 2011) which yielded different scale effects in their PV module based LC estimations, it was not found significant.

As a result, in the estimations carried out in this thesis, the cumulative capacity was incorporated into the models as an indicator of LBD which covered the continuous investment effects that accumulated within time. Scale effect was not included since it was hard to determine a reliable indicator and it would probably be collinear with the cumulative shipment which ended up with insignificant results in other studies in the literature.

b. R&D intensity and R&D employment

LBR effect was tried to be captured by different parameters in the LC literature. These can be listed as R&D Expenditure (Wiebe & Lutz, 2016) and cumulative R&D expenditure or patents corrected with certain lags and depreciation values (de La Tour et al., 2013; Kobos et al., 2006; Watanabe et al., 2000; Yi Zhou & Gu, 2019). The cumulative version was usually called knowledge stock. It was explained in (de La Tour et al., 2013; Samadi, 2018) that high correlation between two cumulative values incorporated in the model i.e. LBD and knowledge stock was inevitable. As addressed in subsection 3.3.2.4, though some of the authors found LBR significant (Kobos et al., 2006; Watanabe et al., 2000; Yi Zhou & Gu, 2019), either they did not include it in the same model with LBD or the variance inflation factors (VIF) reported were slightly below 10 which was still high. Therefore, the coefficients that were estimated may not have been so reliable.

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[84] At global level, authors took the industrial average (Kavlak et al., 2018; Nemet, 2006; Yu et al., 2011) or the scales reported in magazines as industrial standards (de La Tour et al., 2013).

In the estimations conducted in this thesis, R&D intensity which was obtained by dividing R&D expenditures with total net sales was used. The normalization of quantitative R&D efforts with firm size can allow to capture a dimension of absorptive capacity within firms (Ayala et al., 2015; Cohen & Levinthal, 1990). In this study, the relative amount of research activities was seen as a measure of dedication to learning by researching and it was hypothesized that it contributed to absorptive capacity of firms and thus facilitated their recognition and understanding of external progress. The acquisition and assimilation of external knowledge were defined as the first two steps of absorptive capacity in (Zahra & George, 2002). They can be shortly described as recognition of new knowledge out of the firm boundaries and its deep understanding and interpretation respectively. More details were provided in subsection 3.4. Research efforts within firms can improve these abilities and may contribute to transformation and reconfiguration processes in terms of creating new routines as well. Thus, they can trigger the cost decline. Therefore, expected sign of the coefficient of R&D intensity was negative.

In addition, effect of R&D Employment was separately investigated in the estimated models. It can be an important instrument for absorptive capacity and thus can be effective in various dimensions of improving dynamic capabilities. The first three dimensions of absorptive capacity i.e. acquisition, assimilation, transformation can be easily affected by the quantity and quality of the R&D staff. Quality cannot be identified from the company reports however number of R&D employees was mostly available. The first two dimensions i.e. acquisition and assimilation of absorptive capacity can be enabled by R&D labor through learning by interacting with others and their potential skills to discover technological opportunities outside which were defined as determinants of dynamic capabilities in section 3.4. On the other hand, the knowledge transformed into new routines and repeating trials based upon, can enable learning. Therefore, LBR through R&D employees can work synergistically with LBI by increasing the possibility to be informed about external knowledge and LBD through the feedback mechanisms between operational activities and the research staff.

As a result, it was hypothesized that number of R&D employees can have an impact on learning in terms of identifying and interpreting the knowledge outside (which correspond to acquisition and assimilation dimensions of absorptive capacity) through external interactions but also it contributed transformation of these knowledge into new routines thereby functioning as a supportive factor of LBD for the cost decline based on internal interactions. Hence, the sign of its coefficient was expected to be negative.

For this purpose, number of R&D employees was introduced into model with its different lags. Based on the literature analysis carried out, this was the first time that effect of R&D labor was investigated in terms of its effect in PV LCs.

c. Variables for External Effects (Industrial dynamics after 2011, efficiency of PV modules and time trend)

In Chapter 2, the dynamics of overall PV industry in the last two decades as well as its historical development were examined in detail. In Figure 2.11, it was clearly seen that the share of China in all steps of PV value chain exceeded 50% by the year 2011 except the feedstock (polysilicon) production. Despite staying below this level, China was the world leader in it as well. It was indicated in subsection 4.3.2 that the sample was composed of the firms which carried out their PV manufacturing activities substantially in China. Therefore, the industrial structure in China can be an important factor that affected the learning in PV firms in the sample. First, the amount and variety of entrepreneurial activity are important measures for a well-functioning Technological Innovation System (TIS) and they represent a portion of the relevant actors in a National Innovation System (NIS) when they exist at country level. Entrepreneurial experimentation, together with the other functions, determines the innovation potential. In section 3.5, the theoretical frame of innovation systems was provided. In sum, since the response of firms to this breakthrough in industrial dynamics in terms of learning was worth examining, a dummy variable that separated the period after 2011 was incorporated into the model to control external effect related to the industrial dynamics in China. The firms that had certain level of absorptive capacity were expected to benefit from this effect in favor of cost decline. Therefore, the expected sign of this dummy was negative as well.

In (Wiebe & Lutz, 2016), the years 2011 and 2012 was introduced as dummies into model through which cost decline of PV modules was investigated for the time interval 1992-201. They were utilized as an indicator of overcapacity since it was claimed that there had been a supply surplus in those years. However, based on the analysis made throughout the years which was depicted in Figure 2.10, despite observation of supply surplus in certain years, it was not specific to the years identified in the mentioned article. As a result, by Wiebe and Lutz, it was found significant when estimated jointly with LBD and lost its significance when LBR was kept in the model (Wiebe & Lutz, 2016). However, the specified years might have captured the effect that was investigated within this thesis as mentioned in the previous paragraph. It is noteworthy that, with a similar approach, in (Gan & Li, 2015), effect of the supply-demand gap on PV module costs was examined for the years between 1988-2006 together with LBD and silicon prices and it was found insignificant. Consequently, rather than having an effect on costs due to a supply surplus, those years employed in (Wiebe & Lutz, 2016) can indicate a factor related to industrial dynamics which was addressed here in this thesis.

On the other hand, the average efficiency of commercial PV modules in the market which was provided in Figure 2.5 shows a clear progress in the overall industry. Therefore, it was investigated to discover the effect of external product performance increase on firms’ cost decline. In (Pillai, 2015), efficiency records of each firm were included in firm level panel data estimations which were conducted for the years between 2005-2012 and as a result, the relevant variable was found significant together with polysilicon price and usage, China dummy, annual industry investment and initial PV module efficiency of firms. Indeed, investigation of this effect was somewhat trivial. Module efficiency has a well-known certain effect on the dependent variable. Unit cost is obtained by dividing the overall cost to the power that can be generated by the module. On the other hand, efficiency is defined by the ratio of this output power to the power coming from the sun as incident light (please see subsection 2.3.1 for more details). As a result, the increase in efficiency of PV modules produced in a firm will definitely decrease the unit cost when other things remain constant, since they are mathematically dependent. Therefore, in the estimations of this thesis study, the overall industrial efficiency of commercial PV modules was utilized to capture the ability of firms to adapt the external technological development rather than the development within firm (i.e. efficiency of firms' modules) which was already known to have an effect. Since the firms were expected to utilize the external development regarding device efficiency for reducing their costs jointly with their internal efforts, its coefficient was anticipated to have a negative sign.

Efficiency is only one dimension of external technological progress and there is always a possibility that there might be other improvements outside that accumulated within time. Time trend was used in some PV LC studies to capture these effects. However, it was either found insignificant (Mauleón, 2016; Pillai, 2015) or hindered to observe the real effect of other factors (Papineau, 2006) when jointly utilized with multiple independent variables. Indeed, time trend is not a different thing than accumulated static output in terms of slope. Therefore, it is probable that it has a high correlation with the LBD variable and the multicollinearity between them can preclude to rely on the estimates due to manipulated standard errors and thereby unreliable significance levels (Dougherty, 2007). Nevertheless, time trend was employed as an alternative variable to efficiency and since any external progress would mean nothing without the internal abilities of firms, the learning variables were expected to remain significant when the models controlled with time trend in case multicollinearity problem was not so severe.

From innovation capabilities point of view, it is clear that the external knowledge has a critical role in innovation. The abilities of firms are utilized to embody this knowledge properly. In that sense LBD and LBR parameters discussed above indicate the internal efforts which can function more effectively when there is interaction with outside. Therefore, exploiting the external effects that are related to industrial dynamics or technological progress can be associated with the existence of learning by interacting (LBI). Interaction was mentioned as an important determinant of dynamic capabilities in subsection 3.4. In that sense, relations with different stakeholders and collaborations were defined as channels to learning which could help firms to identify their non-functioning routines and help them to overcome the drawbacks of internal blindness. Hence, it was hypothesized that thoroughly flourished industrial PV activities in China by 2011 could have speeded up the learning rates due to potential interactions of the firms with the increased number of stakeholders in the NIS which were entrepreneurial actors of the PV TIS. Thus, these firms could be evaluated to have dynamic capabilities.

On the other hand, recognition of technological opportunities can be enabled by different kind of networks and external relations as well as research efforts and staff. Interactions can also contribute to reconfiguration and transformation ability i.e. creation of new routines from existing knowledge and external progress through following and evaluating the environment i.e. markets, technologies, competitors and benchmarking. Based upon, it was also hypothesized that external progress either represented by efficiency or time trend contributed to learning jointly with internal firm efforts dedicated to research i.e. R&D intensity and R&D employment which all together indicated a certain level of absorptive capacity within these firms.

d. Vertical integration and vulnerability to raw material cost (polysilicon sensitivity and structural break)

Polysilicon as the raw material is explicitly effective on cost of PV modules. Many studies that aimed at investigation of its impact found it significant (de La Tour et al., 2013; Gan & Li, 2015; Mauleón, 2016; Pillai, 2015; Trappey et al., 2016; Wiebe & Lutz, 2016; Yu et al., 2011). The structure of polysilicon industry was described in subsection 2.3.3 and the change of polysilicon spot price as well as its unit use in PV modules was depicted in Figure 2.13. It was also mentioned that the survival of firms against the crisis in this feedstock material and maintenance of the cost decline in PV modules might have been associated with certain level of dynamic capabilities.

As mentioned in section 3.4, integration is a determinant factor of dynamic capabilities. Effective integration of new routines into existing organization and their coordination which can be challenged by the currently established coherence and complementarity in the existing processes[85] were defined as a sign of dynamic capability (Teece & Pisano, 1994). On the other hand, it was discussed in subsection 3.3.2.4 that though transaction cost approach favored vertical integration within firms, interactions within formally independent units could be more flourishing in terms of product innovation (Lundvall, 1988) which was correlated with the process innovations as well (OECD, 2022). It was also addressed in the scope of dynamic capabilities discussions that vertically integrated firms might suffer the drawbacks of being closed to external environment in terms of supply activities. Since firms were expected to evolve according to their best practices within time, knowledge flows limited to daily internal communications and interactions could prevent recognition of new knowledge and even its absorption if the existing knowledge base was challenged. (Fagerberg, 2009). As a result, the effect of vertical integration was found worth investigating in estimation of PV LCs in the thesis study.

For this purpose, a dummy variable that took the value of 1 in case the firms were fully integrated except the feedstock production at any year of their activities within the time frame was defined. Being fully integrated might have enabled more cost reduction in PV modules compared to not being integrated, due to the decrease in transaction costs as well as the interactions within the firm. However, the condition of being vertically integrated was not found significant in any of the preliminary trials. Then, it was decided to examine its interaction with the feedstock cost and the variable named polysilicon sensitivity was created by multiplying the unit cost of polysilicon, which

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[85] Here, the author implied that these could act as barriers.

is the product of polysilicon spot price (USD/Watt) and unit polysilicon use (kg/Watt), with the full integration dummy. Thus, a new term that was expected to measure how vulnerable the PV firms were to raw material cost when they became vertically integrated was generated.

When the firms are not fully integrated they have to purchase the upstream product from outside which requires a certain level of interactions with the external stakeholders. In case they have vertical integration, their interactions are limited to their own daily routines and they have to produce all products along the value chain with a cost that their own abilities enabled. The PV industry as it can be understood from the graph in Figure 2.13 was very responsive to polysilicon spot price which peaked in 2008. Therefore, any improvements in the decentralized companies and the vertically integrated ones might have been different and the polysilicon sensitivity parameter was generated as an indicator to measure it. In (Lee, 2011), vertical integration was found to be one of the effective factors that secured the raw material price as well as lowered production costs by eliminating transaction costs. By keeping the possibility of diminishing returns of internal interactions and complementary routines based on the discussions made in (Fagerberg, 2009; Lundvall, 1988; Teece & Pisano, 1994), it was hypothesized that full integrated firms could be more robust to polysilicon price fluctuations due to decrease in transaction costs. Thus, it was aimed at revealing if either the internal (in case the sign of coefficient would be negative) or external interactions (in case the sign of coefficient would be positive) were more effective in developing dynamic capabilities.

Finally, this variable was controlled with a time dummy that defined the peak year of polysilicon spot price to understand if the effect found was mitigated which was expected if the sensitivity was specific to crisis years.

4.2.4. Summary Statistics

The available observations with respect to time and firms were provided in Table 4-1. The summary statistics of the key continuous variables utilized in the estimations are presented in Table A-1 on yearly basis and in Table A-2 on cross-section basis. These variables were introduced into models after their natural logarithmic transformations were made. As to the time variables regarding the year 2008, the years after 2011 and time trend, their summary statistics were not given since they were just dummies that took 1/0 values for certain years and the last one was an ordinal variable that increased by one each year. Moreover, they were the same for each firm.

On the other hand, summary of the vertical integration within firms and change in unit polysilicon cost as well as the variables that it was generated from are presented in the Appendix A in Table A-3 and Table A-4. It can be seen from Table A-1 that while three firms were vertically integrated within the entire time frame; one firm had never been. In general, the structure of firms in the sample changed in favor of vertical integration within years. Also, as can be seen in Table A-4, though the polysilicon spot price peaked in 2008, due to the decrease in its unit consumption, the highest value of the unit cost of this feedstock material was observed in 2007.

The pairwise correlations between independent variables are provided in Table 4-4. The highest correlation is observed between LBD and other persistently increasing firm invariant variables. In that sense, efficiency and time trend have very close relation with cumulative module shipment and therefore they are highly correlated with each other as revealed by the coefficient that has the value of 0.996. As a result, it does not seem a sensible approach to introduce them in the same model. The risks that multicollinearity among other variables may bring along are examined by post estimation analyses.

Table 4-4. Pairwise correlations of independent variables

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) lCumModShip	1.000						
(2) lRDint	0.226*	1.000					
(3) lRDEmp	0.706*	0.410*	1.000				
(4) polySisensitivity	-0.161	-0.219*	-0.298*	1.000			
(5) eff	0.834*	0.400*	0.581*	-0.391*	1.000		
(6) after2011	0.685*	0.331*	0.432*	-0.365*	0.850*	1.000	
(7) timetrend	0.860*	0.282*	0.598*	-0.332*	0.996*	0.837*	1.000

* $p<0.05$

Beyond the summary statistics provided in the tables above, the change in the variables with respect to time are depicted in Figure 4.3, Figure 4.4, Figure 4.5 and Figure 4.6. They were included in the plots in the form as they were introduced into the models with the required transformations. In addition, the integration status of firms and polysilicon cost in the corresponding years are depicted together in Figure 4.7. As depicted in Figure 4.3, average selling price of PV modules has a decreasing trend of which rate changes within time and between firms. Cumulative outputs of firms seen in Figure 4.4 are persistently increasing in time as expected due to being a summed variable. Change of R&D intensity (Figure 4.5) and quantity of R&D employees (Figure 4.6) as LBR measures have a fluctuating behavior with respect to time while the latter tends to maintain its increase. Finally, by looking at Figure 4.7, while the attitude of some firms against increase in feedstock costs seems to have been in favor of being vertically integrated, some acted earlier and some had a lagged action after the exacerbated prices were mitigated.

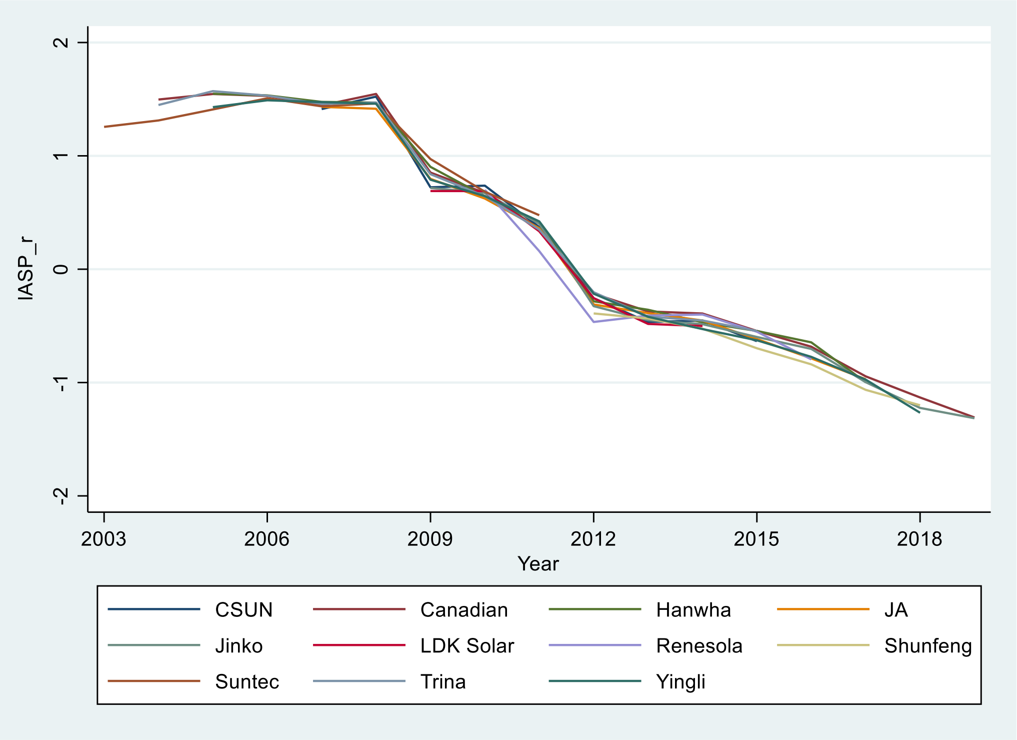

Figure 4.3. Natural logarithm of ASP of PV Modules with respect to time

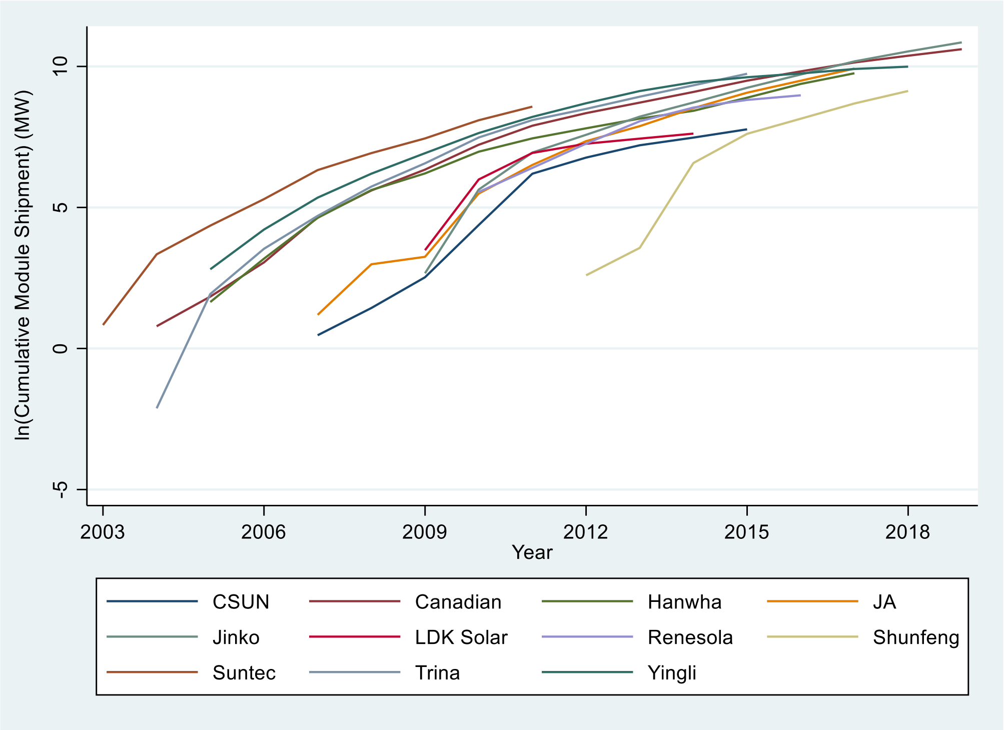

Figure 4.4. Natural logarithm of cumulative module shipment with respect to time

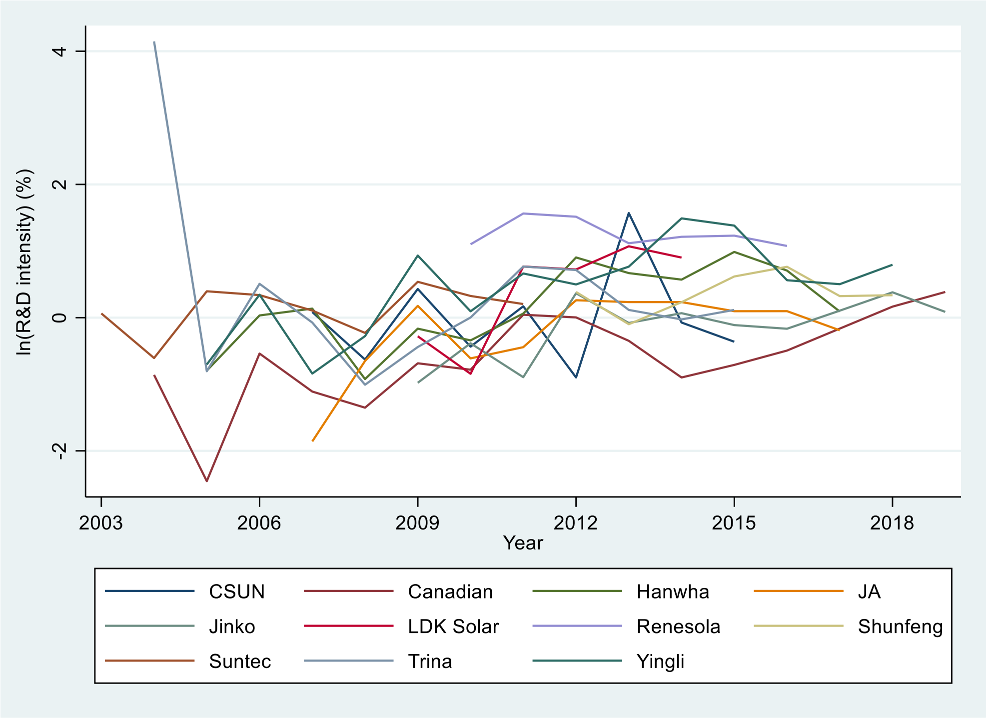

Figure 4.5. Natural logarithm of R&D intensity with respect to time

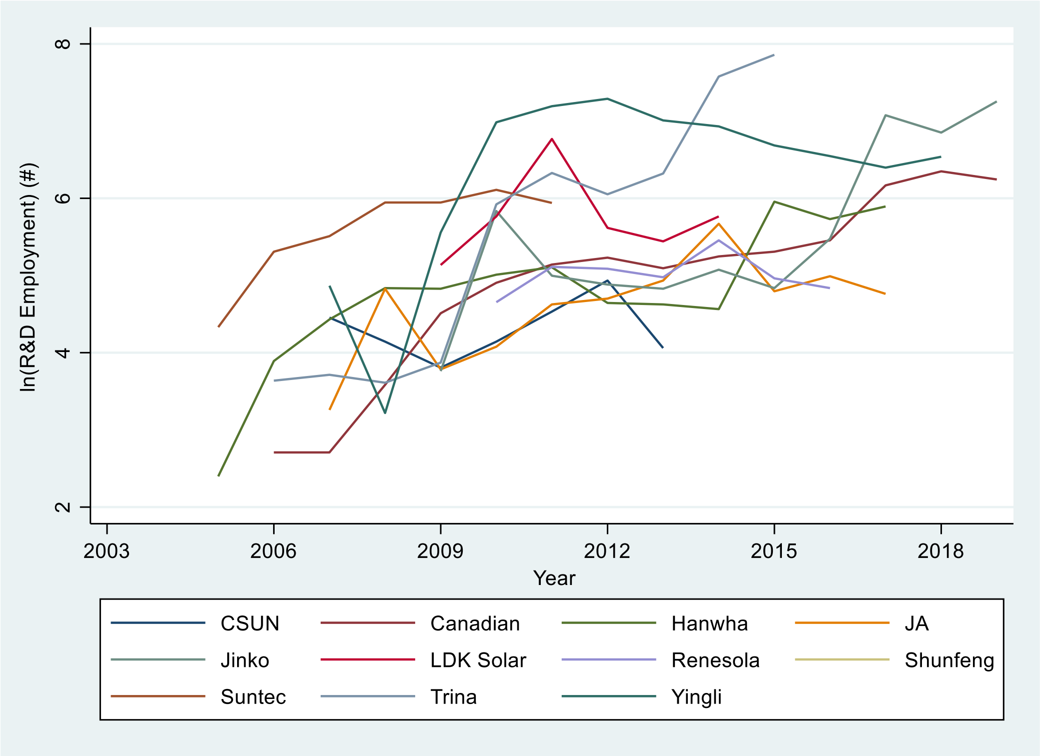

Figure 4.6. Natural logarithm of R&D employment with respect to time

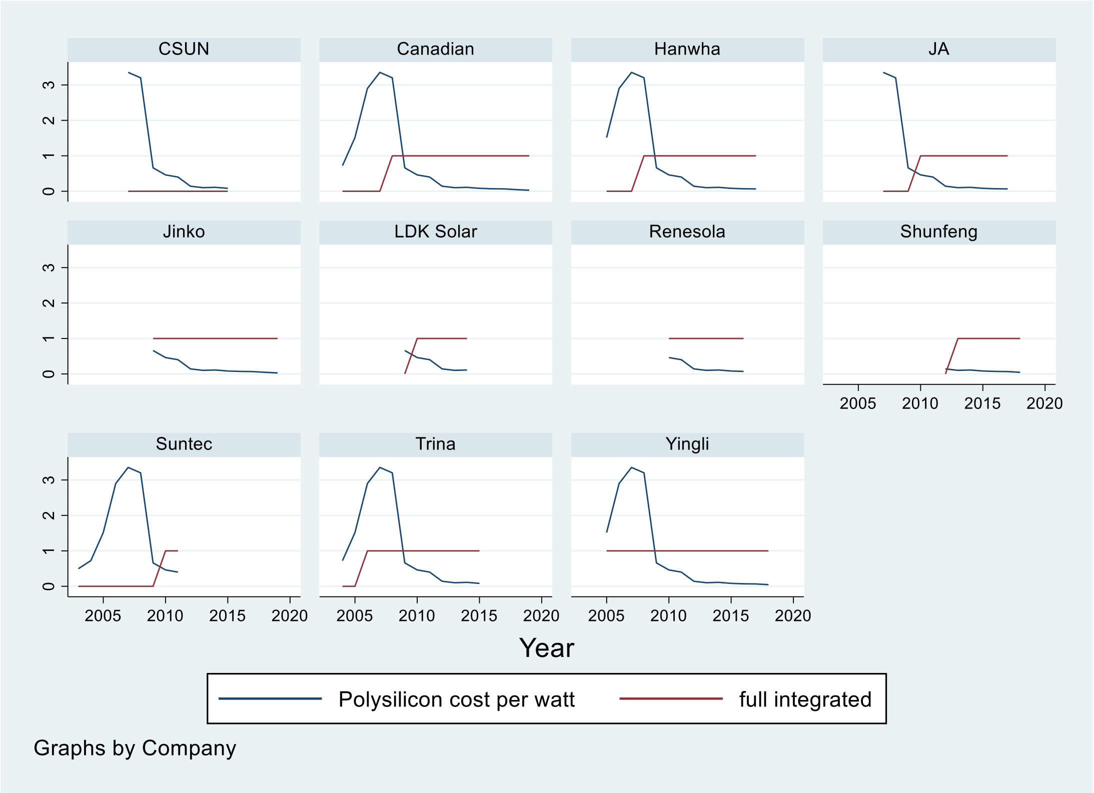

Figure 4.7. Vertical integration status of firms and corresponding year's pSi cost

Finally, persistently increasing variables which include LBD, average efficiency of PV modules and time trend are depicted in the same plot to investigate the similarity observed in their behavior. Time trend has the highest slope at most of the times which makes it gather all linearly accumulated progress during these periods. As discussed before in sub section 4.3.2.4, time trend itself, though it was aimed at capturing the external progress with it, creates a black box in the LCs. On the other hand, efficiency has almost a constant slope as well despite not being a generated parameter like time trend. Therefore, time trend can gather all effect emanating from efficiency improvements in the PV industry as well as other external progress. For some firms, while there are some years where cumulative module shipment have identical slope with the other two, at certain years its slope exceeds theirs. As a result, these variables may have a certain correlation but they are still worth investigating in alternative models together as much as multicollinearity allows.

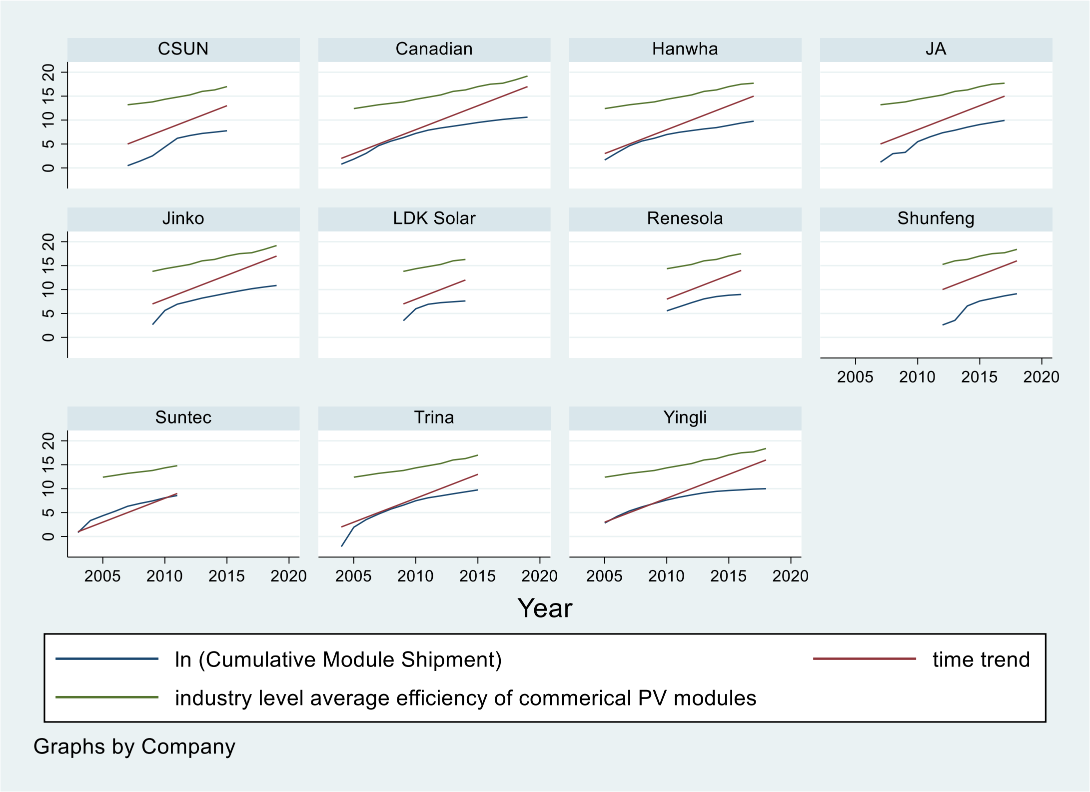

Figure 4.8. The change in LBD, efficiency and time trend with respect to time.

4.3. Estimation Results and Discussion

In subsection 4.4.1, the estimations based on OFLC and TFLCs which were composed of LBD and LBR parameters are provided. Following, in subsection 4.4.2, the results of alternative MFLC estimations are presented and evaluated by comparing different models. In addition, for the finally selected models, some sensitivity checks were made by omitting the outliers detected and then imputing the missing variables thereafter. Estimation results of these alternative MFLC models obtained after these statistical arrangements are provided and discussed separately.

The models were estimated under fixed effect to eliminate the unobserved heterogeneity that could arise from individual entities after the relevant tests for other alternative models (i.e. pooled OLS and random effect models) were carried out.

In all estimations presented in the tables, robust standard errors were utilized through Huber/White/sandwich estimators available in Stata (StataCorp LLC, 2021), since a certain level of heteroskedasticity and auto correlation were observed in the many of the models estimated.

For multicollinearity, pair wise correlation tables presented in Table 4-4 and variance inflation factors (VIF) as a post estimation instruments are examined. VIF indicates a problematic level of correlation between multi independent variables in case it takes a cut-off value higher than 10 (Wooldridge, 2009). For the models selected, VIF values was much below 10 though there were some correlations between specific variables. As to stationarity of the variables which could indicate presence of a unit root, the available unit root tests in Stata 17 for unbalanced panel data (Fischer type Phillips–Perron unit-root tests) were implemented and for all variables except a slight suspect for one, non-stationarity was rejected. The results were also supported by the regressions described in Equation 28 of which interpretation for existence of unit root was described in subsection 4.2.1. Finally, the causal relations between the independent variables employed in selected models and the dependent variable were tested in two way by applying relevant regressions based on Granger causality approach as described in (Leszczensky & Wolbring, 2022).

4.3.1. Preliminary Estimations

The results of OFLC and TFLC estimations can be seen in Table 4-5. In the first column, the most basic PV module cost prediction with respect to LBD represented by the cumulative module shipments of firms was estimated. The results indicate a learning rate (LR) around 17.1 % LBD[86]. In (Pillai, 2015) where firm panel data estimations were implemented as well, it was found a little higher (18.7%) for the time interval 2005-2012. The LR in (Wiebe & Lutz, 2016) where the years between 1992 and 2012 were examined for the decrease in global module prices was almost found

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[86] LR=1- 2^(β)

identical (i.e. 17.2%). On the other hand, as discussed in sub section 3.3.1. there is a high variety among the estimated LR arising from different levels of analysis. This variation can be seen for the OFLCs in (Rubin et al., 2015; Samadi, 2018). In Table 3-1, the long-term PV LRs based on different data sources and years were provided for global level. If the changing rate is ignored, the estimates for more than 30 years, usually yielded one factor learning rates around 20-25%. However, due to potential omitted variables which may not be same for analyses at different levels and non-constant rates in different time periods as depicted in Figure 3.4, the results are not comparable. Still, the learning by doing rate estimated in this study for PV firms and the years from 2003 to 2019 was more or the less coherent with the ones found in the literature.

In the TFLCs carried out in this study, introducing the R&D intensity as the first LBR term did not cause a noticeable decrease in LBD due to probably normalization of the research expenditures which were often employed directly or in accumulated format by considering the lags and depreciation factors in the PV LC literature. As claimed in (Wiebe & Lutz, 2016), multicollinearity problem was the main reason of insignificance in variables when LBD and LBR effects were intended to be examined jointly. However, as revealed in Table 4-5, this LBR variable had a very low correlation with LBD after having been adjusted for the firm size. The overall variance inflation factors seen in the table supports this evaluation as well[87]. In the end, it seems that firm’s research efforts have a significant contribution on cost decline without shadowing the effect of LBD. Rather, as expected based on the dynamic capability discussions in section 3.4 and subsection 4.3.3, LBR and LBD might have functioned synergistically in creating new routines as a part of transformation activities. In that sense, the hypothesis regarding LBD as addressed in sub section 4.3.3.2, seems to have been validated. It was discussed that LBD could act as a dynamic capability instrument by facilitating transformation of routines and exploitation of new created ones in the

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[87] The overall vif included the ones coming from firm dummies.

firm’s operations through the repetitive activities and trials. On the other hand, it was assumed that through LBR efforts, the required knowledge could be acquired from the environment and assimilated through internal dedication to research and external relations. By leaving the external part to the following estimations, the joint significance of these two variables could be a sign of successful reconfiguration and transformation of the routines by new knowledge and thereby the dynamics capabilities that the firms own.

In the extended version of the TFLCs, while the current value and the first lag of R&D employment yielded insignificant results, the second lag ended up with higher R square and jointly significant variables with the expected signs. Practically, it can be inferred that R&D labor could be effective on cost decline in the firms after the second year they were employed. Similar to R&D intensity, in terms of absorptive capacity and thereby dynamic capabilities of firms, learning enabled by R&D employees seems to work jointly with LBD. As discussed in sub section 4.3.3.2, R&D employees might have enabled information flows and recognition of external knowledge and thus supported LBD through the feedback mechanisms between the internal operational activities and research staff. Thus, the hypothesis that R&D employment “contributed to transformation of external knowledge into new routines thereby functioning as a supportive factor of LBD based on internal interactions” is partially validated by leaving the investigation of relevance of external knowledge to the MFLC estimations.

Table 4-5.Results of OFLC and TFLC estimations

VARIABLES	(1) OFLC	(2) TFLC	(3) TFLCextended
lCumModShip	-0.271***	-0.250***	-0.327***
	(0.028)	(0.019)	(0.041)
lRDint		-0.285***	-0.222**
		(0.028)	(0.096)
L2.lRDEmp			-0.161***
			(0.034)
Constant	2.032***	1.927***	3.373***
	(0.189)	(0.132)	(0.264)
Observations	115	115	80
R-squared	0.758	0.812	0.914
Number of firmID	11	11	10
Model	Fixed	Fixed	Fixed
std err	Huber-White	Huber-White	Huber-White
Rsq within	0.758	0.812	0.914
Rsq overall	0.651	0.682	0.676
R sq BW	0.297	0.287	0.181
F test of the model	94.45	115.4	169.2
p value of model	2.06e-06	1.23e-07	3.12e-08
rho	0.521	0.585	0.833
sd_res_panels	0.429	0.432	0.461
sd_res_overall	0.411	0.364	0.206
VIF (mean)	-	1.96	2.41
F test that all u_i=0	9.27	12.27	28.65
Prob > F	0.0000	0.0000	0.0000

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Consequently, the preliminary estimates above resulted in (based on the extended TFLC model) 20.2%, 14.3% and 10.6% learning rates against each doubling of cumulative module shipment, R&D intensity and number of R&D employees, respectively.

Nonetheless, though these estimations might indicate a certain level of learning that emanated from mere internal efforts within firms and their capabilities for acquisition

And assimilation of the progress outside, the external factors should be incorporated into the models to unveil the exact response of these internal efforts. Therefore, by the MLFC estimations in the following subsection, it was aimed at enlightening the relevant hypotheses.

4.3.2. Multi Factor Learning Curve Estimations

MFLCs were carried out to investigate the effects of learning efforts employed in TFLCs together with the external factors which indicated further learning mechanisms based on the innovation capabilities as discussed in subsection 4.3.3. Estimation results of alternative models are presented in Table 4-6. The models were improved for investigation of further effects by adding some variables successively.

In the first three estimations in Table 4-6, the vulnerability of firms to feedstock material cost was measured. The change in unit polysilicon cost and vertical integration status of firms were depicted in Figure 4.7. While some firms had been integrated against the polysilicon crisis, some had lagged behind in terms of taking such an action. In the dynamic capabilities theory, vertical integration was seen as a cause of corporate blindness and resistance to innovation due to coherence in routines and internal communications against knowledge that challenges them externally (Teece & Pisano, 1994). In (Lundvall, 1988), despite potential transaction cost advantages, since it limited limiting interactions with outside, vertical integration was seen as a potential hampering effect on innovation. On the other hand, in (Lee, 2011), based on the descriptive studies and expert interviews vertical integration was found helpful in terms of securing the raw material cost in PV companies. As a result, it was hypothesized in subsection 4.3.2.2 that "being fully integrated might have enabled more cost reduction in PV modules compared to not being integrated, due to decrease in transaction costs as well as the interactions within the firm."

However, the estimation results yielded on the contrary. The variable polysilicon sensitivity as the product of unit polysilicon cost and being vertically integrated along the whole PV value chain were found significant with positive coefficients. No change was observed in the other variables except R&D intensity. The magnitude of the coefficient of R&D intensity decreased one third and its significance was reduced from 95% to almost 90%[88]. As presented in Table 4-4, there was no meaningful correlation between this variable and the others in the model. On the other hand, vertical integration is a more production related attribute and in case it does not exist, a certain level of supply chain relations is expected. Therefore, it was primarily and secondarily associated with LBI and LBD in Table 4-3. In that sense, R&D employees might have channeled a certain level of recognition of knowledge embedded in the supply chain outside through LBI and this knowledge could have been exploited through LBD as a result of repeating activities and trials in operations.

In the following steps, when the polysilicon crisis year 2008 was introduced into the model as a dummy control variable, polysilicon sensitivity lost its significance. The previous and following years were introduced to the model separately instead of 2008 and together with 2008 as well; but the outcome did not change. Then, by omitting polysilicon sensitivity, only year 2008 dummy was kept in the model and its behavior was controlled in presence of 2007 and 2009 again. Only 2008 which was the year when polysilicon spot price made peak remained significant. Therefore, the models were continued to be improved with the year 2008. When the models that were estimated with polysilicon sensitivity and 2008-year dummy variables and shown in MFLC1 and MFLC3 respectively were compared, the results were very close[89]. As a result, full integration condition was found to have made firms more vulnerable to polysilicon cost in crisis years, while in standard conditions its effect was not significant. Nevertheless, this finding regarding the polysilicon sensitivity which was investigated as a firm variable for the first time in the PV LC literature up to now

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[88] In Table 4-6, the significance levels were limited to 90% confidence interval (CI). Since the p value of R&D intensity was 0.102 which yields a slightly lower CI 89.8%, it was not labelled with star in the mentioned table.

[89] R&D intensity is seen to turn out a significant variable when year 2008 was used instead of polysilicon sensitivity. But there was a minor difference indeed since p value of the R&D intensity changed from 0.102 to 0.99 in MFLC1 and MFLC3 respectively.

obtained is still worth considering. Even its drawback at crisis year is ignored, at regular times, vertical integration does not bring along any advantage to the PV firms compared to being integrated or in other words.

From innovation capabilities point of view, it can be concluded that when the firms were integrated, their internal capabilities to decrease costs emanating from polysilicon use were not as fruitful as in case they procured the intermediate products from other suppliers. Beyond the suppliers' ability to somehow provide cheaper upstream products, learning through supply relations might have contributed to the improvements in the downstream processes[90]. As addressed in section 3.4, relations with different stakeholders and collaborations were at the heart of learning process since they were found helpful to identify their routines that did not function well (Teece & Pisano, 1994). In that sense, it can be said that for acquisition of external knowledge and at some level for its transformation, being actively involved in supply chain outside, might have been fruitful for the firms that were not fully integrated. Though these implications made from the quantitative findings are made by reckoning the underpinning literature, it is hard to infer a certain conclusion in the absence of a qualitative analysis. These findings and the relevant discussions will be revisited again in Chapter 5 by means of the insights attained from the expert interviews.

In the following models seen in column 4, 5 and 6 in Table 4-6, effect of the variables associated to industrial dynamics were examined. First, the effect of Chinese PV industry status on cost decline of PV modules manufactured by the firms in the sample was investigated through a dummy variable generated as 1 for the years after 2011 and otherwise 0. As it was exhaustively discussed in Chapter 2 and revisited in subsection 4.3.3.2, 2011 was a turning point in terms of industrial dynamics in PV since China had dominated more than half of the shipments in all steps of PV value chain[91]. Though

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[90] Except 1 case being full integration condition was violated by not having operations in the upstream. Therefore, when a firm was not fully integrated, for the current data set, it meant, it had not any operations in the ingot and wafer steps.

[91] Except feedstock in which it was still the leader but with a share less than 50%.

the breakthrough year was 2011, it was interpreted as the threshold and effect of the years following were examined for the difference. For this purpose, the relevant dummy was incorporated into the model represented by MFLC4 in Table 4-6 in the presence of other learning factors and under control of polysilicon crisis.

As a result, explanatory variable that defined the years after 2011, was found significant with a negative coefficient and indicated 36% more decrease[92] in the PV module prices (as proxy of costs) for the years when China became the world leader of the PV manufacturing value chain. On the other hand, the magnitude of the coefficients of the learning variables was reduced while their significance and signs remained same. Thus, this may indicate that a certain level of LBI with external actors in the growing PV TIS in China could have contributed to cost decline jointly with internal learning factors which were often associated to LBD and LBR. Moreover, effects attributed to these often-used learning factors when they were investigated in isolation might have been inflated due to the ignorance of other patterns and mechanisms that had a role in cost reductions. While learning could have been realized through internal efforts associated to repeating operations and research activities, a portion of their effects might have been enabled through their contribution to dynamic capabilities enabled by LBI. In terms of sensitivity of the model to the selected years, the same variable was generated for the previous and later years as well. However, they were insignificant when the years were shifted backwards or yielded less R squared value of the model when they started later.

Entrepreneurial experimentation i.e. increase in variety and number of entrepreneurs was discussed as an important inducement factor for innovation in a TIS (please see section 3.5 and subsection 4.3.3.2 for further details). Therefore, it can be justified that a certain level of new knowledge arising from the growing industry in China could have nourished the TIS within the NIS that the firms in the sample were a part of.

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[92] The dummy independent variable effect on logarithmic dependent variable was calculated by the formula $100x((e^\beta)-1)$.

Since the variable regarding the dominant situation of China in PV value chain was significant in terms of decreasing the costs together with the other variables, the firms in the sample seem to have successfully managed to embody this external industrial knowledge through their internal learning factors included in the model. Thus, these findings support the hypothesis that thoroughly flourished industrial PV activities in China by 2011 could have speeded up the learning rates due to potential interactions of the firms with the increased number of stakeholders in the NIS which were entrepreneurial actors of the PV TIS. Ultimately, it can be evaluated as the presence of dynamic capabilities in these firms. Still, as also indicated above, despite the underlying theories and the quantitative support, these implications are indirect and require qualitative investigation for a more conclusive inference.

In the estimations carried based on MFLC5 and MFLC6 seen in Table 4-6, the first lag of industry average power conversion efficiency of commercial PV modules and time trend variables were introduced into the models respectively. The other variables examined in the previous estimation remained same. As given in pairwise correlation table (Table 4-4) and in Figure 4.8, there was a strong correlation between these two variables as well as with them and LBD variable. Therefore, the models were excepted to suffer a certain level of multicollinearity which made reliability of the standard errors and therefore the significance levels lower. MFLC5 yielded better results in terms of significance levels of coefficients and impact of LBD compared to MFLC6. Indeed, for both of them, a substantial decrease in the magnitude of LBD variable was observable. As can be seen in Figure 4.8, for some years, time trend and cumulative module shipment as the LBD variable were almost the same thing with overlapping portions at certain intervals. Thereupon, it was not surprising that LBD became insignificant when time trend was included. It can be implied that while time trend was able to capture all effects attributed to LBD due to statistical reasons it does not mean that LBD is invalidated in terms of its role in cost decline.

To understand the difference between the predicting behavior of the time trend and LBD variables, estimations were repeated with two alternative models where LBD and time trend substituted each other. The results are presented in Table B-1 in Appendix B. Though R&D employment was still significant when time trend and LBD was included together in MFLC6 seen in Table 4-6, the estimations in Table B-1 showed that, when cumulative capacity was replaced by time trend, estimations yielded similar results for other variables except R&D employment. It was discussed under TFLC discussions that R&D employment could have a synergistic effect with LBD since R&D labor might have facilitated reconfiguration and transformation of the routines depending on the acquisition and assimilation of the external knowledge it enabled. Due to the returns on the same capabilities, a joint effect of R&D employees with the overall external progress which was represented by the time trend parameter, was expected as well. However, this effect was not observable when LBD was replaced by time trend as seen in Table B-1. In that sense, when cumulative progress was represented by the time trend alone for sake of preventing multicollinearity originated problems and thus learning arising from firm’s cumulative output was disregarded, the model seemed to have suffered omitted variable bias which ultimately deteriorated the estimation results in another way. Indeed, as addressed in subsection 3.2.2.4, this is not a different attempt than creating a black box for learning. On the other hand, incorporation of the current value of the efficiency variable into the model had yielded lower values for all other variables in the model. But when its first lag was employed in MFLC5, both the significance of the estimates and their values for all variables were higher. It was an expected outcome since identification and assimilation of external technological knowledge might have taken some time.

Table 4-6. Multi Factor Learning Curve Estimations

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	MFLC1	MFLC2	MFLC3	MFLC4	MFLC5	MFLC6
lCumModShip	-0.311***	-0.311***	-0.318***	-0.240***	-0.076**	-0.036
	(0.036)	(0.037)	(0.039)	(0.042)	(0.029)	(0.021)
lRDint	-0.141	-0.142	-0.168*	-0.099*	-0.085**	-0.073**
	(0.078)	(0.078)	(0.091)	(0.046)	(0.033)	(0.026)
L2.lRDEmp	-0.152***	-0.151***	-0.163***	-0.097***	-0.063*	-0.046*
	(0.023)	(0.026)	(0.030)	(0.029)	(0.028)	(0.025)
polySisensitivity	0.155***	0.159				
	(0.045)	(0.113)				
y_2008		-0.010	0.290***	0.387***	0.450***	0.405***
		(0.303)	(0.065)	(0.068)	(0.057)	(0.042)
after2011				-0.459***	-0.417***	-0.421***
				(0.061)	(0.045)	(0.039)
L.eff					-0.221***	
					(0.032)	
timetrend						-0.136***
						(0.013)
Constant	3.138***	3.137***	3.287***	2.607***	4.470***	2.146***
	(0.260)	(0.268)	(0.256)	(0.255)	(0.256)	(0.167)
Observations	80	80	80	80	80	80
R-squared	0.925	0.925	0.920	0.950	0.978	0.985
Number of firmID	10	10	10	10	10	10
Model	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed
std err	Huber-White	Huber-White	Huber-White	Huber-White	Huber-White	Huber-White
Rsq within	0.925	0.925	0.920	0.950	0.978	0.985
Rsq overall	0.712	0.712	0.702	0.841	0.953	0.975
R sq BW	0.197	0.196	0.214	0.555	0.908	0.963
F	350.5	282.4	355.8	255.1	713	2416
p value of model	7.24e-10	1.32e-09	6.76e-10	2.07e-09	0	0
rho	0.839	0.837	0.830	0.789	0.688	0.613
sd_res_panels	0.440	0.440	0.440	0.308	0.157	0.110
sd_res_overall	0.193	0.194	0.199	0.159	0.106	0.0873
VIF (mean)	2.57	2.85	2.43	2.93	4.20	4.62
F test that all u_i=0	27.00	25.90	25.20	11.08	4.52	3.23
Prob > F	0.0000	0.0000	0.0000	0.0000	0.0001	0.0027

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Consequently, though the models that included the internal learning factors and some external effects before adding efficiency and time trend resulted in outcomes of which underlying reasons were supported by the theory, the last two factors complicated the estimations due to the correlation effect. Therefore, it became harder to corroborate the hypothesis that external progress either represented by efficiency or time trend contributed to learning jointly with internal firm efforts dedicated to research i.e. R&D intensity and R&D employment which jointly indicated a certain level of absorptive capacity within these firms. Still, despite substantial loss in LBD coefficient, MFLC5 can validate that the external technological progress can be embodied by the firms through their internal learning efforts. Before, reaching a conclusion, some post estimation analysis and sensitivity checks were carried out in the following subsection.

4.3.3. Post Estimation Analyses and Sensitivity Checks

As mentioned in the beginning of section 4.4. all models were estimated with fixed effects. Therefore, the error terms were isolated from the panel specific residuals. The F test for the zero hypotheses that all ui =0 was rejected for the all models estimated. Thus, the potential endogeneity that could raise due to unobserved heterogeneity among firms was eliminated. The underlying results can be found at the end of each table. In addition, variance inflation factors that showed the severity of multicollinearity among all independent variables included in the model were also presented similarly. Based on the cut-off value for considering omitting collinear variables from the model (Wooldridge, 2009), none of the models required such a treatment. However, outcomes of pairwise correlations for specific models were evaluated in the text where their results were discussed.

Before carrying out further tests that might address endogeneity issues, the last two models MFLC5 and MFLC6 estimated with efficiency and time trend variables as well as other effects, were controlled for outliers through leverage against normalized squared residual plots. Thus, it was aimed to reveal the variables or their residuals which deviated too much from the mean and estimations. The estimations with the mentioned two models were repeated after omitting 4 variables which were observed to be common in two base models. The base plots obtained via Stata can be found in Figure C.1 in Appendix C. Results of the estimations after omitting these outliers are seen in column 1 and 2 in Table 4-7 for efficiency and time trend-based models respectively. For both, there was no dramatic change in variables when compared to the versions with outliers except recovered significance levels of LBD. In addition, when these improved versions of MFLC models i.e. MFLC7 and MFLC8 were benchmarked, they looked similar despite the former had higher estimate values. Therefore, some statistical tests and visual inspections were carried out for both models to reach a final conclusion. All results were provided in Appendix C.

For all models, if otherwise not indicated, heteroskedasticity and autocorrelation (AR) robust standard errors were utilized based on Huber-White sandwich estimators to have reliable estimates despite changing variance of the residuals and serial correlations and not to violate the unbiasedness condition of the estimations. When the models after omitting outliers were tested for these two statistical concerns, heteroskedasticity problem seemed to have been mitigated totally for MFLC6 while it still existed at 90% level for MFLC5. On the contrary, as to AR, for MFLC5 it was almost invisible except a mild sign at order 4, while MFLC6 still suffered it severely at order 1 and 2. The heteroskedasticity test results were summarized in Table C-1 and serial correlation tests were shown in Figure C.2 and Figure C.3. The two models were estimated without robust standard errors as well but there was not any significant difference except a small change in significance levels. These alternative estimations can be found in Table C-2.

The histograms of fixed effect isolated residuals for the two models are depicted in Figure C.5. The residuals of both models seem to have been distributed around zero. On the other hand, when the observed values of dependent variable were plotted against the predicted ones, both models were seen to have good fits which can be seen in Figure C.6. Finally, residuals plotted against common non-dummy independent variables which are depicted in Figure C.7 exhibited very similar distributions for the two models as well. There was no clear sign of any trend in the residuals that indicated a correlation with the common independent variable when fixed panel effects were eliminated.

Moreover, as addressed in subsection 4.2.1, unit root in time series data and causality relations might be critical in reliability of the estimates in terms of endogeneity problem. It was also mentioned in the same subsection that it was possible to mention unit root when the correlation was tended to be persistent in terms of non-stationary. To test it, the procedure described in (Stock & Watson, 2020; Wooldridge, 2009) was utilized and the results Table C-3 were attained. They were also cross checked with the readily available unit root test commands in Stata[93]. The test estimations with absolute value of the coefficients below 1 as well as the other complementary tests conducted, rejected the presence of a unit root in all variables except efficiency[94]. Time trend was not tested since it was an artificially generated variable. Indeed, as seen in Figure 4.8, efficiency values progressed with an almost perfectly linear trend like time trend within the time frame examined. Therefore, it was not surprising to find it non-stationary. Rather than a unit root, industrial efficiency values may be endogenous to many things from global R&D expenditures to other improvements coming from the industry. However, it is not possible to anticipate and include all these as instruments. It is also noteworthy that weak instrument are known to deteriorate the estimations results as well (Stock & Watson, 2020). Therefore, accepting overall industry efficiency values as proxy of technological progress similar to time trend but with a more sound justification may not be so wrong when all other statistical results were considered.

In addition, for testing the causality of the variables in terms of mathematical relation, Granger causality test procedures (Lopez & Weber, 2017) described in sub section

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[93] For unbalanced panel data Fischer type, Phillips–Perron tests were utilized with demean option which assumed fixed effects (StataCorp LLC, 2021). However, they only can be utilized for time and panel variant variables since the available commands for unbalanced data is based on the zero-hypothesis that all panel entities have unit root. Therefore, test attempts for a variable like efficiency which is same across the panels give error.

[94] It was mentioned in subsection 4.3.1 that when the condition $-1<\beta<1$ was satisfied in Equation 28, presence of a unit root could be rejected.

4.2.1 were followed. A certain number of lags for each variable including the dependent one was included on the right side to predict the dependent variable itself[95]. Since at least one of the coefficients of all independent variables was significant, it was validated that there was a causality from each independent variable to the dependent variable. On the other hand, though R&D intensity had a significant lag as well, the t tests implemented on the zero hypotheses that all lags defined for each explanatory variable were jointly zero was rejected for all variables except R&D intensity. In this test estimation non-robust standard errors were utilized since Stata yielded missing F value due to calculation complications while still giving estimation results. When the joint t tests were repeated after robust standard error based estimations, the zero hypothesis that all lags of R&D intensity were jointly zero was rejected as well. As a result, all variables utilized were found to have a statistical causality on average selling price of PV modules which was employed as a proxy of cost. The estimations utilized for the mentioned tests and t tests carried out for as presented in Table C-4 and Figure C.8 respectively.

Shortly, same tests were repeated for reverse causality which might be one of the reasons of endogeneity as discussed in sub section 4.3.1. The results were provided in Table C-5 and Figure C.9. In those estimations, the dependent variable was replaced with each independent variable successively which were regressed on the lagged values of all variables among which the original dependent variable was treated as an explanatory variable. Following, t tests based on the same hypothesis mentioned above were implemented. Efficiency was resulted in reverse causality or more accurately in simultaneity relation with the original dependent variable since the lagged values of the original dependent variable was significant and t test was unable to reject they were jointly insignificant. Indeed, the precondition for these tests is stationarity (Lopez & Weber, 2017) which was violated for the efficiency variable as discussed in unit root test evaluations. Therefore, similar to unit root, this reciprocal causality appeared as a

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[95] The number of lags were defined based on the condition provided in (Lopez & Weber, 2017). Time series length (T) > 5+3 x (# of lags).

statistical concern might not have a sound background in real life beyond the mathematical relations that deteriorate the estimations' reliability. Still, time trend based estimations can be referred instead. In addition, a significant lag of original dependent variable was also observed for the R&D intensity but then by the t tests carried out, joint significance of all lags thereby presence of reverse causality was rejected.

Finally, since number of observations was decreased too much due to missing R&D employment data in some firms for certain or along the whole observation years, the dataset was imputed for missing R&D employment data except the firm of which relevant data were missing for all years. This was carried out via multiple imputation technique that was available in Stata. The results of these versions of the selected MFLCs are given in Table 4-7. All signs and significance of the variables were conserved while the magnitudes of the coefficients were a little improved. Though one of the fundamental drawbacks of this study was low number of observations, the alternative models estimated after omitting the outliers and the imputing the missing values did not cause a dramatic change in the influence of the investigated factors and their directions on the cost decline.

Table 4-7. Multi Factor Learning Curve Estimations after outliers omitted and missing values imputed

	Outliers omitted		Imputed	
	(1)	(2)	(3)	(4)
VARIABLES	MFLC7	MFLC8	MFLC9	MFLC10
lCumModShip	-0.060***	-0.036***	-0.13***	-0.08***
	(0.010)	(0.009)	(0.03)	(0.02)
lRDint	-0.072**	-0.064**	-0.11***	-0.09***
	(0.031)	(0.025)	(0.02)	(0.02)
L2.lRDEmp	-0.043**	-0.034**	-0.05**	-0.04**
	(0.016)	(0.014)	(0.02)	(0.02)
y_2008	0.554***	0.485***	0.39***	0.39***
	(0.045)	(0.024)	(0.04)	(0.03)
after2011	-0.449***	-0.448***	-0.37***	-0.40***
	(0.035)	(0.029)	(0.03)	(0.02)
L.eff	-0.223***		-0.18***	
	(0.013)		(0.02)	
timetrend		-0.128***		-0.12***
		(0.006)		(0.01)
Constant	4.253***	2.000***	4.29***	2.28***
	(0.156)	(0.067)	(0.20)	(0.10)
Observations	70	73	78	81
R-squared	0.989	0.992	0.988	0.992
Number of firmID	10	10	10	10
Model	Fixed	Fixed	Fixed	Fixed
std err	Huber-White	Huber-White	Huber-White	Huber-White
Rsq within	0.989	0.992		
Rsq overall	0.972	0.984		
R sq BW	0.914	0.970		
F	1248	2040	410.5	1321
p value of model	0	0	1.45e-07	7.38e-10
rho	0.698	0.645		
sd_res_panels	0.110	0.0834		
sd_res_overall	0.0727	0.0619		
VIF (mean)	4.07	4.60		
F test that all u_i=0	3.67	2.96		
Prob > F	0.0012	0.0058		

Robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

In terms of sensitivity of the models, beyond the post estimation operations for outliers and imputation of the missing variables, the models were also controlled against different changes in successive steps starting from the beginning. Many of them were mentioned in the text above. To sum up, through the inclusion of the polysilicon crisis year 2008 in the model where the polysilicon sensitivity (i.e. vulnerability of integration of raw material cost) was investigated together with other internal learning factors, the specific effect of the peak year was controlled. In addition, the years around 2008 were tried too. As to the parameter which measured the effect of the years after 2011 when China became the dominant player in the PV value chain, the specification of the variable was validated by trying other years around as the starting year of the breakthrough time. Finally, replacing LBD with time trend as a cumulative progress variable yielded insignificance of R&D employment. It indicated the joint role of learning patterns that led to dynamic capabilities within firms.

4.4. Concluding Remarks

In the exhaustive estimations carried out within the scope of this study, the learning patterns some of which were ignored in the previous studies as well as their joint behavior with other external factors, which could be an indication of dynamic capabilities within firms, were investigated. Both attempts have certain novelties which are ultimately expected to contribute to the literature.

It would be more accurate to perceive cumulative output that was utilized in many of the LCs due to its empirically validated correlation, as a “surrogate” parameter which embodied effects of many other factors influential on the cost decline as underlined in (Mauleón, 2016). Since some authors were aware that attributing all meaning to one factor was statistically not sound and it might be misleading by masking other factors when it was utilized to build firm strategies and design detailed policies, different parameters were proposed for investigation (Wiesenthal et al., 2012).

Various variables were comprehensively discussed not only but especially in subsection 3.3.2.4 under methodological level of analysis and somehow revisited in subsection 4.3.3. Most common examined effects in the literature were confined to: LBD; LBR which was represented by the accumulated R&D expenditure with a certain lag and deprecation (i.e. knowledge stock); scale; polysilicon price; some other input prices; time trend and industrial parameters like different year dummies or the supply-demand variables. A list of these variables at a certain extent can also be found in the review studies (Elia et al., 2021; Rubin et al., 2015; Samadi, 2018). As discussed in the mentioned subsections, many of them were left to future studies by the authors due to data availability but also low number of observations in time series analyses would not allow to investigate too many variables. As to ones that were somehow incorporated into the models in the previous studies, except LBD and polysilicon price, they were mostly found insignificant due to multicollinearity problems, selection of non or weakly influential variables or misspecification of the models.

In this thesis, LBR effect was not restricted to expenditures or number of patents in the firm, country or industry. LBR effect was first, tried to be investigated through the R&D intensity which was normalized to the firm size thereby indicating the firm's relative dedication to research at a certain extent; second, the quantity of R&D employment with two years lag was employed. The normalization approach and thus getting rid of multicollinearity concern as well as including the research labor in the estimations were both a novelty for the PV LC literature. In the end, they were found jointly significant with LBD in terms of their contribution to the cost decline of PV modules. Another important contribution was investigation of firm structure regarding vertical integration through its interaction with the raw material cost. The results disfavored being full integration of the firms along the PV value chain at the industrial crisis times since the integration made firms more sensitive to price peaks of the polysilicon in terms of reducing their costs.

As to the external effects, in the presence of other internal learning factors tested before, the unit cost of PV modules manufactured by the firms in the sample was reduced more in the period that China dominated the overall PV module manufacturing value chain with more than 50% share. Thus, industrial dynamics were shown to have a significant effect on PV module costs through the learning mechanisms that contributed to the capabilities within firms. The commercial module efficiency in the overall industry was also shown to have an impact on the costs of PV modules produced by individual firms. This was an indication of effective knowledge flow from outside to the firms. Based upon the proven relation between the efficiency and the costs when other variables were kept in the model, these firms should have been somehow capable in identifying and assimilating this external technological knowledge, reconfiguring it and then transforming their routines accordingly. Thus, ultimately exploiting these efforts in their operations could have been enabled. In that sense, based on the dynamic capabilities and absorptive capacity theories, R&D labor might have channeled the recognition of the new knowledge available outside through LBI and its assimilation and reconfiguration together with other internal learning factors such as dedication to research (i.e. R&D intensity) and cumulatively repeating activities (LBD). Finally, using time trend as an overall progress term instead of efficiency did not cause any conflicting change compared to the previous findings and it was interpreted as a validation of presence of the innovation capabilities within these firms which were a joint outcome of internal learning mechanisms stimulated by the external dynamics/ technological improvements.

In (Candelise et al., 2013) the learning curve estimations as well as bottom up cost calculations were criticized due to having been focused on long term effects like LBD and accumulated research efforts (i.e. LBR) and ignoring immediate, country specific factors like scale effects, industrial and market dynamics that might have an impact on the cost and price trends of PV modules. The authors recommended increasing the diversity of the learning mechanisms that could have been influential and evaluating them in terms of their interactions with the policy for a better design of supports. In this study, the quantitative research carried out somehow addressed these requirements by (I) investigating different variables regarding the internal learning efforts some of which were utilized for the first time in PV LC studies; (II) examining some interaction parameters that revealed the sensitivity of the firm structure to the structural breaks; (III) observing the joint effect of the firm activities that were related to internal learning mechanisms and the external factors regarding industrial dynamics or overall progress.

As a result, all hypotheses in sub section 4.3.3.2 were more or the less validated by the econometric estimations and their post statistical analyses were carried out. Although most of them had a solid theoretical foundation based on the innovation literature from evolutionary economics perspective and were supported by the quantitative findings, there was still a requirement for a qualitative evaluation of the inferences in terms of confirming the causality behind. Moreover, enlightening some factors that might have a relation with different types of learning or external stimulus but of which indicators could not been included in the models due to availability of reliable and consistent data[96], homogeneity of observations[97] or not being quantifiable without surveys[98], required the contribution of the experts from the field. Therefore, in Chapter 5, the expert elicitations were utilized to build a more solid foundation for the policy recommendations oriented to maintenance of the cost decline in the PV industry which are expected to be guiding for the other technological fields as well.

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[96] For example, skills of labor, research alliances.

[97] For example, being involved in downstream applications was common among the sample.

[98] For example, type and quality of external relations.

CHAPTER 5

A QUALITATIVE ANALYSIS FOR FURTHER UNDERSTANDING OF LEARNING MECHANISMS IN c-Si PV INDUSTRY

I've come to hang the sun on your heart
Don't be exhausted
....
I came to offer you from the sun
....
I present you brand new songs
That come from beyond the far mountains
I gave you the newest flowers
Open the door, let the clouds in
Children who know to laugh have arrived
Don't be exhausted!

Lütfü Erol & Ayşegül Çelik

(from the lyrics of a Turkish song)

5.1. Introduction

PV LCs can provide important information about the factors that might have an effect on cost decline of PV modules. However, a qualitative clarification is usually required to understand the causality behind or how the variables utilized as indicators of these factors channel the outcomes arrived. There are studies in the literature that utilized expert elicitations directly for estimation of cost decline in PV as well as the ones that focused on understanding the technological and industrial improvement recorded so far. In their quantitative use, contributions of some variables were identified based on the views of experts (Nemet & Baker, 2009) or the future costs under certain scenarios were estimated directly based on expert anticipation (Bosetti et al., 2012; Verdolini et al., 2015). In these studies, respectively, the expert surveys were carried out ex-ante to provide data input for the calculations and to be utilized as the main data source that future cost forecasts were based upon. The second group of studies utilized the expert interviews in a more qualitative way to understand the innovation process that led to cost decline (de la Tour et al., 2011; Huang et al., 2016; Lam et al., 2018; Nemet, 2019).

Here in this study, semi structured interviews made with 19 experts from the field were conducted and evaluated for post estimation analysis. By embracing a complementary approach, the qualitative survey results were analyzed whether they supported the quantitative findings and elucidated the mechanisms that enabled them. Since some mechanisms regarding dynamic capabilities were indirectly inferred from jointly significant outcomes of internal indicators and external factors examined in the quantitative analyses, the detailed elaborations of the experts provided important clues to understand the presence of these innovation capabilities and how they were channeled. In that sense, using econometric LC estimations and qualitative expert surveys together to attain a deeper and well-founded understanding of cost decline of PV modules seems to be a novel approach in the literature. In sum, the aim of this chapter was carrying out a qualitative analysis to fortify the quantitative investigation of learning mechanisms in the PV industry.

The following subsections provide the details regarding the preparation of the survey, the way that the interviews were conducted, description of the sample and finally the analysis and evaluation of the results.

5.2. Methodology and Sample: Expert Elicitation

In this thesis, mainly two different methodologies were utilized. The econometric estimations of which results were discussed in Chapter 4 provided a certain background about the learning mechanisms that might have contributed to the cost decline of PV modules from the beginning of the 2000s. On the other hand, despite all theoretical foundations and econometric estimations, understanding the cost reduction process as well as the technological progress in the PV industry thoroughly, required qualitative investigation of the factors that enabled such a fast and consistent learning. Therefore, in the second part of the empirical research, expert elicitations were utilized as a complementary methodology to underpin the econometric findings and the inferences made from them as well as to reveal the factors that cannot be quantified in the first part.

The qualitative part of the research was built upon semi structured interviews. In this type of interviews, there is a set of written questions; therefore, the content is defined but the format of the interview is not fixed and can be oriented according based on the responses of the participants to enable further elaborations (Corbetta, 2003). As a result, a variety of the comprehensive answers of which degree can differ among the participants are collected. The answers are not confined by predetermined coding. Thus, investigation of the factors that are not considered before is enabled. One of the objectives of the interviews conducted in this study was validating the empirical findings regarding the learning patterns investigated in the quantitative part. Nevertheless, rather than inquiring the effects of ex-ante defined learning types directly with an expected set of answers, the underpinning mechanisms were intended to be captured through the semi structured survey designed based on the expertise of the field experts. Still, the interview included a few questions which were structured with certain orientations for the sake of collecting some auxiliary information.

For in-depth analysis, the sampling can be purposeful which enables to collect answers that are information-rich (Patton, 2015). As defined in (Patton, 2015), key knowledgeable people or reputational sampling is categorized under purposeful sampling strategy. The views of the participants in such a sample are utilized to enlighten the issues under inquiry relying on their vast knowledge and influence in the field. The sample employed in this study was selected with the criteria of having at least 5-year experience in PV module R&D or manufacturing.

Also, a geographical balance was considered between the West and the East but the interviewees were not distributed randomly among the experts who at different places of the world had certain years of experience in the field. The participants were selected deliberately among the ones who worked at worldwide known R&D institutions, public organizations or companies in different regions of the world and were highly possible to be known by the overall PV community due to being head of certain industrial unions, science communities, R&D organizations.

As a result, the interviewees included in the sampling were not only the people who could have observed and analyzed the factors that might have facilitated learning that led to innovation and technological progress in PV. Moreover, they were the actors who had been the subjects of learning that shaped the PV industry with a certain impact on changing and orienting the relevant capabilities. In that sense, they were the key informants or the key knowledgeables as articulated in (Patton, 2015). Therefore, their strategic approach as well as common aspects may be enlightening for the past records but also can be beneficial for design of better and sustainable policies in the future.

As to the evaluation, it was possible to identify a convergence between the views of the experts in terms of how specific learning patterns or innovation capabilities were formed and facilitated. In addition, the semi structured interviews allowed to capture important aspects regarding the details of different instruments that might have facilitated hypothesized learning patterns. These findings could have been missed if the questions had been oriented to pre-determined directions rather than semi-structured interviews. Therefore, both ex-post coding of the common answers which could be indicative for certain mechanisms and direct quotes where the interviewees narrated their distinctive experiences or opinions were employed in the evaluation of the findings. Moreover, the aspects that were identified to correspond to blocking and inducement effects on the functions of overall PV TIS were examined through a further analysis.

In the following subsections, the way that the survey questions were designed, how the interviews were performed, a more detailed description of the sample selection and profile of the participants and finally the framework utilized for the analysis of the results were addressed.

5.2.1. Description of the Survey

As mentioned above, the survey was not designed in a way that somehow the already quantified learning factors or facilitating and hindering mechanisms behind were inquired very explicitly and systematically. Despite the fact that specific learning types or instruments investigated quantitatively or the ones that could not be included in the econometric study due to data and modelling issues were on the focus of each question at some extent, the questions were designed in a more open-ended format to be able to capture any kind of answers that could be provide information beyond the hypotheses constructed or the findings attained previously. Thus, any kind of mechanisms or instruments that might have channeled learning and innovation capabilities were tried to be found out by inquiring the presence or effectiveness of precursor activities. Moreover, since some learning mechanisms were intertwined and functioned jointly as described in Chapter 3 and Chapter 4, this mutual relation could be captured more easily when the questions thereby the answers were not restricted to a certain direction. Otherwise, the answers of the participants would be oriented to certain learning types. Hence, some open-ended questions were designed to collect answers that could cover more than one type of learning. In addition, to discover different dimensions of the learning patterns which ultimately could have instrumented improvement of innovation capabilities, multiple questions that addressed same type of learning were directed to the interviewees.

In the following subsections the details of the questions included in the survey, the preparatory process for the interviews and how they were performed are described.

5.2.1.1. Design of the Survey Questions

The survey questions were designed based on various objectives. First one was to confirm the effects of the variables which were examined through econometric estimations and to unveil the causes that led them to yield either significant or insignificant outcomes. This ex-post evaluation was beneficial in terms of increasing reliability of the findings obtained from the quantitative analysis and understanding them deeply. Thus, it served for answering the second sub-question of the research which can be found in Chapter 1.

Secondly, semi structured interviews enabled investigation of further mechanisms that somehow resulted in learning or the factors that might have affected the cost decline but could not have been directly investigated through econometric estimations due to data or model constraints. The intentionally designed questions and further elaborations of the field experts provided the required data. Thus, the expert elicitations helped to unveil the learning patterns more comprehensively and capture the indicators regarding different dimensions of dynamic capabilities and well-functioning or hindering patterns in the domains of technological innovation systems. In that sense, this objective provided useful answers that unraveled the third sub-question of the research.

Third objective was to obtain some auxiliary information which were considered to ultimately enrich the policy recommendations in the conclusion chapter. Hence, some questions were designed to identify lag and depreciation values of R&D in PV; the orientation of research and industrial efforts that helped to decrease the costs and make technological improvements; and the effectiveness of some trade precautions and the future of c-Si PV technology.

The interview questions were prepared by considering these multiple points. However, answers to some questions provided information that clarified multiple objectives of the study due to the semi structured design of the interview and open-ended questions included. The list of the questions that guided the interview is provided in Appendix D. The questions asked can be categorized under 3 groups[99]. Their relation the quantitative part and the literature background were explained below.

The first set of questions was designed to verify the effect of the indicators that were associated with certain learning types of which theoretical foundations were built in Chapter 3 and which were investigated in Chapter 4 either through directly represented variables in the econometric models or of which presence was inferred from the joint significance of some variables. As mentioned before, the quantitative analysis did not allow to investigate further instruments that could be associated to these learning patterns. However, their qualitative investigation through the interview questions revealed mostly consistent results with the dynamic capabilities theory described in section 3.4 (Teece & Pisano, 1994; Wang & Ahmed, 2007; Zahra & George, 2002). As mentioned there, R&D expenditures, R&D intensity, research staff, networking activities, machinery i.e. new knowledge embodied in capital investment, organizational structure, conditions in the surrounding environment are different channels for improving absorptive capacity (Ayala et al., 2015). By the questions asked in the first set, revealing these effects which was not possible to find out quantitatively was targeted. In addition, instruments that could be derivative of those factors were inquired.

R&D related questions constituted a substantial part of the first set. To understand the effect of R&D funding, dedication, labor and other unmeasured dimensions, the ways that speeded up R&D processes and enabled their efficient and faster commercialization were inquired through open ended questions. There were also a set of questions through which the lag and depreciation of PV research activities by considering their differentiation based on the type of research activities and value

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[99] The questions presented in the guideline do not follow the same order as grouped here. Questions asked in the interview were ordered by considering the fluency of the interview.

chain steps were tried to be revealed[100]. There are some studies in the literature which determined the values of these parameters through numerical trials (Wiebe & Lutz, 2016; Yi Zhou & Gu, 2019) or by referring to an industrial survey (Kobos et al., 2006) mentioned in a very old paper (Watanabe et al., 2000). Therefore, a contemporary investigation based on field experience of the system actors and thereby contribution for the future studies was aimed there. To set a common understanding for the levels of R&D studies carried out, the technology readiness levels defined by the European Commission for PV were utilized as reference. The table that showed the definitions of these levels was presented to the participants in a slide when the relevant questions were asked (Rose et al., 2017).

The first question set also included some relevant questions associated with LBI which aimed at capturing the types of networking activities that could be related to dynamics capabilities of the firms or within the countries when the national boundaries were considered. Indeed, this question was also related to functionality of PV TIS within NISs. For this purpose, types of interactions that have led/could have led to improvement of PV technology were inquired. Though there was no variable that was directly aimed at measuring the effect of interactions in the quantitative estimations, the presence and impact of interactions were implicitly unraveled by the jointly significant results regarding the internal and external factors in the model. Therefore, expert elicitations allowed to validate the implicit findings at a more reliable level.

Another question that can be categorized under the first set which aimed at qualitative validation of the learning mechanisms or dynamic capability indicators that were directly or indirectly included in the econometric models, was related to functionality of vertical integration. While vertical integration was found effective based on transaction theory (Lundvall, 1988), the complementarities and settled

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[100] Indeed, these questions provided some auxiliary information and were not directly related to the estimations carried out in Chapter 4. Therefore, they can be grouped in the last set of questions mentioned in the last paragraph of this subsection as well.

communications within firm routines were seen as potential barriers to diffusion of external knowledge (Fagerberg, 2009; Teece & Pisano, 1994).

As a result, the factors that were addressed in the econometric estimations except LBD were somehow revisited in the expert elicitation study. This learning mechanism of which background theory was exhaustively founded in Chapter 3 was not asked directly since the participants were expected to have been highly familiar with the sectoral roadmaps or market reports that were referred in Chapter 3 and where the traditional PV LCs based on LBD were often employed to explain the cost decline. Still, since LBD parameter utilized in the quantitative analyses of this thesis study was covering continuous investing that accumulated within time rather than a constant output, the effect of equipment investments on cost and performance was inquired to identify the knowledge it could have brought along. Thus, the learning effect that might have been triggered by capital investments which was mentioned as one of the instruments of dynamic capabilities and was found an important stimuli for a continuous LBD (Arrow, 1962) was addressed.

As a result, the questions in the first set were both aimed at addressing the second sub research question i.e. validating and understanding the quantitively examined factors as well as the third sub question i.e. investigation of further dimensions of learning and the mechanisms that facilitated them.

On the other hand, the second group of questions aimed at clarifying the impact of the remaining learning pattern i.e. LBU that was not included in the econometric model as well as the other inputs of C-D production function i.e. labor and capital. As discussed in Chapter 3, LBU was a concept proposed in (Lundvall, 1988). But due to the skewness of data and limited number of observations, it was not possible to investigate it quantitatively based on the sample employed.

Finally, the last question set included some additional questions regarding orientation of R&D topics to certain areas in the pursuit of cost decline, quality issues that might have affected the cost decline due to change in market orientation, effectiveness of some policy measures against Chinese production i.e. anti-dumping precautions which have been applied in different regions of the world since the first years of the last decade (European Commission, 2016; U.S. Department of Commerce, 2012) and future of the c-Si based PV technology. Answers to these auxiliary questions which were aimed at enlightening some controversial issues in the PV industry were mostly utilized in TIS evaluations and policy recommendations.

5.2.1.2. Performing the Interviews

Studies that require gathering information from human participants are subject to approval of Human Subjects Ethics Committee of METU. The expert interviews to be carried out in the scope of this thesis were accepted with the protocol number 378-ODTÜ-2021. The approval letter can be found in Appendix E.

Upon approval of the Human Subjects Ethics Committee, the experts were invited to the interview via the email text presented in the application file by attaching the voluntary participation form as well. With the ones who accepted to participate, the appointments were arranged.

The interviews were carried out via online meeting applications such as Skype and Zoom. Except 1 interview which was not allowed to be recorded by the participant, 18 out of 19 interviews were recorded. 1 interview was audio recorded due to technical problems, and 17 were both audio and video recorded.

5.2.2. Description of the Sample Frame

In the following two subsections below, how the invited experts were selected and the final profile of the participants were described subsequently.

5.2.2.1. Selection of the Experts

Based on the discussion made in the beginning of this section, it was mentioned that the selection of the participants was not random but purposeful and the type of sample was defined as key knowledgeables which can be preferred when information rich interviews are intended (Patton, 2015). Therefore, the target group was the experts who had a solid background in PV technology and sufficient experience which ensured their familiarity with the dynamics of the industry. The lower limit of experience was set as 5-year in the field of PV at academic or industrial levels.

The most common number of qualitative samples in dissertations was determined as 20 and 30 in (Patton, 2015). Here, the main aim was reaching a number which was expected to provide sufficient information that would converge to each other at least for certain learning mechanisms. Thus, some elaborations which were found distinctive could somehow be evaluated as indicative when articulated by more than one key knowledgeable. For this purpose, 37 worldwide well-known experts in PV technology or the ones who held critical positions at prestigious PV organizations were invited by expecting at least reaching 20 of them based on the response and acceptance rate. In overall, 21 out of the 25 respondents gave positive response and after eliminating the ones with whom an appointment could not be arranged due to their inaccessibility or calendar availability despite their positive response, the final number of experts who were interviewed was 19.

As to the way of connection to the final participants, with 37% of them, I have worked together at different organizations during the years of my technical career. With 32% of the interviewees I somehow met at PV conferences/meetings and contacted later in scope of collaborations for research or industrial projects. Among the rest, with 16% of the experts, I contacted via social media while then remaining 16% were advised by the other participants.

Regardless of the degree of connection, most of the experts in the invited group had a profile which could be characterized: by having highly cited papers; being key speakers or organization committee members at international PV conferences; holding senior researcher or head of department positions at prestigious worldwide well-known research institutes or being top-level managers at PV companies. In sum, they had a wide range of experience in PV industry and were known in the sector via various ways. The attributes mentioned above can be confirmed by the information available in the subsequent subsection.

5.2.2.2. Profile of the Interviews

Since, all participants allowed to reveal their open identities as long as the direct quotes were not labelled with their names, the list of the interviewees with their open identity information can be found in Appendix F. In Table F-1, the personal profiles of the participants with their full names, the countries they were located, the organizations they were affiliated to and the positions they held at the time of interviews are provided.

A categorical evaluation of the interviewees can be seen in Table 5-1. Participants labelled with a number (P#) are not ordered same with the alphabetic name list already provided in Table F-1.

Table 5-1. Categorical classification of the interviewees.

Specification	Category	Number of participants	Share (%)	Participant labels
Years of experience (c-Si)	<15	7	37%	P5, P8, P9, P12, P13, P14, P15
	15≤years<25	7	37%	P1, P3, P4, P11, P17, P18, P19
	≥25	5	26%	P2, P6, P7, P10, P16
Location of recent experience	EU	9	47%	P1, P2, P3, P5, P6, P7, P15, P18, P19
	APAC	6	32%	P8, P9, P10, P11, P16, P17
	other	4	21%	P4, P12, P13, P14
Primary domain of current activity	private company	12	63%	P1, P2, P3, P8, P9, P10, P11, P13, P14, P16, P17, P19,
	RI, university, public organization	7	37%	P4, P5, P6, P7, P12, P15, P18
Value Chain (VC) segments of experience	all VC from ingot to module & PV systems	9	47%	P1, P2, P5, P6, P9, P13, P14, P15, P16
	all VC from ingot to module	4	21%	P3, P8, P10, P12
	rest	6	31%	P4, P7, P11, P17, P18, P19

Based on the years of experience in c-Si PV technology, the average was found 19.5 years with 9 years standard deviation, a minimum 6 and a maximum 44 years respectively. Though the lower limit was determined as 5 years, the final profile was much beyond it. When the sample was stratified based on the duration of activities in c-Si PV field based on <15, 15-24 and >25 years, the share of experts that corresponded to these groups were found respectively 37%, 37% and 26%.

Second, during the selection of experts, a certain level of geographical diversification was regarded since learning and its perception might differ due to location and national effects. The distribution of countries was so diverse. Therefore, they were clustered in regions. Based on the location where they carried out their current activities primarily at the time when the interviews were made, 47 % were from Europe, 32 % were from Asia-Pacific countries (APAC) and the rest 21 % was from other regions. However, excluding PhD level graduate studies[101] and including industry focused long-term close collaborations/consultancies, dense and frequent business or long-term research activities in the field of PV, more than half of the experts (53%) had worked or were working at multi-locations which were outside the current regions they were primarily affiliated during the interviews. Finally, 10 of the experts were somehow involved in relevant activities in China (53%) while 13 of them had experiences in Europe (68%) and there were only 2 experts (%10) who were directly experienced in the US at a stage of their professional careers in PV.

According to the primary domain of their professional activities, 63% of the interviewees were working at a private PV company while 37% were carrying out studies at a RI or university with a specific focus on PV. However, these ratios define the primary activities of the participants. A portion of the experts who were focused on commercial and mainly industrial business (12) were also affiliated to a RI or university as advisors or lecturers in PV (5). Also, 2 of the experts which were classified based on their primarily RI and university affiliation had recently been or were currently active in spin-off business. But there were also other interviewees which conducted close collaborative business with industry. Finally, 68% of the participants was experienced in the substantial part of the PV value chain, while 32% were only experienced in one or two steps.

Since the study was based on expert elicitations, the information attained was an extraction of their opinions, evaluations filtered from self-observations and experience in the field. The sample had a long-term expertise with an average of 20 $\mp$ 9 years, experience in diverse regions of the world as well as in different steps of PV value chain. It also covered both the industry and the academics of which weights were not closely equal but when hybrid involvements were considered it could be evaluated as fairly balanced. As a result, the length of the average years of experience can reinforce

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[101] Undergraduate and graduate level studies until PhD level was attained were not included.

validity of the findings while fair distribution of the sample in terms of the locations and domains of relevant activities can contribute to the reliability. This expert elicitation part of the research was not aimed at making probabilistic implications and the sample size may be relatively small but still the strength of the sample in terms of the features mentioned above can make the findings to be taken as indicative.

5.2.3. Framework for Analysis of Survey Results

The analysis of the interviews was implemented in three main steps. First, the interviews were transcribed.

Second, the transcription was examined analytically based on a manual coding technique. The answers given by each interviewee to each question were transferred to excel with the keywords or the phrases articulated by the experts. Then the excel file was secondarily evaluated by aggregating those indicators under common aspects which were evaluated as codes. The definitive indicators of these codes were able to enlighten the mechanisms related to learning and/or indicate the instruments of dynamics capabilities. Moreover, functions of PV TIS which were defined in section 3.5 were evaluated as another coding level as well. The underpinning guide was provided in Table 3-3. As a result, the codes with their corresponding frequency, their indicators i.e. the phrases that define these codes as well as TIS functions that consolidated all are given in the relevant tables in the following section.

Third, the parts in the text that described a situation which were found very inspiring in terms of understanding the complicated or distinctive mechanisms and could not be squeezed into codes or generalized statements were highlighted in the text for direct quotes to be used in learning and innovation capabilities discussions, functional dynamics evaluations and policy recommendations[102].

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[102] Though the approvals for the use of survey results were already got from the participants before

conducting the interviews as well as at the end of the appointment, the parts that were selected for direct quotes were sent them again and secondary permissions were taken for using their specific words

5.3. Results

In this section, the findings obtained from the examination of the expert interviews were provided. A detailed evaluation of the findings from learning and innovation capabilities perspective in overall as well as their relation to TIS functions are evaluated in the discussions following this section. As to the subsections below, the results that were obtained from the interviews were evaluated by using codes that indicated different dimensions that might have channeled the cost decline through learning or by aggregating the views within groups which somehow diverged between.

Some of the experts elaborated the factors or mechanisms that had an impact on the learning paths or their instruments with their narratives which reflected the codes comprehensively thereby providing a clear understanding. Also, some elicitations included distinctive examples that could widen the perceptions about the underlying reasons and/or provide solutions for the dimensions that were thought to have needed improvement. In the evaluations below, these parts of the interviews were quoted to reinforce the rationales behind the findings.

Though the frequency of the factors were given based on the keywords gathered under common codes, it was just to provide an impression about the prevalent mechanisms that were at a certain extent directly addressed. However, by the expert interview part of the study it was aimed at revealing the detailed underpinnings of the investigated factors rather than making a probabilistic implication like already was done by the econometric analyses, as well as finding out complicated and indirect effects which could not be identified easily when a structured inquiry was done. Therefore, the excerptions made contributed to convey these aspects which might not be short cut as keywords but might be worth considering comprehensively.

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directly which was told to be labelled with their participant numbers given in Table 5-1. After their review or direct approval, the ones who allowed were quoted in the text.

5.3.1. Findings regarding LBR

Despite guidance of technology readiness levels (TRL), the questions related to lag and duration of obsolescence of PV technologies yielded very complicated results due to the diversity of the answers based on the value chain steps, change of these values within time periods and the type of R&D activity. Too conditional responses were not taken into account since it was not easy to decide which value to employ ultimately. The interviewees were first asked to select a reference TRL for the R&D activities carried out in the PV industry. This question could not be answered clearly for the upstream steps by substantial part of the sample. But for cell and module, 17 and 11 of the answers respectively were clear enough to make an evaluation. The average of the levels was TRL4-5 for cell and TRL5-6 for PV modules and the standard deviation of each was 1 level. Based on the levels chosen, the type of R&D addressed here can be identified as applied research which focuses on investigation of new knowledge oriented to a defined purpose (OECD, 2015).

Then, the duration of reaching TRL9 was asked as an indication of lag for PV R&D oriented to product development. Since the final output was PV modules, the answers were usually given as from cell R&D to the finally commercialized PV modules. Only 12 of the answers were clear enough to be evaluated and the average was 4±3 years. Two experts told very high values around 10 years and when they were omitted, the remaining yielded 2.5±1 year. The obsolescence time was inquired as well for the depreciation factor. The answers were various again. But for the main technologies, only 6 out of 19 experts gave clear answers with an average result of 11 ± 4 years. Though the answers and their evaluation were somehow complicated, the findings did not differentiate from the ones found in the literature too significantly. In (Watanabe et al., 2000), the lag for PV R&D and depreciation durations were identified as 2.8 and 5 years respectively based on the surveys made with Japanese companies, while in (Kobos et al., 2006) 3 and 10 years were found significant based on the econometric estimations where a set of values were tried. However, the complicated answers revealed that these values should be handled very carefully since they may change too much unless the boundaries were defined very strictly for all dimensions that can variate.

In addition to those, the duration for the process improvement oriented R&D was asked as a separate question, which corresponded to experimental development that was defined as systematic work carried out by utilizing the knowledge attained through research and practical experience in Frascati Manual (OECD, 2015). The responses given by 13 experts were much more consistent and clearer when compared to the previous questions. As a result, the average value was found as 6 ± 4 months. This finding was well supported by participant 2 (P2) who explained this orientation with his own words below:

> This sector is a non-disruptive sector and has a very clear game play which embraces an evolutionary approach with small improvements… Every 15-20 years we have larger innovation steps … Innovation cycles were shortened to 5 to 7 years (from Al- BSF to PERC technology and from PERC to Topcon/HJT technology). We still spend money for innovations. But most of the fruits come from upscaling or incremental improvements. …We need a certain maturity level for bankability. It has to last 25-30 years, even 40 years for the final product. So, it makes us reluctant for aggressive innovations. Most of the innovations fail because of cost/Wp as well as reliability and thereby bankability.

Participant 16 (P16) addressed the similar attitude in PV technology by his following articulation:

> We are still making the same solar cells that we were making in the 1970s. In the late 1970s, the basic solar cell was based on multi crystalline 10x10cm square wafer and was screen-printed with silver and basically it was the same solar cells that we were making in 2010, almost 40 years later. Over 40 years, there was a lot of small or millions of small innovations and improvements that brought the efficiency from 10% to about 21-22%. But it was basically the same cell.

The factors that affected the required time for commercialization of these activities or the efficiency of R&D studies in overall were evaluated together. Despite a little nuance between them, mainly similar issues were addressed by the experts under these two questions. The indicative phrases extracted from the elicitations of the experts and the codes they were aggregated under were presented in Table 5-2. The indicator column built the base of the codes utilized, therefore they defined the extent of these codes. The frequency that was determined by how many experts they were addressed was provided in the table as well. In addition, the codes were gathered under corresponding TIS functions of which guiding definitions were in subsection 3.5.1.

Table 5-2. The evaluation of the mechanisms that facilitate or prevent efficient and faster utilization of PV R&D activities.

Functions of TIS	**Codes**	**Indicators**	**Frequency**
Resource mobilization	skills of human capital/knowledge of human capital	capability of the manpower; hiring senior consultants	13
	quantity of skilled labor	quantity of R&D labor	4
	sufficiency of financial resources	financial resources/funding	11
	infrastructural issues	flexibility of the manufacturing line to try new things for scale up; availability of R&D infrastructure	5
Entrepreneurial experimentation	existence of suppliers and their capabilities	existence and capabilities of suppliers to meet new material requirements; existence and capabilities of machine vendors to meet new equipment requirements	9
	critical mass of producers	Sufficient number of mass manufacturers; number of facilities that use similar systems; existence of a maintenance people/firms	7
Knowledge exchange	collaboration and knowledge exchange	collaboration with material suppliers/machine vendors; collaboration with RIs; dissemination and exchange activities; informal knowledge sharing; labor exchange/mobility; involvement of firm R&D personnel in mass manufacturing	15
Guidance of search	national/sectoral/firm level guidance	firm's strategy/orientation/dedication of managers; national plans; common sectoral targets	7
	IPR concerns	Weakness/violation of IPR protection; knowledge diffusion&development prevented by IPR	5
	IPR obstacles		
Guidance of search/ Legitimacy	market expectations	market match/acceptance; standards, regulations for new innovations	7
Knowledge development	educational system	relevant curriculum	2
	knowledge accumulation	many trials and patience	2
	technical requirements/ technological limits	technical issues (nature of process/technical limits/complexity of innovation)	9

Some issues gathered under codes were mentioned by the experts in detail. The cases that were distinctively elaborated and could be representative for the codes which were prevalently addressed were examined in detail through the excerptions from the interviews conducted.

Human capital

Effect of skilled human capital was found one of the most critical components for effectiveness of the research activities in PV. Participant 8 (P8) articulated it very clearly and briefly as follows: “Some good companies have very good engineers or universities research students like PhDs with very good background they formulate the technical core on which they make more process improvements or new products for their companies.”

On the other hand, words belonged to Participant 10 (P10) who was from APAC and working for a private company with longer than 25-year experience in the field revealed the effect of skilled labor which should have had sufficient knowledge to be able to solve the problem he narrated:

> We solved a patent case in 2 months. We already knew how to circumvent the patent. You can get some information from the old papers in the literature that people didn’t use in that patent. We tried it in the lab and then we went to production, and after a couple of months, the things worked. This patent was quite an exception for us.

Funding

The financial resources were found very critical too and their effect was elaborated with many different aspects by multiple experts. A different approach to availability and orientation of funding was articulated as follows by Participant 18 (P18) who was working in the EU with more than 25 years experience in PV. He emphasized that the funding schemes should have considered the risks in commercialization of proven PV technologies since it could not be easily dared by the investors even though higher level of TRLs were already attained:

> R&D is quite well funded by the support programs. But if there is no industrial player willing to step in and say that "I see the potential, I even go to a lower TRL4-5 and bring it up to a level where it can be really done", this research will not be transferred into innovation or the innovation will not reach the manufacturing site. Usually the companies are reluctant to take this risk unless they have to.…Therefore, for certain technologies there should be some risk facilitating programs to enable a faster transfer of these R&D results into industrial application. Public risk guarantees (not necessarily funding) to lower the financial cost of these steps could be a suitable measure. There should be a risk facilitating tool like this; in other case we have guarantees for export or currency guarantees e.g. the IMF is very successful at the moment in the deployment in Africa that they guarantee the investor you will get your PPA (power purchasing agreement) in US dollars and they take the financial risk if the local currency depreciates; then investor will be sure that they can focus on their core business but don't have to look into these additional risks.

Indeed, the reason behind the reluctance of industrial players as well as the private finance can be understood from the elucidation of Participant 2 (P2) who had more than 25-year experience in c-Si PV and was mainly located in a European country as well:

> The companies that invested in Metal Insulator Semiconductor (MIS) cells had serious problems since the contacts on cells were degrading and hundreds on megawatts went to the trash bin. Also, some thin film technologies in Asia that were installed at harsh climate conditions, their hundreds of megawatts went to trash bin after 2-3 years as well; since Standards Tests do not always show the truth, since they are more for Western type of applications. Even elaborated test conditions (proven at different conditions) failed. That led banks/financial institutions to be very strict for the maturity level of the technology. That is totally anti innovation.

Then, he added "…banks are not willing to fund new things in PV since they failed in the past. Equity investors want a success story with destructive super new technology but banks not."

From the elaborations above, it can be understood that not the amount of the finance is the only concern but also the type or the level it is available for is critical for PV. In sum, it should be noted that R&D intensity of the firms were found positively significant on unit cost decline. However, when the narratives about the hesitations or reluctance of the industrial players as well as the private finance entities to mobilize resources even for the new PV technologies that had relatively higher TRLs were considered, the companies that have been successful to realize commercialization of these technologies might have somehow accessed to public supports for their R&D activities. Regardless of the source of the finance, the attitude of the firms in terms of R&D spending or in other words, dedication to research upon the cognition of its impact was narrated by Participant 16 (P16) who had again more than 25-year experience in c-Si PV and was located in APAC region as follows: “There are some companies that have a great R&D lab in China”.

He elaborated his telling by mentioning a company in China which had shown how to do research to other companies according to him:

> A lot of engineers at X had left the company and gone to other big companies like Longi, Canadian Solar, GCL and Jinko. What they had learned at X was diffused throughout the industry. So, company X was a very good example of a PV company that invested a lot in R&D. Then the company had some point to realize that it should not have invested so much because all of the competitors benefited from our research. Because all of the engineers had gone to other companies. Then the company decided to slow down the work on R&D for a few years and then realized very quickly that they were losing their advantage. Now it is back into reinvesting a lot in R&D.

Relations between innovation systems actors

The existence of supply chain actors as well as the importance of interactions with them were the other factors that were found highly effective on success of R&D efforts. The mechanisms that could have facilitated the faster commercialization of PV research were explained based on the attitudes of interaction by Participant 3 (P3) who was from a European country with more than 15 years of experience in the field. He articulated:

> Very simple. This is why Chinese machine manufacturers have advanced so quickly. You need a very strong and intense cooperation between a solar cell manufacturer and the machine/material supplier. If you have a very fast exchange of this industrial data set with PV R&D community as well as to the suppliers of machinery or materials, then you are able to move faster. Companies that do manufacture of solar cells and have good findings, they keep their IP and are not willing to share. This is why industry moves slower than it could be if the faster exchange of data would be available. This is why the industry was developed quite fast in the beginning because the young industry where the manufacturers were a few and they strongly cooperated with everyone to improve processes. But today the landscape has become very competitive and this nice starting condition that we had in the beginning has gone. This is why R&D moves much slower than that happened in the past.

The interactions were also highlighted in terms of efficient use of R&D resources by Participant 5 (P5) from Europe with less than 15 years of experience in specifically c-Si but holding research expertise between 15-25 years dedicated to PV. He articulated it as follows:

> Companies are making their own R&D and product and maybe working together with some partners but everybody is doing this on their own and everybody in the end more or the less is working on the same technology or variations of this. This is how business work somehow; you want to keep your findings sort of secret but it means that you have a lot of people doing the same thing parallel… If there was more open collaboration, we could probably move much faster. It would be better if all these R&D expenditures and skilled people were not on small islands that were independent but they were in one big pool. We are spending probably not enough money for R&D today for the way that we are working. If we had spent the same amount of R&D money but everybody worked together it would be probably be enough to have much faster progress. Everybody is solving the same problems all over again. That is inefficient from money point of view also.

The resistance to knowledge exchange and incongruency in the pace of actions between the industrial actors in Asia and the research institutes in the West as well as how it ended up were narrated by Participant 10 (P10) with a case he had experienced. Indeed, this supports the excerptions from P3 and P5 above in terms of the outcome of European type of interactions:

> Sometimes it happens very quick. When you have an ingot, you make wafers by cutting the ingot like salami. That cutting was done with slurry, and as soon as the diamond wiring was in place we had the problem that we cannot etch these wafers very nicely so that you get very good light trapping. So, we were eagerly looking for ways to etch these very, very smooth diamond sawn wafers. And there was a race going on. I asked to the people in Europe ‘please you know how to do it from other projects because you had actually edge defined growth in 1980s/1990s; you know it from there how to etch, please give that recipes’. They were a bit slow in actually doing those experiments with our diamond wire sawn wafers and before they gave us a solution, we already had three solutions from Asia that would do it. Within about 4-5 month, there were 3 different companies offering a ready solution.

On the other hand, rather than core knowledge development activities based on basic or applied research carried out in the field of PV, the knowledge externalities from other related industries like semiconductor as well as innovation capabilities of industrial PV firms were found more effective in terms of leading to commercial PV technologies by Participant 2 (P2). Therefore, not only the interaction within the PV industry but also the relation of the companies to other industrial segments might have been influential on recording improvements in PV. According to him, many of the contemporarily commercial technologies could have been/could be developed based on firm level R&D efforts rather than the ones carried out by the PV research institutes. He explained it by his own words as below:

> Even if there was no scientific knowledge published/basic knowledge has not existed for PERC years ago the industry would do it since the time came to do PERC. For heterojunction, more impact did not come from any research institutes at the beginning of the life cycle of this technology, it was Sanyo and also it was stimulated by other sectors like display sector that we had large area coating machines available and we could apply them to solar industry what the semiconductor guys were doing it. …The neighboring sectors like semiconductor; MEMS; sensors; display, glass sector, PCB have had more serious impacts/more beneficial on improvement in PV industry.

Effect of refrainment from interaction and lack of open knowledge sharing between especially the Western RIs and the industry as well as the alternative approach between the Far East actors are partially mentioned here in terms of efficient research. They will be revisited again under the findings from directly LBI related questions.

Top down guidance

Another group of aspects that was addressed by the experts was top down guidance of improvements in PV at global, national and firm levels. Presence of a clear roadmap at sectoral level was articulated as triggering for innovations as well as to have had an organizing effect by making industrial players well aligned around the defined targets. It was mentioned by Participant 10 (P10) as follows:

> Someone who works on both electronic industry and PV just recently told me that electronics industry has a very organized roadmap. They know how much small scales they will go; the tool suppliers know what to do within years. It is a very steady planned thing. But he called PV chaotic since it is a very young industry where someone comes in with a new idea, puts it to practice and others will take it over very quickly.

The views of P10 above can guide the actors to be focused on the same target with well shared roles and tasks. Another dimension of this approach was addressed by P5 as mentioned in the excerptions made from his elicitations above about the efficient use of R&D resources which was depending on open exchange of knowledge rather than being isolated in the pursuit of individual success by allocating resources to similar efforts. However, it was also added by *Participant 10 (P10)* that even the knowledge and the future requirements from the industry side were revealed, there were still problems regarding the approach of the PV research community and the PV industry. He told how he confronted it in his quote below:

> They spend time on cell structures that never ever will have a chance to be commercially viable, even though people like me tell them in the plenary or introductory presentations at conferences in which I give as a senior. … It wasn't the problem that I did not get their attention. People listened to my presentation. But they did not go home next week and tell their boss 'he said we need a transparent passivating contact and he actually had the arguments why it is needed urgently'. That doesn't happen. At the whole community level, there is

> a quite different world between the research carried out by the research institutes and the universities and what is going on in the industry.

Similarly, P2 mentioned how the technology prospects of private actors and the PV research institutes differentiated below:

> By analytical skills and troubleshooting, research institutes can do excellent jobs like studies on Potential Induced Degradation (PID), Light Induced Degradation (LID), Light and elevated Temperature Induced Degradation (LeTID). The solutions are found so they can stop and do something else, but they still go on. The solution was found by the sector after 3 years but they still study it for 10 years and are digging into depths to find a small bite and making hundreds of PhDs and master theses after we already got the understanding.

On the other hand, P10 also expressed that reaching global climate change targets as fast as possible would be possible by having common goals and dedication to the same research agenda. He elaborated his impressions as follows:

> Many people work with really odd materials like indium. There is not enough of these materials to scale the industry up to TWs. We don't have enough scarce materials. I tell this at conference after conference. I show them a list of materials we cannot use for scaling PV up. Then you will get the papers afterwards that come out after these conferences. Quite a big proportion of these papers still use those materials. I wonder why we do have these materials while knowing that these materials won't be able to make a significant difference to the Paris Climate Agreement.

As a result, the incongruency of the agendas of the research entities and the industry which might have arisen from the differentiation between their motivations seems to have deteriorated the fruitfulness of R&D efforts or in other words might have decelerated the innovation in PV up to now. Therefore, setting common goals at global and/or national level and having a consensus at some extent through the solutions that would address the other handicaps might be promising.

In addition to importance of macro level guidance at global and national levels as addressed by a few experts with similar reasons, dedication of company managements to research activities was also highlighted. Participant 8 (P8) from a private company who was working primarily in APAC region but also in other locations of the world summarized it shortly with the words following:

> We see some examples in Chinese companies, they have a very good R&D will. They set up an institute which is like doing in house R&D like a research lab at a university. They have such a good commitment and it will really help them to keep on improving and becoming much better for the selected technologies.

Another perspective of firm level guidance was articulated by Participant 14 (P14) who was from a private company located in other regions than APAC and the EU. He emphasized not only the importance of guidance but also the functionality and quality of dedication. He elaborated as follows: “Firms may have some financial barriers in terms of making R&D but the R&D centers of private companies which are subsidized should be functional and the vision should be beyond ‘utilizing subsidies without changing the mindset’.”

Intellectual Property Rights (IPR) were also underlined by the experts mainly as a barrier to innovation in PV and thereby slowing down the diffusion of research outcomes. In addition, some suggestions were provided about how it could be overcome. These are related to the overall attitude of the community and therefore were associated to the guidance of the search function of TIS. Participant 2 (P2) explained the lower market share of c-Si technology variations in the past years though the technologies were proven with certain advantages against the conventional one (i.e. PERC technology) with the IPR obstacle. He told that:

> IP protection slows the process. Like Sanyo HIT (heterojunction with intrinsic thin layer) patent which caused this technology 20 years to roll out and SunPower IBC patent is the same. Even PERC patents caused fight between Hanwha QCells and Chinese players and slowed down the implementations especially in IP protected areas such as Europe.

Participant 16 (P16) gave the same example as well with his words below:

> One of the reasons that heterojunction is still a niche market product is that Sanyo and Panasonic kept it captive for so many years and didn’t want anybody to work on that technology. Same thing with IBC (Interdigitated Back Contact). Why is it a niche product and not a standard one in the market? It is because Sunpower kept that captive and never want the technology to share with other people. By the fact that PERC became a standard throughout the industry because of leaks, because of sharing, because of collaboration…Doing research is important, we need to do it.

He also discussed the both sides of the medal. As can be implied from his elicitations, while the lack of appropriation especially in China was crowding out R&D spending of PV firms, on the other side, fast and easy spread of knowledge it allowed had contributed to the knowledge development and decrease of costs. As a solution, he proposed establishment of national centers which would be funded collectively and research would be carried out for the sake of benefit of all.

> It would be great if there were no trade/IP/patent barriers between countries regarding RE technologies. That is the ideal world. What I found in the industry that it is very difficult to invest in R&D particularly in China because you spent a lot of money in R&D to realize that your competitors have stolen your ideas and then implemented that in the market faster than you. That is one of the biggest issues in China for the return on invested in R&D. It is good for the learning rate, good for the industry in general, it is good for the market, good for the climate change. But it is not good for the earnings of the companies. I think the best way to help R&D i.e. to have a national research center where many companies contribute proportionally to their revenue and benefit from the research. That is the best way to help R&D because PV is a very low margin business and it is very difficult to invest in R&D.

A more global approach to mitigate the international conflict between the Far East companies and the Western society because of the IPR concerns was proposed by Participant 10 (P10) with his words below:

> Many national research institutes are not allowed to collaborate directly with the Asian companies because they say you are only allowed to collaborate with the national companies. But there are no solar cells produced in Europe at the moment. So, they cannot. Let’s set up a fund that an Asian company donates solar cells to a project in poor countries. Then its value is paid by the Green Fund from the Paris Climate Agreement to you. So, you are not paid by Asia. You are paid from an UN fund. It makes possible to have funds to work with Asia. Thus, you can overcome the funding barriers which are very high in Europe.

To sum up, as can be understood from the discussions above, efficiency of the LBR activities were closely related to the following factors: skilled labor, availability of supply chain actors around, exchange of knowledge between as much as high number and variety of actors, requirement of financial resources and R&D spending even at higher TRLs, having common industrial agenda and research focus. It can be understood from the already shared quotes and the elicitations that the factors above were somehow associated with the routines in China and they were seen critical globally for the future of PV and its contribution to climate change. It is also noteworthy, either in the excerptions or in the remaining parts utilized for aggregate evaluations, rather than the core activities of knowledge development, supporting factors seem to have been more primarily concerned in PV.

5.3.2. Findings regarding vertical integration and LBI

Vertical integration

The responses given to the question oriented to understanding the effect of vertical integration on performance of PV firms were evaluated in three categories and the findings were summarized in Table 5-3 with the codes that directly define the reasons that underpinned the views of the experts. Reasons articulated by the experts corresponded to one or more relevant codes. One response was eliminated since it was not clear enough. One third (33%) of the participants thought being vertical integrated along the PV value chain provided a certain advantage that could not have gained otherwise due to the security of supply, control of product quality and the costs as well as providing a room for improvements. On the other hand, rest 67% thought either it had currently certain disadvantages or was partially effective but could be substituted with other solutions like joint ventures, strategic alliances where the main company was not mainly involved in the additional steps. The most articulated drawbacks were need of specialization at certain steps and high investment costs. However, there were very clear and distinctive descriptions about how it became ineffective while all experts including the ones that found it disadvantageous in overall were all aware of the advantages. These will be examined with the excerptions below.

Table 5-3. The evaluation of the reasons behind the effectiveness of the vertical integration

View	Codes	Frequency
yes	security of supply	6
	ease of improvements	
	better quality (internal)	
	lower costs	
partially	security of supply	9
	ease of improvements and process control	
	better quality (internal)	
	lower costs	
	possible through supply relations or JVs	
	need of specialization	
	high investment costs	
No	diminishing return of internal communication	3
	possible through supply relations of JVs	
	need of specialization	
	high investment costs	
	internal competition (departments blaming each other)	
	external suppliers have more knowledge development capabilities due to competition and connection to many customers	

Participant 9 (P9) who was from APAC region with his experience specific to c-Si PV slightly lower than 15 years but was involved in all steps of PV value chain, mentioned

hardship in management of vertical integration due to the divergence of focus and need of specialization. Having close relations with suppliers was found more preferable by him. He articulated it as:

> The question is if the management teams will be able to manage the very divergent set ups in integration. Only a few companies can set up such a divergence. The others are typically integrated in cell and modules. Whereas there may be some tie ups like OEM ties ups, Joint venture ties ups i.e. those things for their downstream and upstream. Within the same company having all these steps is becoming very difficult sometime. If you guarantee for supply or strong relation for upstream and downstream is sufficient you don't need to be vertically integration to take its advantage. Being in relation may help as well.

P16 mentioned the contemporary approach in PV industry and added that vertical integration might have been functional more than 10 years ago but the current trend was product differentiation rather than vertical integration upwards. He emphasized the need for specialization and did not consider it as a parameter of success with his own words:

> I compare the PV industry to car industry, they are very similar. A lot of people compare the PV industry to the mobile phone industry and that is wrong. It is not comparable. If you look at the history of the car industry what made Ford successful is vertical integration. At some point Ford was making everything in the car, it was making the tires, the engine, the body the chassis, absolutely everything in the car was made by Ford. Nowadays a car manufacturer is basically an assembler…. The car industry doesn't need to move this entire production to China to be successful. That is gonna happen in the PV industry as well. We see some signs. The vertical integration has been important 10-20 years ago. This vertical integration of the industry was very important to bring the cost down. It is not true anymore. Today big players like Trina has emerged larger capacities of making modules than making cells. They don't make wafers anymore.... They buy solar cells from other companies.…Trina makes the modules and that is the main product, they make cells also but that is not 100% of their need. They still have to buy…. It is a mixture of things but Trina also makes batteries, makes storage systems, makes invertors, makes ribbon, makes EVA, makes materials to integrate the modules to car roof etc. There has been aswitch from the vertical integration to horizontal integration…People will be more specialized in what they do best instead of trying to be vertically integrated.

The most comprehensive elicitation about the dimensions that could make vertical integration disadvantageous was made by P10. First, he addressed the competition between the external suppliers which had an inducement effect on their capabilities. Therefore, they were faster and better than the internal supply solutions. He articulated it as:

> The big manufacturing companies wanted to be vertically integrated. The thinking was ‘if we buy the ingot, make cells from the wafers cut, there is always someone making profit on the way and we save this profit by vertical integration.’… It turned out that is proved wrong because when you are a vertically integrated company you don’t have internal competition. … If you are not vertically integrated you have many suppliers that compete with each other … More people buy from them so things get better optimized. …. Based on my own experience, … company X gave up since it was not able to optimize it at a speed that the wafer companies did it. It is good for 2 years then you become more obsolete in your parts of your vertical integration because there is not enough competition in one company.

Second, he justified his view with the better interaction performance of external suppliers. According to him, in the same territory, the communication might not be as fruitful as assumed since the individuals within the same boundary might not be motivated at meeting each other’s expectations as much as suppliers from outside. He explained it in his quotes:

> Additionally, the communication internally in big factories like X, between the ingot and the cell people, wasn’t much better than with the external companies because the external companies are really keen on knowing how they can improve things to keep you as a customer and the internal people were not as keen to keep you as a customer because you are not a customer…The motivation is not good like in competitive market and it is not just company X, I also know many other factories. They also have the same problem.

Third, beyond inefficient communication, the possibility of internal conflict was another concern. Since the performance of the departments that were focused on different steps were linked to the upstream, any problem that could be solved collectively might also be an issue of others’ fault since the departments were probably much familiar to each other's vulnerability than the external actors. The quote regarding this aspect was given below:

> Actually, in many companies there are many problems between the cell and module producing departments. The module producing department needs a certain watt/module output. So, the people in the cell department improve the cells, and if the module people don't improve the module the cell people blame the module people. They say we make better cells but the module is not better, so it is your fault. But the module people say since you changed certain things, this and this in the cell, we cannot exploit that improvement in the module; it is not possible. … When you have a vertically integrated company you have many problems between different departments. It is just human. That is why it would surprise me if a vertically integrated company comes back.

LBI in general

One of the questions in the survey was directly related to the ways of interactions and their fruitfulness in terms of leading to improvements in PV technology and industry. However, as can be understood from the discussions above, role of different type of interactions in PV industry was already addressed in scope of the factors that affected the duration for commercialization of PV R&D and efficient utilization of research. Therefore, here it is revisited with more focused responses and the overall evaluation of the findings will be made in the discussion section.

The related survey question was designed in two main and with two sub steps under each. The interviewees were first asked to share their views about the interaction ways in their own territory for both the national and international levels and also to differentiate them for China if they had any idea except the participants who were Chinese. As a result, the general view about the type of national and international interactions in the PV industry and subsequently in Chinese PV industry were examined separately. The coding results similar to the factors related to the efficiency of R&D activities are provided in Table 5-4, Table 5-5 and Table 5-6 for overall and China versions respectively.

The ratio of the experts who were primarily carrying out their PV related professional activities in the European area was 69%. However, the only 3 of the remaining were located in China and 1 one of them was currently there while he had been in Europe for academic roles in the past. Therefore, due to the multi-regional activities of the substantial part of the participants, they were familiar with the overall attitudes in the industry. Moreover, more than half of the overall sample was at some extent at a period of their experience years in PV had been involved in professional activities in China (please see subsection 5.2.2. for more details).

Even though the investigation for the national and international level of interactions was differentiated for China and the rest of the world, many of the experts somehow addressed Chinese way of interactions even during the discussions about their own country. In addition, since the industry has been mostly located in China, rather than the current interactions they found fruitful in their territory, they referred to the past attitudes and the sides that they thought to have been positive and negative. In their own country scope, the experts emphasized the role of relations between different stakeholders especially with machine and material suppliers, formally organized knowledge sharing activities like conferences and trade fairs as well as bilateral relations between industrial players and research institutes through R&D projects, trainings and labor as efficient ways of interactions almost with equal impact at both national and international levels. On the other hand, the interactions arising from the presence of industrial unions/technology platforms were seen more important at national level. The other ways of interactions that were gathered under corresponding codes can be seen in Table 5-4. Similar to Table 5-2, the indicative phrases guided the generation of these codes. But as mentioned above, the elicitations of the experts were expressed in a more criticizing manner or focused on the desired ways rather than promoting the current interactions in their own countries as elaborated in the following quotes shared below.

Table 5-4. The evaluation of the ways of interactions in PV in overall

			Frequency	
Functions of TIS	**Codes**	**Indicators**	**National**	**International**
Entrepreneurial experimentation	Relations with manufacturers and suppliers/machine vendors	Collaboration with different stakeholders and their existence with sufficient mass/interactions with machine and material suppliers	9	11
Legitimacy/guidance of search	Existence of unions and official networks	lobby organizations/sectoral union/industrial unions	5	2
		technology platforms/common targets		
		Existence of a PV community		
Network externalities/ Knowledge exchange	Knowledge sharing activities (formal)	conferences	6	7
		trade fairs/exhibitions		
		sectoral workshops/panels		
	Knowledge sharing activities (informal)	informal meetings to share some ideas and comment	2	-
		informal conversations, relations to exchange of ideas		
		constant dialog and periodic meetings		
Knowledge development	Bilateral relations between industry and RI/univ	R&D projects	6	5
		Trainings by RIs		
		Access to skilled labor		
		Scientific and IPR oriented interactions		
Guidance of search/resource mobilization	Interactions with government organizations (vision/engagement)	Market strengthening/market implementation activities	5	NA
		National funding schemes		
Resource mobilization	Public funded supranational collaborations	Research programs	NA	2
		Networking projects		

P18 mentioned that the efforts were more oriented to bringing the PV industry back to the EU; therefore, the interactions between the equipment vendors and the research institutes were more frequent as he articulated. Because of the attempts to realize the innovations emanated from the European research institutes, their relation with the upstream machinery suppliers seems to have been critical in Europe as can be inferred from the excerption below:

> In the EU we had very strong interaction between the PV industry about 10-15 years ago with research institutions when there was still a considerable part of the production in the EU. Due to the fact that the most of the production industry has disappeared in the EU, now interactions are more between those who try to revitalize the manufacturing along the value chain so very often with equipment manufacturers in order to get the innovative processes from the research institutes into the manufacturing.

While the change in the way of interactions were explained through the disappearance of the industry in the EU in the quote above, Participant 1 (P1) evaluated it from the reverse perspective. According to him, the approach of the innovation system actors in Europe to collaborative relations and knowledge exchange was one of the reasons that paved the way to loss of industrial position in PV. He articulated it as follows:

> It is good if there is good cooperation between different stakeholders. In our country, producers, equipment/technology providers and research institutes; everyone wanted to keep it in secret, there were not good collaboration and communication between companies. It was not too much even when we had too many stakeholders 10 years ago. If it had been otherwise, it could have been helpful.

On the other hand, approach of Western actors to international interactions, was explained with a different perspective by P16 as articulated in his quote below:

> I know a lot of people in the R&D world. They wanted to work with the industry but they did not want to go to China. That's their decision. That is the way they want to see their careers. But I think it is important to go to China. It's like Silicon Valley in the 1970s, where you wanted to work on electronics, computers

> and integrated circuits. You were going there because that was where it worked, where you learned, where the other experts were, where you learned from your peers.

LBI specific to China

As to interaction ways and their effectiveness in China, at national level, the most prevalent ones seem to have been supply chain relations which were easily built due to having too many and high variety of actors as well as national conferences as a formal way of knowledge dissemination but more importantly informal peer interactions. On the other side, the most fruitful international interactions were the ones realized through technology acquisitions from the Western countries, overseas educations, by employing key experts from the world, attending international conferences or conducting R&D projects with other developed APAC countries and trade relations with the EU supplier and finally following the scientific knowledge developed outside the country. These are summarized in Table 5-5 and Table 5-6 with the corresponding codes, their underpinning indicators articulated by the experts during the interviews and the TIS functions defined in Chapter 3.

Table 5-5. The evaluation of the Chinese ways of national interactions in PV

Domain	Functions of TIS	Codes	Indicators	Frequency
National	Knowledge exchange	interactions between value and supply chain actors (corporate level)	strong network between nationally entire value and supply chain	13
			strategic alliances between Chinese companies	
			fast and open bilateral interactions between different stakeholders	
		informal/personal interactions	job change/labor turnover	8
			ease of labor mobility within clusters	
			lack of codes in knowledge sharing/no secrets	
			peer communication via Wechat	
			personal acquaintances	
			friend meetings/informal parties	
		knowledge sharing activities (formal)	frequent conferences in Chinese	5
			focused workshops in Chinese	
	Resource mobilization and guidance of search	financial relations with the government	national incentives	2
			public funded projects	
			financial supports from the local governments	
			interaction with the EU tool suppliers	

National level interactions within China seem to be very critical. But the most prominent one was informal communications and mobility of labor. P2 articulated both with his own words below by putting an emphasis on the culture that indicated lack of codes in sharing the knowledge that might be perceived confidential at another place.

> China is doing conferences in a very smart way. They mostly do specialized types of conferences on specific topics like PERC, pSi, new wafer trends and they are all held in Chinese language so that means the knowledge is kept inside the sector. Interestingly they share quite some details. I would not expect it. This

> is driven by the fact that the Chinese PV sector is much more connected. The reason lies in the culture of China. The people like exchanging knowledge with friends from different companies and share the latest results in their companies. Also moving of people is much more and faster than in Europe. Informal exchange which sometimes challenges IP limits by movement of people. That is speeding up the innovation in China very much.

Similarly, P10 underlined the trait of not keeping technological secrets in China as well and pointed out its impact on progress of PV industry. Also, he elaborated the reason that enabled easy transfer of people between companies which ultimately boosted the knowledge exchange. He somehow considered the social aspects of industrial clusters that provided a flexibility to the labor and contributed to dissemination of knowledge by keeping and transferring it within the industry.

> Within China, the national interaction is very important. Basically, in China you cannot keep a secret. What somebody knows will many of the people know too. It is how people collaborate in China. This has been very important for fast dissemination, for accelerating progress. Second element I see in China: many big factories are located quite close to each other. Even workers not just scientists, they can easily go to another company without relocating or losing their wider family. Due to these two elements of exchanging knowledge from company to company, even if they are competing, the work force is quite flexible.

Participant 11 (P11) from a private company in APAC region with experience between 15 and 25 years in c-Si PV emphasized the importance of national PV conferences in China which were held very frequently as an important source of knowledge flows. On the other hand, in the excerption below, he articulated how informal ways of knowledge exchange either at conferences or networking activities in China were more effective than the ones enabled during officially organized collaboration tasks in R&D projects. It is also noteworthy that he added the knowledge shared was not the trade secrets but the ideas.

> We can share some information; of course, this information is not confidential. We have many many conferences in China every month. Rather than formal project types, we share some ideas between the R&D guys in different companies. Not information, we just share ideas/comments at conferences, parties, while we are drinking.

Participant 17 (P17) with a similar profile with P11 addressed the informal knowledge sharing behavior in China once more. His elaborations also revealed that the transfer of codified knowledge might not have been as simple as it might be anticipated since there were some precautions taken against it. He articulated as follows:

> It is quite normal in China that people exchange ideas from different companies if they know each other for a long time, if they are friends. But for some core technologies like top secret recipes, I don't think they even know this even if they are in production line. For the recipe you can see the parameters on the screen of a doping furnace but many companies protect this know-how by modifying the parameters, by giving offsets; which means that what you see is not the true value. They input some parameters in the recipe settings, for example, you can give a factor for the temperature, a coefficient like 0.9. So, sometimes you exchange the ideas but you exchange the wrong parameters.

There seems to have been a consensus on the role of knowledge dissemination in development of PV industry in China. However, attributing too much importance on the effect of knowledge transferred due to violation of IPR and lack of codes in secrecy should be considered carefully. The last two quotes indicated that dimensions of the knowledge shared can be more complicated than the confidential codified knowledge which can spread easily in lack of IPR.

Table 5-6. The evaluation of the Chinese ways of international interactions in PV

Domain	**Functions of TIS**	**Codes**	**Indicators**	**Frequency**
International	Knowledge development	Purchasing machinery/technology	purchasing Western machinery	5
			technology transfer from the West	
			investing a lot in imported machinery	
		scientific/research activities	following up EU R&D	5
			reading papers	
			learning from international conferences	
	Resource mobilization and knowledge exchange	Hiring foreign professionals	transferring professionals for factory setting up & industrial culture/attitudes	3
			hiring foreign key scientific experts	
		Overseas educations	Sending people abroad for education	7
			Brain remigration	
			Overseas educations	
	Knowledge exchange	Two-way scientific/research interactions	projects with Australian/Singaporean RIs	7
			interaction with the EU tool suppliers	

The international interactions in China which were found most fruitful were more oriented to acquisition of knowledge through attendance to international conferences or less interactively following up the scientific literature worldwide, machinery imports or others official ways of technology transfer as well as by having education abroad, hiring professionals and developing it due to bilateral interactions with Australian/Singaporean institutes and European machinery companies. The evaluation of these mechanisms in terms of their relation to learning and roles in dynamic capabilities will be made in the next section. Below, the excerptions from the experts who articulated the international interaction ways that China utilized in the PV industry are provided. The capability of China in improving PV technologies and one of the instruments that might have contributed to it was articulated by P8 as follows:

> For China, they reach out and see other people's technology how they are doing and try to learn from them which can be the latest technology and how it can be possibly applied to the manufacturing process. This is where China is very good. … They also hire very good people around the world who bring their expertise to set up a factory or the culture for the manufacturing.

As seen above, P8 put emphasis on skilled labor which might have been an important channel to the capabilities that were well described in his previous sentences. On the other hand, Participant 11 (P11) elaborated why the interactions with the European suppliers could sometimes be ineffective compared to the fruitfulness of the domestic ones. As it can be inferred from the words below, the existence of sufficient number and variety of actors seems to have had a very positive return:

> Collaboration between Chinese companies is fruitful. It is easy to upgrade the equipment since there are many guys doing research so the response between them is so quick. Sometimes we collaborate with the EU companies but it is complicated. We communicate in hours and but it takes several days with the EU guys. When we make experiments, you need to spend a lot of time in the EU lab or company but in China it is very quick. Between supplier-manufacturer, machine vendor-manufacturer, also between competitors i.e. manufacturer-manufacturer we can share some information.

Finally, by P5, the machinery imports were found an important way of international interactions in China. But he admitted that presence of educational organizations and skilled labor were also effective in addition to availability of financial resources and the knowledge gained through purchases of Western equipment. In the end, as it was supported by his quote below, all these were successfully exploited by China which in the end yielded an outcome that made it a very strong actor in PV technology.

> But what they did was they bought a lot of equipment and turn key lines outside of China and built lots of factories and they started producing like that. When you start producing at this massive scale by buying equipment from the US and the EU, you of course after some time you gain a lot of knowledge including knowledge about equipment. Now they are building their own equipment also. Some people say they copy a lot. But it is more than just copying, it is also just gaining the knowhow and in a smart way. Everything fits together, they are also a very big country. They have also some very good universities and they have also started training well-educated people. They did it in a smart way. Starting from nothing and now they have everything in 10-year time. The way they did it is somehow since they had enough money to pay for everything they needed. We can do the same in the EU by working together, but not working by our own.

5.3.3. Findings regarding other learning or cost factors

LBU

Learning by using was tried to be investigated through a dummy variable that was generated based on the involvement of the firms in the sample in PV downstream applications. However, the data was skewed in favor of 1 and a significant result was not obtained. Moreover, since the econometric estimations were panel fixed effect, it was not sensitive to the effect of LBU between firms. Therefore, based on quantitative analysis, it was not possible to differentiate whether the firms that had involved in PV application activities officially had a learning gain compared to the ones that did not.

In one of the survey questions, ideas of the experts about the effectiveness of being involved in downstream applications was inquired by asking if they had beneficial feedbacks from such activities. Three of them had no idea, 13 of them told it had positive effect and 3 of them said they had positive impressions without direct experience. Participant 18 mentioned a software that they developed for users which was useful for the manufacturers as well since thus they could adapt their products to the expectations and requirements of the users:

> We also work on resource evaluation by having an open source tool where people can check what they can expect from a PV power plant or rooftop system

> in their location. This is again for safeguarding the interest of the final consumer but obviously it has also a feedback on the industry that they know they can or they have to apply the standards in order to be able to sell the product.

When the extent of improvements and the cost advantages are considered at system level i.e. the final cost of electricity, learning by using seems to have been effective as can be understood from the quote of P5 below.

> Normally when you are just in you are in the lab or in the production line and developing or producing the PV module you do not really realize all the things that can happen once it is installed somewhere. But if you involve in that part of the value chain i.e. downstream, you can learn a lot of things which can help to improve your PV module…If you only look at the PV module what you will do is you will try to lower the cost, increase the efficiency, the throughput and so on. But maybe the other things which at first sight do not really tell you much about if it is better to do it like this, might be better to do in the application.

However, as it was articulated by some other experts as well, the benefits were more focused on the long-term yield in the field based on the materials or designs modified and improved while it remained ambiguous whether they ultimately contribute to the decline in cost of PV modules. Nonetheless, substantial part of the experts thought that LBU was important and caring about downstream had a certain effect on developing better systems.

Effect of production labor

As to role of labor in PV module manufacturing costs which was not included in the econometric estimation in overall but investigated though skilled labor by using R&D employment as a proxy, 15 out of 19 experts thought it had no effect and 12 of the those 15 (80%) underpinned it with high automation in PV manufacturing. Also 9 out of these 15 experts indicated that quality of labor was still a concern. Among the rest 4 who did not share a clear-cut view about the quantity, 2 had no idea in overall while 2 of them thought quality of employees had still an effect. As a result, enhanced automation that was enabled through capital investments which increased within years seemed to have mitigated the cost of labor. P3 who was located in a European country and belonged to the sample group categorized with c-Si PV experience between 15 and 25 years explained the role of automation and its substitution of labor effect with his very definite description below. Thus, his words revealed that low labor cost could not be an argument anymore in terms of explaining the unit costs of final products in China.

> Labor force actually does not affect very much anymore due to high degree of automation. It plays a minor role in PV manufacturing today. In the beginning it was affecting at the beginning the quality and everything because there was a lot manual loading such as solar cell. So, skills of labor force were important. But modern lines even with AGV (automated guided vehicle) driven logistics, labor does not play any major role in cost in PV manufacturing. You could take any plant and put it everywhere in a world and exchange local labor force but you would not see a real effect in the manufacturing cost.

Moreover, one of the experts, P10 addressed the quality of labor in PV from a social perspective and elaborated how they reciprocally affected each other with his views below:

> For example, when we compare to textile industry, the workers there learn how to sew at home. So, if they cannot sew well they send them off and bring new ones. But in PV, people learn everything there and they are better valued and better treated. It is the main reason. This is why people in textile industry are treated very badly because they learn all the skills outside of the factory/the business. This is different in PV. Workforce has been treated much better in PV. I don’t have a bad social conscious about PV products. Because these people are valued and well treated. They have got long work shifts, they have got from 8 to 8 work shifts in China. But they are treated well as human, they have got good clothes, good food, they have got leave, etc. That increased the technical quality of people in time while the influence on cost decreased.

Effect of equipment investments

Effect of another parameter that was not included in quantitative analysis directly was investigated through the question regarding the capital investments for new machinery.

Learning by doing parameter employed in the econometric study intrinsically included annual capital investments since the rate of output was persistently increasing for substantial part of the observations. However, it was hard to distinguish it from the accumulated learning effect as well as from the scale advantages that was brought by new capacity added. Therefore, to understand if new systems and the technology they incorporated could have an effect on cost decline, the experts were asked to evaluate if any change in machinery could make a difference in cost and performance.

Substantial part of the sample (12 experts) thought either it had less or more effect, it was still crucial. Much part of this group i.e. 7 of the participants emphasized that gradual investments that could make small changes in the lines were at the heart of maintained cost decline in PV. The rest of this group i.e. 5 experts who gave conditional answers were also included in this group. They can be summarized as follows: 2 of them thought it could be critical but would have no meaning without the know-how and knowledgeable people while 3 of them told it was not required in the past but was inevitable due to the progress in manufacturing technologies or techniques that speeded up in recent years. Additionally, there were 2 unclear responses and 5 of the participants thought it had no significant effect that to be considered. However, some answers were prone to ambiguity since ‘what significant meant’ could change very dramatically. This was clearly understood from the narrative quoted from P10:

> There is a Chinese cell manufacturer. They actually are a fish processing company. In fish processing in China you have a margin of one percent to max 1.5%. You can understand how much their philosophy is on making things lean. Making the things/the processes very lean, the amount of people working, etc. These people entered into PV manufacturing market with exactly that mindset. Of course, they can compete very well.

This finding was somehow supported by P9 as well who mentioned different capital investment attitudes between Chinese and Western PV companies. He articulated that:

> In China they never change the whole lines. They would like to maximize their investment to as many years of productivity as possible. So, they are using the same existing equipment by doing incremental improvements or by adding one or more additional tools. In between; if they can keep using the same equipment, it is the best. That is the China and India model. In the EU and US, they remove the whole line and put a new line. In the decreasing cost market of solar, the US and EU model, just replacing the whole line with something new/new technology lines, is no more productive or economic. So, the Chinese or the Asian model of doing incremental changes in the existing line only, is more advantageous.

As a result, similar to labor, capital investments might have a minor effect in short term when the answers given to the duration of obsolescence of PV technologies were considered as well. However, like the quality of labor, the contribution of the incremental changes in the equipment gradually might have had a learning effect by being related to certain determinants of dynamics capabilities owned by the Chinese PV companies. They will be revisited in the following section 5.4.

5.3.4. Findings regarding auxiliary questions

The issues inquired through the questions categorized as auxiliary can be summarized as: orientation of R&D activities; difference in the quality of PV modules, anti-dumping measures against China and future of c-Si technology.

Orientation of PV R&D activities

For the orientation of PV R&D activities, four options were provided to the experts and they were asked to evaluate them in terms of their contribution to the cost decline in PV module technologies by giving a free space for discussion of additional topics that they found effective and important. Among the participants, 4 out of 19 experts did not make a clear selection or mentioned that all are important. For the rest, 4 of them ranked the decrease in amount of or replacement of materials and efficiency improvements equally too important while 4 selected the former and 7 selected the latter as the most important tasks for R&D. As a result, device conversion efficiency-oriented research and then material improvements were found most prominent by the experts in the sample. The third and fourth topic were related to process yield enabled by process optimizations and the enhanced throughput based on new machinery designs respectively which were both found more industry and mass production related and in overall were not highlighted as much as the first two. Moreover, the participants proposed other topics that were found prominent and should have been taken into account in R&D portfolio. These were presented in Table 5-7 below.

Table 5-7. The additional topics that should be considered in PV R&D

Additional tasks for R&D	**Frequency**
reliability (long term performance)	4
power yield	3
environmental footprint	3
product diversification for different applications	2
localization of exported materials	2
novel materials	1
product format (size, thickness)	1

Relation of quality of PV modules to cost decline

The quality of PV modules manufactured in China might have been a factor as well that had affected the decrease of costs in the recent years. In addition, as seen in Figure 2.10 (please consider the logarithmic scale) and Figure 2.3, by 2011 China had been an important market for installations as well after almost one decade of its leap as a manufacturing actor. Therefore, in the relevant survey, the quality was intended to be inquired in terms of this aspect whether the growing market in China had caused the module costs decline due to quality requirements defined for domestic use. After eliminating 4 experts which had no idea, 9 of the 15 experts thought there were no difference between the Chinese modules sold to the West or used in the Chinese national market. The rest did not give a certain yes or no answer but told that might be.

The main justification who thought no difference was availability and common use of international certificates for PV module quality assessment (e.g. certificates based on IEC, UL standards) for many of the big companies. Therefore, according to P16 even if there had been a difference, it might have happened because modules that were sent to different regions could have a different bill of materials list due to climatic conditions but still it did not necessarily mean lower quality. On the other hand, P9 indicated that by excluding big reliable suppliers called PV Tier 1 PV companies, it could have been possible at Tier 2 companies since it was possible to find modules in the market with different levels of quality. It was not directly related to the destination of delivery but could be explained with the requirement of modules to be sold to anyone who wanted to buy at a lower price. However, in his following quote, he also articulated that there were always side ways:

> Though there are standards or various safeguards especially in the PV industry like IEC certificates, CE labels etc., always there are methods to certify those things without violating those and then sell. It depends on what you pay and how tight are those contracts. But in case of there are opportunities they export to low cost countries then they may do outsourcing of their production within their brand name. So, there are various matters within the IEC also. You can do co-branding, you can do co-manufacturing, outsourcing. So many things are available. They may do the manufacturing in some Tier2 Tier3 companies, and then export it at a lower cost. There may be smart differences in what they did but then you differentiate the contract in that case. What you're are able to impose regarding the problems that you may face in the future.

In sum, it seems that the quality of the PV modules in the contemporary period and for the large corporations with certified products was more related to differentiation of the need and sources. Therefore, relation of overall cost decline in PV modules with decreased quality due to change in market destinations did not find a strong support in the qualitative investigation. Nevertheless, there might have been some micro cases where the quality was decreased when low cost products were intentionally demanded.

Effectiveness of anti-dumping precautions

Another question was about the anti-dumping sanctions against PV products manufactured in China. These tax measures were applied against Chinese PV modules in different regions of the world which were led by the implementations of the EU and the US enacted in 2012 and 2013 respectively (European Commission, 2016; U.S. Department of Commerce, 2012). The experts were asked to evaluate if these precautions had been beneficial for the domestic manufacturing in these regions. Shortly, none of the experts thought they had been totally effective in the past and regardless of the effectiveness in the past, 11 of the participants believed that they could be made functional by implementing reinforcing solutions like promotion of local production or replacing them either with carbon tax or higher tax rate. On the other hand, 8 experts thought these tax precautions were totally obsolete, unsustainable and ineffective anymore. P9 elaborated his views about the functionality of these precautions with his words below:

> They were not so successful since they were not implemented in a desired commitment level in those countries so local manufacturing did not get any help. The anti-dumping is not one word alone, there are so many subpoints in that. If they are done very properly then it is going to help the domestic manufacturers in any country but if it is only done for some cosmetic purpose then it will not help.

On the other hand, P11 articulated how these precautions had contributed to cost decline and functioned as a triggering force for learning in China. He articulated that:

> Indeed, anti-dumping process was very helpful for Chinese guys. This led Chinese guys to improve the product performance to decrease the cost, to optimize the supply chain. We did new machines, made process optimizations, expand the capacity, have the whole supply chain and do many many equipment improvements to decrease the cost.

Participant 7 (P7) who had more than 25 years of experience in c-Si and working for a research institute/university in Europe, supported the view of P11 in previous quote in terms of positive effect of these measures on Chinese industry. But as seen in the excerption below, he also added that availability of finance and its mobilization with low costs had been very vertical in this success.

> Because the anti-dumping succeeded in making China very powerful but also having economies of scale that came as a reaction of cost. I am not an expert with no means of economic aspect but I can say this is not only about PV this is also about the finance in EU and China and it is a general problem. You have an infinite funding and a very cheap one in China. Then for us here, it is difficult to compete.

Finally, P2 told his views about the requirement of these precautions though they have not been effective in the past. He articulated his approach in the quote below:

> It should be an international attitude to respect international rules on IP, rules of financing, cost transparency and some social implications, respecting countries' companies, research institutes to impose the same level playing field for everybody.… when it is not on the same rules then we will have very strict walls.

As a result, despite not being certainly beneficial for the countries that implemented these measures, they seemed to have been effective on cost decline of PV modules with other complementary factors.

Future of c-Si technology

The thesis study was mainly focused on c-Si PV technologies which have dominated the market with a substantial share from the beginning. However, knowing how it would evolve could be guiding in terms of orienting the learning mechanisms or the innovation capabilities and considering the functions of TIS investigated in this study accordingly. The future of alternative materials that could replace c-Si or be utilized together with c-Si in tandem structures was inquired and the experts were asked to evaluate the potential materials in terms of their advantages and disadvantages.

Among all, 2 of the experts were relatively optimistic about the combination of new materials i.e. perovskite with c-Si. While 1 of them believed that in five years tandem structures might come out, other said tandem would be very soon demonstrated by the companies. For the rest of the sample: 7 were conditionally hopeful about the future of perovskite-silicon tandem if problems related to technological performance (conversion efficiency and stability), material issues (like presence of lead in the main structure of perovskite material) and sustainability were solved properly. Moreover, knowledge stock accumulated in c-Si PV and the cost advantages it held were articulated among the barriers in front of new structures even they were combined with silicon. In addition to those relatively or partially optimistic views, based on the same reasons mentioned above, 5 experts thought that at least in 10-15 years, full replacement of currently available c-Si technologies in the market with a new one or their use in large applications would not be realized. Finally, 5 of the experts were totally negative without elaborating the reasons too much but only one explained that it was more important to focus on carbon footprint, sustainability and increasing the lifetime of current technologies rather than dealing with new materials either in tandem or alone. In sum, 9 of the participants were conditionally or optimistically hopeful for the perovskite/c-Si tandem structures and 10 experts thought either they would not be widespread at least in one and a half decade or go beyond very niche applications.

The elaborations of Participant 7 (P7) below described the c-Si technology lock-in very clearly and articulated the mechanisms that channeled learning existed in c-Si PV technology as well. The excerption below explains why most of the experts were hesitant or did not believe a new technology in near future.

> Apart from the standard PV products there is a quite range of options like niche market. As tailored modules, the companies already differentiate the modules for utility, for commercial, for residential and even for integration. There you don’t only think of just the cheapest euro per kWh, there are other considerations like statics, flexibility for other applications…Si is already in a situation that is a very mainstream technology which is very difficult to replace because of economies of scale because the developments that so many people are focused on thinking on, invest in R&D and innovations in there. It is just the niche market

> that you can propose an alternative. I don't promote perovskites…. Perovskite on its own, it would be very difficult because of the scale and you will not be able to compete with the cost of Si because of the learning that Si accumulates.

5.4. Discussions

In the first subsection below, the contribution of the findings to understanding of learning mechanisms and innovation capabilities were discussed. Subsequently, the factors that caused or triggered the PV TIS functions to be hindered or facilitated were identified and evaluated in the next subsection.

5.4.1. Contributions to Further Understanding of Learning Mechanisms and Innovation Capabilities

In the quantitative part of the thesis study, three learning patterns were investigated directly via the precursor activities that were assumed to ultimately have channeled them or indirectly by interpreting the joint outcome of multiple variables that indicated internal efforts and external stimuli. The impact of these variables was evaluated based on their statistical significance in the models. Also, the presence of some innovation capabilities was inferred from these findings. In the qualitative part of the study, elicitations of the experts regarding different learning mechanisms and potential cost decreasing factors were examined. In this subsection, the qualitative findings above will be utilized for evaluation of the validity of the different dimensions of the learning patterns examined in the econometric models and the dynamics capabilities they were associated with. In addition, the complicated ways that enabled them will be discussed based on the narratives revealed by the experts.

LBD effect was not addressed directly in the interview questions since PV LCs based on cumulative production or installations have been a commonly utilized in tool industrial roadmaps or sectoral reports which many of the PV community was assumed to have been familiar with. However, as discussed in different sections and subsections of Chapter 3 (please see section 3.1 and subsection 3.3.2.4), LBD could be considered much beyond the learning that came along with the static output accumulated. Since the aim of the qualitative part was somewhat unveiling the overlooked or underestimated mechanisms behind the cost decline, these parts of the learning pattern were intended to be investigated instead of directly asking if cumulative output led to learning.

Since, the annual capacity employed in the sample of the quantitative study was continuously increasing for substantial part of the observations, the new machinery investments were already included in the LBD parameter. Moreover, similarly scale could not have been investigated separately in the quantitative analyses because; first, when return to scale coefficient was assumed 1, the output parameter was dropped from the cost equation; second, using the output did not make sense because there were a variety of plant scales at firm level due to multiple facilities embodied which might have been at optimum size inside; third, furthermore, the overall output itself was highly correlated with the LBD parameter which was generated by adding the annual output. As a result, both the scale effect and the new technology investments was somehow covered by LBD. Even if the scale effect was introduced into the model as it was done in different studies which assumed a common value based on the industry average or trends, at firm level it would cover the new investments as well and prevent its effect to be unveiled. Therefore, neither LBD (when the output was not static and no changes were made in the infrastructure) nor the scale effect alone can be isolated from the knowledge and learning stimulated by the technologies that comes along with new machinery.

To verify the anticipations above, the effect of equipment/machinery investments on the performance or cost of PV modules were inquired and 15 out of 19 experts had found equipment investments effective on performance and cost decline, while 12 of them emphasized the importance of gradual and incremental changes rather than the big investments that created great changes at once. Moreover, the elaborations of two experts which revealed the difference of understanding and approach in Chinese firms in terms of making capital investments were excerpted in subsection 5.3.3. It can be inferred that instead of great margins Chinese persevere on small gains and can remain upgraded with persistently made small steps. Since the sample employed in the econometric analyses was mainly composed of Chinese firms or the ones that had manufacturing facilities mainly located in China, the significance of LBD effect measured by accumulated value of annually increasing outputs cannot be only reduced to learning that emanated from repeating activities.

Moreover, as mentioned in section 3.4, new knowledge brought along by the equipment investments can be an instrument for developing firms' absorptive capacities i.e. the ability to sense, understand, transform and exploit the external knowledge which ultimately leads to innovation. Therefore, the jointly significant outcome of LBD and time trend or efficiency value may be related to the contribution of new equipment for embodying the external knowledge. But path dependency as one of the determinants of dynamic capabilities may deteriorate the process if many parameters in the environment change simultaneously since it becomes hard to make adaptive experiment and develop cognitive abilities and as a result, hinders learning. This supports the elicitations in the excerptions referred above as well. The effect of gradual and incremental equipment investments and the success of Chinese to extract a benefit from it may depend on the balance in between being insistently upgraded and keeping the pace sufficient that allows accumulation of knowledge and improves learning.

Finally, in subsection 5.3.3. it was mentioned that 2 of the experts gave conditional answers about the impact of capital investments on cost and performance. The requirement for skilled labor and knowhow were articulated as the conditions to create this effect. Moreover, in the results obtained from LBR related question in the survey given in subsection 5.3.2, involvement of firm R&D personnel in mass manufacturing was found as one of the factors that made research activities efficient. These findings indicate the relation between LBD and R&D employment parameters which resulted in joint significance in the econometric models. Moreover, in Table B-1 in Appendix B, R&D labor did not yield significant result when LBD parameter was replaced by time trend while it was significant when all three were included in the model (please see Table 4-9). Thus, it seems that contribution of R&D labor is strongly related with the new knowledge arrived through equipment investments and accumulated through production. It was also addressed in the description of dynamic capabilities that R&D labor can be an indicator of absorptive capacity. As a result, both equipment investments and R&D labor can contribute to improving the dynamic capabilities within PV firms by means of which they acquire, assimilate, transform and finally exploit the external knowledge.

LBR was investigated through R&D employment and R&D intensity parameters in the econometric estimations. R&D labor and R&D intensity can both be the instruments that enable the development of dynamic capabilities. Firms can recognize, transform the knowledge outside through its abilities improved due to the research work they carry out. R&D expenditures can capture the amount of these efforts while R&D intensity which is normalized against net sales can indicate the level of dedication to these activities as well. On the other hand, R&D employees which were assumed to be the main source of skilled labor enable sensing and understanding phases of new knowledge absorption mentioned above by utilizing the embedded skills/competences and its transformation through the learning they gained due to their communication with external actors and interactions with the internal production team.

The joint significance of both variables with the dummy variable that defined the years after 2011 when China had reached to more than 50% market share in all steps of PV module manufacturing chain as well as with time trend and industrial average power conversion efficiency of PV modules which were utilized as indicators of overall external progress and improvements in the technology performance was interpreted as the presence of absorptive capacity in the firms examined.

On the other hand, in the elicitations of the experts regarding the mechanisms that could make R&D efforts more effective and facilitate its faster commercialization (please see Table 5-2), the most prevalent factors articulated were related to labor skills, availability of sufficient funding but also existence of suppliers and other actors in manufacturing, formal/informal knowledge exchange/dissemination and collaboration activities. The relation of LBD to R&D labor was partially addressed in the previous part. However, LBR seems to strongly relevant to the LBI factors based on the qualitative study as well. Therefore, the evaluation of LBR factors is somehow intertwined with the survey findings related to LBI.

As indicated above, labor skills were the most frequently articulated factor for PV R&D. The effect of production labor was inquired in another question and 12 out of 15 experts who gave a clear answer to the relevant question indicated that the labor effect was ignorable since PV had been a highly automated industry and by 9 of these 15 experts, the skills of PV employees were still found critical though it was not seen as a burden on cost. In his elicitation quoted, P10 narrated how people working in the PV industry in China were behaved well due to their skills and as a response how they were contributing to the technological improvements in the field. As a result, despite labor was not an effective factor, the qualitative findings supported that the learning that skilled labor channeled seems to have made it a critical instrument of LBR.

R&D employees which were assumed to be the main source of skilled labor were found effective on cost in the quantitative part. As to how the skilled labor is mobilized or the skills were improved in Chinese PV firms, the responses of the experts to the question regarding the LBI dimension (please see Table 5-6) revealed that at international level, abroad education or hiring foreign people were highly favorable and articulated by 10 out of 19 experts. As excerpted from P8 in the relevant discussion, the expertise and the working culture that the foreign experts brought along were respected.

At national level, interactions with supply/value chain actors and informal communication/knowledge exchange at unofficial meetings and through labor mobility between peers were the mostly articulated effective ways. P10 had elaborated in his quote that the geographical proximity of PV firms due to clustering was a facilitator for mobilization of employees which let flow of the industrial knowledge. However, it should be considered that the econometric estimations yielded significant results for R&D labor with 2-year lag. Thus, it can be concluded that R&D employees in PV firms become effective after 2 years. As a result, the circumstances in the PV firms that exploited the skilled labor might have attained an optimized position in terms of the knowledge gained through the mobility and the learning effect or absorptive capacity benefits that the R&D employees endowed.

As mentioned above after the years that China dominated the PV value chain, decline of PV module costs was found higher compared to the years before. On the other hand, interactions with suppliers were found as the most effective way of interactions at national level for China as well as for both level in general scope for all regions (please see Table 5-4). Thus, the effect of number and variety of entrepreneurs as the innovation system actors were strongly supported by the qualitative findings. Supply chain relations can be associated with improvement of dynamic capabilities which can be triggered by the partnerships/alliances and the conditions in the surrounding environment as mentioned in section 3.4. Moreover, shown in Table 5-2, the existence of sufficient number of value chain actors and interactions with them were listed among the highlighted factors that made R&D activities efficient. As a result, research efforts and R&D labor as the prominent instruments of research in the Chinese PV companies as LBR proxies and the interactions with the simultaneously flourished domestic production environment along the whole value chain seem to have facilitated an efficient LBI that ultimately led to improvement of dynamic capabilities.

Availability of funding and dedicated to research through guidance of the management or the policy makers in PV were the other dimensions listed in Table 5-2. As addressed above R&D intensity embodies both. It requires mobility of resources as R&D expenditures but since it is normalized to net sales also it can also be a measure of level of dedication to research. Therefore, its significance in the econometric models is not unexpected and is supported by the qualitative findings. In his quote, P16 elaborated how funding was important and the PV firms even when they had appropriation (i.e. exploitation of IPR) concerns did still continue to invest in R&D in China. It was also mentioned in the excerptions made from both P18 and P2, how firms and private finance entities were not willing to spend money for the development of the technologies that had even reached to TRL 5. Therefore, the firms examined in the sample which had a certain level of R&D intensity and exploited its advantage on decreasing their costs, might have got public support which was not easy to identify from the company filings utilized. The availability of finance in China and its influence on the industrial improvement was already addressed in some of the quotes utilized in the previous section under different learning dimensions. Indeed, in the quote of P18 below it was somehow explained again:

> Finance! This is probably one of the reasons why the technology progress in China or the Southeast Asia is very fast because there is a dedicated industry and policy gives it priority for the administrative processes; whereas in other countries like India, very often the regulators are not aware what they really have to look into, what are the critical issues and that financing availability can be an issue.

According to survey results, conferences or access to codified knowledge had equal weights in terms of their frequency of articulation as efficient ways of national and international interactions in China. However, as addressed above informal relations were more favorable at national level. The external knowledge represented by time trend and industry average of power conversion efficiency of PV modules which were found to have a significant effect on cost somehow should have been brought to the firms. In his quote given in subsection 5.3.1, P10 narrated that they had solved a patent issue in their company by referring to studies in the scientific literature. As elaborated in other excerptions made from P2, P16 and P10 in the subsequent text and based on the overall evaluation in the same subsection, knowledge leaks due to IP violation and lack of codes for secrecy in China were addressed as reasons of fast knowledge flows. This exchange might have either been enabled through formal or informal interaction mediums where flow of codified knowledge or well-defined trade secrets was implied. But on the other hand, it was also elaborated by P11 and P17 in their quotes shared in subsection 5.3.1, respectively the Chinese guys shared ideas rather than confidential information and even if they intended to do it unofficially, there were smart barriers. R&D intensity and R&D labor might have channeled the transfer of codified knowledge at a certain extent but the impact of close and open interactions through informal communications in China which were emphasized most frequently by the experts should not be reduced to confidential knowledge leaks which can spread easily in lack of IPR. As addressed in section 3.4, networking activities, meeting at the events were other enablers of absorptive capacity. Therefore, rather than the dimensions and type of the knowledge shared, the contribution of these LBI activities together with the components of LBR should be considered from dynamic capabilities point of view as well.

Vertical integration was also another factor that was interpreted from interactions point of view. In the quantitative part, the firms were found to have been more vulnerable to raw material crisis when they were vertically integrated and for the rest of the time (when the model was controlled for the crisis year), it created no difference. Nevertheless, it indicated that the any learning effect arising from being integrated did not exist. Maybe it might have provided a certain level of security for some firms and their survival but among the ones which survived as in the sample it did not brought any cost advantage. The relevant question in the qualitative survey yielded in favor of strategic alliances and specialization rather than being vertically integrated. The findings were summarized in Table 5-3.

The views of many of the experts were in favor of not being integrated since it was not useful or the advantages it brought along could be substituted by other solutions which would be more effective. It was articulated by the experts that handling a diverse range of activities within the PV module manufacturing value chain was a great problem. Also, as elaborated by some, the internal communication was not efficient and the external suppliers since they had contact to other customers were more competent to find solutions and make improvements. It was elaborated thoroughly in the quote of P10 given in subsection 5.3.2 that the fruitfulness of the communication between internal departments was diminishing after a certain point and the competition of the external suppliers as well as their focus on specific steps were making them superior innovators. Indeed, his words were almost perfectly compatible with the theoretical foundation built in section 3.4 based on (Teece & Pisano, 1994) and (Fagerberg, 2009).

Shortly, the existing coherence and complementarity between processes were not easily changed and moreover prevented the external knowledge to be absorbed. As a result, despite transaction advantages, vertical integration might not be fruitful in that sense. The most favored aspect by the experts instead was having competent actors in the national supply chain and establishing strong relations with them. Thus, first the reasons behind the quantitative finding related to vertical integration were enlightened; second, vertical integration was found to make a blocking effect on dynamic capabilities when compared to strong relations with the variety of actors in the value chain in case they are available.

LBU which was not inquired quantitatively but in the qualitative part of the study revealed that it had definitely a positive effect at least for PV systems. Since it was not easy to distinguish if it was only at system level or could be valid for the PV modules, learning attained by using the end product (PV modules) in system applications can be seen a learning pattern that has a broader effect than improvement of the cost of PV modules.

Finally, the findings regarding the anti-dumping measures can be interpreted from dynamic capabilities point of view as well. Indeed, it was clear that China had been successful despite these precautions. Though experts associated it with the availability of finance and violation of the social and trade rules in China, especially the words of P7 and P11 are worth considering in terms of the influence of external stimuli on the improvements as far as the dynamic capabilities of the agents are strong enough and there are sufficient channels to mobilize them. China seems to have exploited all assets defined under positional determinant of dynamic capabilities in section 3.4 very successfully. But especially in terms of anti-dumping response, the locational assets which could provide either positive or negative effects might have been reverted from negative to positive by China through developing new locational advantages domestically as well as managing its complementary, financial, and technology assets in a very clever way through creation of a whole value and supply chain, clustering, mobilizing central and regional funds and benefiting from abroad education, foreign trade and international knowledge base.

5.4.2. Evaluation from PV Technological Innovation System Perspective

It was mentioned in section 3.5, since this study was mainly structured based on the LC theory as well as the innovation capabilities improved through learning activities, rather than a systematic analysis of PV TIS, functional dynamics approach was just intended to be utilized as a complementary part of the study. The elaborations of the participants in the qualitative study indicated some hindered and facilitated parts of the PV TIS functions and the mechanisms that caused them. The issues articulated by the experts most often corresponded to mainly different dimensions of resource mobilization, guidance of search and entrepreneurial experimentation, knowledge exchange/network externalities. Usually the attitudes and actions in China were emphasized to have led these functions to work fruitfully while the reasons that caused other regions to have lagged behind were associated with the same as well. Knowledge development was not too prominent but rather it was addressed in terms of the mechanisms that enabled its transfer and absorption more. The status of PV in terms of radical knowledge created was already described in the first excerptions made in subsection 5.3.1. Market formation was rarely on the focus of elicitations since it was not a concern for c-Si PV technology anymore. Legitimacy was not often addressed either except some issues like availability of standards and regulations. Since the findings regarding the last two somehow corresponded to both, the last two were evaluated together.

The qualitative findings that were discussed in terms of learning patterns and dynamic capabilities in the previous subsection are examined here from functional dynamics framework. Indeed, in Table 5-2, Table 5-4, Table 5-5 and Table 5-6 where LBR and LBI effects were examined, the findings were preliminarily aggregated under the functions that they corresponded. In this subsection, all findings are evaluated collectively and the prominent mechanisms that were identified to have a blocking or inducement effect on the PV TIS in overall or in specific regions are summarized. The evaluations are presented in Table 5-8 below. Since they depend on the only quoted narratives of the experts or the coded findings discussed in the previous section, they are not explained once more to prevent repeating work.

Table 5-8. Evaluation of the qualitative findings based on functional dynamics framework

Functions	Inducement	Blocking
Resource mobilization (finance)	• Availability of public resources in China with low rates • Support of local governments in China • Public funded projects	• Unwillingness of private finance to invest in products that have unproven reliability in the relevant environment • Refrainment of industrial actors in R&D spending due to IP concerns and knowledge leaks • Lack of awareness in governments except China about the requirement of finance for PV technology improvements
Resource mobilization (labor)	• Availability of skilled labor • Studying abroad or student exchange programs for PV in China • Hiring foreign PV professionals in Chinese companies • Easy mobility of labor/job turnover within PV clusters in China	• Inexistence of appealing medium for keeping skilled labor (regions other than China and Europe)
Resource mobilization (infrastructure)	• Existence of production lines in China suitable for the commercialization of outcomes R&D	• Inefficient use of R&D infrastructure globally.
Entrepreneurial experimentation	• Sufficient mass of value chain entities in China • Presence of all supply chain actors from materials to machinery in China	• Though there were upstream machinery equipment suppliers, lack of PV module value chain manufacturers in Europe
Knowledge exchange	• Dense and frequent formal and informal knowledge exchange in China through multiple ways • Frequent national PV conferences on focused topics • Peer communication through personal acquaintances, the very frequently used national social media application (WeChat) and social meetings • Lack of codes in terms of sharing knowledge • Involvement of firm’s R&D personnel in mass production	• Keeping knowledge as secrets with IP violation concerns • Refraining from collaborations with Chinese actors due to risk of IP violations • People who do not want to leave their comfort zones in Western countries

Table 5-8 (continued)

Functions	Inducement	Blocking
Guidance of search	• Existence of industrial unions • Climate change targets, sustainability concerns	• Lack of standards for new innovations • Need for clear national targets • Approach of management to research activities/innovation • Global incompatibility in IPR approach or codes for secrecy
Knowledge development	• Continuous and gradual machinery upgrades in PV lines • Following scientific literature • Educational system	• Inexistence of local manufacturing medium to try and transfer new knowledge in many parts of the world except China • Technical/technological limits in PV
Legitimacy & Market formation	• Cost advantage of c-Si PV • Reliability of c-Si PV	• Lack of standards for new innovations • Market acceptance of certain technologies

As a result, all inducement mechanisms listed above make China to own a well-functioning PV TIS, while it somehow deteriorates the creation and flow of knowledge at international medium. P8 in his quote below indeed summarized the approach of China in PV which can be inferred from the summary evaluation of the PV TIS mechanisms as well.

> In China, the technology dissemination happens very fast, there are many new players coming in, they are successful and their technologies are adapted very quickly in China. Second thing is they develop the ecosystem very quickly, you can find everything what you require for the manufacturing in PV technology. They have very good focus and interaction to build the manufacturing and the ecosystem for the complete industry. They do it very well. Supply chain for the manufacturing consumables, availability of spare parts also the machinery and everything which is indirectly related to the manufacturing such as utilities, as components of ecosystem. All are very well developed in China. They are taking care of the complete ecosystem.

On the other hand, in the excerption below, Participant 12 (P12) from a research institute in other regions than APAC or Europe put too much emphasis on the absence of a facilitating medium which he defined as ecosystem. With his own words below, he articulated:

> We need availability of an ecosystem, a stable medium where people work happily and produce knowledge and experience. Also, there should be a customer of such an R&D. There should be domestic firms which demand this R&D. The research institutes should be competent as well and this competency requires human capital, finance. The main ecosystem in the country should be appealing to have such a skilled capital.

When he was asked to elaborate the components of the ecosystem, he answered:

> Technical support firms, when there is a machine failure, existence of some other people/firms who/which can fix it and their accessibility are critical; material suppliers; entities who use similar systems i.e. sufficient number of users, their availability and accessibility; the culture of working together since these are collective activities.

The reasons that caused China lagged behind before the first few years of 2000 when it made the leap, was interpreted in subsection 2.3.2 from functional dynamics point of view by utilizing the findings in (Lee, 2011). There, similar results were found regarding the functions listed as follows: entrepreneurial experimentation was found to have been induced by the emergence of enterprises in different steps of value chain; knowledge development was mentioned to have been enabled by upgrade of imported production tools, resource mobilization was identified to have been enabled by the labor who had overseas education and the commercial activities of PV firms as well as the finance that local states mobilized. Other functions were addressed too, like the knowledge externalities from semiconductor industry, guidance of search and thereby legitimacy created by the government's deployment policies and finally survival of the new firms due to the market created. The last ones are relevant to the findings in the qualitative study but the former functions were more highlighted since they seem to have still been strongly effective on the continuous success of China in PV industry.

On the other hand, it seems that knowledge exchange has been a more influential factor as the entrepreneurial experimentation increased and has been utilized very effectively in China.

5.5. Concluding Remarks

In this Chapter, the qualitative findings obtained from the 19 interviews carried out with the key PV experts from different regions of the world were evaluated in terms of their contribution to understanding the quantitative results as well as identification of inducement and blocking parts of the technological innovation system functions. The evaluations were examined first, by aggregating the keywords or narratives that were found in the elicitations of the experts under common codes; second, through the excerptions that were thought to have revealed some complicated or distinctive reasons clearly. Then these findings were discussed for the learning patterns they indicated and elaborated. Finally, they were consolidated under the domains of functional dynamics.

The overall findings can be summarized as follows:

- It was revealed that the effect of even incremental new equipment investments on learning should be considered seriously when cumulative capacity with changing output was referred as the main source of learning.

- R&D labor as well as dedication of firms to research activities and mobilizing their resources sufficiently were found to be effective on improvements.

    - R&D labor and R&D intensity may be the channels to absorb the codified knowledge regarding the techniques and technologies that improve the industrial average efficiency.

    - On the other hand, through the informal as well as formal interactions with external stakeholders and colleagues, R&D employees can obviously bring the new knowledge outside and can enable its exploitation in the production line.

- The quantity and extent of supply and value chain actors and close interactions with them are highly crucial for the PV industry. This can validate the significance of the dummy variable that defined the period after 2011 when China was found to have dominated the PV module value chain with more than 50% share.

- Despite transaction cost advantages, vertical integration is not favorable currently in PV if the supply can be secure in other ways.

- Anti-dumping i.e. tax precautions against Chinese PV modules worked as a stimulus for improvement PV in China

- cSi PV technology seems to sustain for a long time in the mid-term (at least 10-15 years) due the knowledge stock it accumulated and the reliability/stability as well as material problems that have not been overcome yet for the alternative technologies like perovskite and silicon-perovskite tandems.

- Though efficiency improvements were preferred as the first R&D item, it was followed by material decreases/substitutes. Moreover, the additional tasks which were mainly focused on sustainability, environmental footprint, lifetime intensions were articulated by different numbers of experts. In overall, the tasks that consider environmental impacts were more featured than efficiency.

- Lag of R&D for PV yielded 3-4 years in overall when the research starts at TRL4-5 at cell level and become obsolescent in 11 ± 4 years. On the other hand, process improvements are measured in months which is usually lower than 6 months. PV is identified as a technology that is based on experimental development and partially applied research.

- Due to hesitations of private funding in favor of long-term reliable PV technologies and appropriation concerns, finance for later stages of TRLs (TRL5) is still needed for moving the PV innovations at least to pre-commercialization stage.

- Moreover, lack of codes at one side was found effective on knowledge flows that caused improvement of PV technology. On the other side, the IP concerns were seen as blocking factor for interactions and collaborations.

- Need of supranational programs for efficient use of financial and labor resources as well as the knowledge base by considering the role of PV in the green transition.

As to the relevance of the qualitative findings to the econometric results, either directly or indirectly they were found supportive.

Effect of cumulative module output on cost reduction was found significant by the quantitative analysis. However, outputs of the firms were not constant but rather increasing annually for many of the time interval. Therefore, it remained ambiguous if the learning was emanating from the new equipment or the repeating actions. It was discussed in Chapter 3 exhaustively that though the learning was observable when the output remained same, new investments had the potential of creating stimuli for learning. The expert elicitations utilized in this thesis indicated that incremental and continuous investments were very crucial in the success of Chinese PV firms. Since the sample was mainly composed of firms that were substantially manufacturing in China, the LBD might have been effective due to these capacity additions and thereby the technology upgrades they brought along as well as cumulative practice.

On the hand, R&D intensity was found to have contributed to cost decline in the quantitative analysis. Similarly, the R&D finance was favored by the experts to attain effective and faster research outcomes in the sections above. It was more or the less expected. However, the dedication of the management which was coded under the guidance of search function of the TIS was articulated by almost 37% of the experts as well. The outcomes that one of the large PV firms had to confront when it had refrained from investing in R&D after a certain level of expenditure was narrated in detail by one of the experts. These qualitative findings supported the significant effect of the R&D intensity.

Another dimension of LBR was represented by the R&D labor in the econometric estimations and it was found to have a negative effect on costs (i.e. contributed to cost decline) as well. The skilled labor was the most frequently articulated code by the experts. Moreover, as discussed based on the detailed quotes shared in the relevant parts above, it was indirectly inferred that some unexpected but highly effective solutions were easily developed by the capabilities embedded in the skilled labor.

Consequently, R&D intensity and R&D labor which were both found jointly significant with the external progress in quantitative analysis in terms of cost reduction, their effect were supported by the experts with indications of absorptive capacity. The firms seem to have improved their innovation capabilities through the external knowledge that was channeled by these learning instruments.

One of the most interesting findings of the quantitative part was ineffectiveness of vertical integration on cost decline and its positive effect on cost (increase the cost) at raw material crises times when compared to being not fully integrated. The expert elicitations substantially supported this finding by specialization, diminishing return of internal communication and less motivation for improvements due to lack of competition within the same firm.

As to the external effects, after the dominance of China in the PV value chain by 2011 with more than 50% share, PV module costs were found to have decreased much more dramatically under control of other effects. On the other hand, dense and frequent relations between stakeholders in China were the most frequently emphasized factors in terms of effective interactions. Therefore, the quantitative findings that captured the quantitative improvements in the supply chain activities validated that the fruitful interactions that accompanied this situation had contributed to faster decline of costs.

Other external factors through which it was aimed to capture the technological and overall progress i.e. industry average efficiency of PV modules and time trend had negatively significant coefficients in the quantitative analysis. It was hypothesized that improvements outside the firms could be captured, assimilated, transformed into new routines to be utilized in their production. The qualitative findings indicated that dense labor mobility within clusters, abroad education programs for skilled labor, hiring key consultants from other countries, new machinery imports, collaboration with EU machine makers and following scientific progress at conferences/through literature had strengthened the internal capabilities of the Chinese PV firms.

In sum, the quantitative results were validated by the qualitative study in terms of the effect of the learning mechanisms investigated, their direction and elaborated more by the instruments and reasons that led them. The overall evaluation of the findings and the policy implications made from them are provided in the following Chapter.

CHAPTER 6

POLICY RECOMMENDATIONS AND CONCLUSION

In the following sections below, first, the policy recommendations that were inferred from the historical and descriptive analyses of the PV industry as well as the econometric findings and the qualitative analysis are provided at different levels. Then, the thesis is concluded with the summary of the findings revealed throughout the analyses carried out, the limitations of the study and the suggestions for future research.

6.1. Policy Recommendations

In this thesis, learning investigated through quantitative analysis was at firm level, while the qualitative analysis enabled examination of the findings from global and national levels. On the other hand, the historical analysis and the review of current trends for the PV industry in Chapter 2 allowed to find out the effective policies at national level and their outcomes at international level. Therefore, the policy/strategic recommendations were made at three levels i.e. international, national and firm. In the subsections below, first the source of the findings that underpinned the implications made which were already addressed in the relevant chapters exhaustively and summarized as conclusion above were reminded shortly and then the policies/strategies that can be utilized in each level are provided in the corresponding tables.

6.1.1. International Level

The international level policy recommendations together with the aims that constitute their motivations and the relevant instruments that can be utilized in design of relevant policies are presented in Table 6-1. For this level, the narratives and the detailed suggestions made by the experts as solutions to common sectoral problems such as future of technologies, finance problems, IP concerns and using resources more efficiently were utilized in the implications made.

Table 6-1. Policy recommendations at international level

Policy Aim	**Policy Recommendation**	**Policy Instrument**
Improving the technologies aligned with the climate change targets	Target sustainability of the materials used and extend the lifetime and reliability of PV modules	Design of research programs that allocate more than half of the resources to the tasks that address: • decreasing material use, • substituting the current materials with the ones which are more abundant and have low carbon footprints, • extending the reliable lifetime, • domestic production that decrease transport load
Increasing diffusion of PV technologies that differentiate according to purpose of use or location of installations with better performance or lower cost.	Support technologies validated at the intended environment (TRL5) at least until pre-commercialization step TRL 7/8	Mobilization of risk facilitating tools like public risk guarantees.
Spending resources dedicated to knowledge development more efficiently and making innovations faster	Enable physical mediums that research community work together for common purposes	Establishment of supranational regional research centers which were donated by the stakeholders proportional to their revenues and where the contributors benefit from accordingly.
Exploitation of different capabilities in global PV TIS for the sake of speeding up innovations that will help climate change	Develop intermediary collaboration models that agents contribute to and benefit from without violating or being worried about IPR	Design or utilization of existing global funds that grant the research activities in the scientific knowledge intensive entities in the West and allow industrially strong commercial actors in the East to utilize this knowledge in exchange of their product (PV module) donations for the underdeveloped regions -which have problems in access to electrical energy and water or need support for the green transformation of their electricity systems.

As seen in the Table 6-1, the main driving force for this level of policies is speeding up the green transformation with sustainable solutions through orientation of international funds and design of programs that consider mutual outcome of efforts rather than reinforcing one region or country. In that sense, PV can have a unifying role if the critical role of technological orientation and thereby allocation of funds as well as constructing a more global knowledge base by exploiting strengths of each region can be understood. Therefore, the programs of the supranational organizations should be clear and guiding for the research agenda. More detailed design of these programs that consider sustainability and criticality of the materials, can determine the future of PV and thereby its impact on green transformation. Also, the orientation of research to specific segments like products differentiated for the hot climate, developed for integrated applications like Agrovoltaics, Building Integrated PV, Vehicle Integrated PV or designed for space stations can be very important since each may have critical roles in the transformation by enabling easier diffusion of the technology, larger applications in idle parts of the world, greater harvesting and continuous power, etc. Finally, the mobility of finance for even higher the level of technologies that were developed for differentiated applications but not commercialized yet should be considered to facilitate their faster commercialization without leaving them to their own diffusion pace.

6.1.2. National Level

The policy recommendations and the other relevant complementary dimensions for the national level are listed in Table 6-2. During the derivations of the policy implications recommended at national level below, a comprehensive set of findings from different studies carried out in the scope of the thesis are considered. They can be summarized as follows: the policies that were implemented in different leading countries and were found to have been effective in the PV industry history review in Chapter 2; mechanisms in the Chinese firms that were identified to have a significant impact on decline of PV module costs based on the quantitative analyses in Chapter 4;

finally, the well-functioning and hindering patterns in different regions for the PV industry that were unveiled by the qualitative analysis in Chapter 5.

As mentioned in Chapter 2, the Flat-Plate Solar Array (FSA) Project which was commenced in 1974 in the USA and the subsequent programs it led, were comprehensive policy tools that did not only aimed at development of the fundamental technologies and techniques which were missing at that time but also the establishment of a domestic industry through public procurement. The most distinguishing parts were: requirement of involvement of a number of enterprises in different steps of the value chain and creation of stimulation within firms by setting standards and technology targets but also between firms by procuring from multiple suppliers. Together with its leading position in the emerging years of PV with space applications, this targeted and well-designed from led the US to be the world leader in PV until the end of 1990s. On the other hand, the US and Germany both had given too much importance on formal knowledge creation and it had made them leaders for a while. However, they could not sustain their positions since despite too much financial resources dedicated to R&D and labor force raised at that time. They had hesitant attitudes for a while upon mitigation of the oil crisis and then changed their strategies in favor of directing the resources to deployment rather than manufacturing. The demand side policies in Germany were guiding the whole world in 1990s and when the capacities planned became large enough, they made German production boost but it did not last more than one decade.

Thus, though the US and Europe had the substantial share in global production meanwhile, the industry was not consistently promoted aligned with the internally growing demand. As the PV market boosted at the end of 1990's, the US had already started to lose its position which was followed by Germany in 10 years. On the other hand, the first leading Asian country in PV, Japan, followed long term targets and dedication of the government was gradual based on first the national needs, then technological development targets and commercialization plans. In sum, the top down attitude was persistent and as a result, while the positions of the US and Germany were lost by the end of 1990s and the 2000s respectively, Japan made its leap near 1995 and stayed on the top almost for 10 years until Chinese attempt. As to China, insistent and sustained dedication of the government gradually to the establishment of a local production medium starting with the agreement made between the USA Science and Technology Commission (of China and the DoE of the US in 1995; then, in the first years of 2000, emergence of the second-generation PV firms that were mainly equipped with the upgraded machinery imported from the West after the state-owned ones in 1970s; finally, the other attributes it endowed which were identified by further analyses carried out within the thesis study, made it make a leap with the increasing demand globally and it has become the world leader since 2011.

As it was summed up in the concluding remarks of Chapter 2, guidance of government was one of the most important sources for the development of PV industry. That was also one of the implications made from the qualitative investigations for the efficiency of research efforts. Nonetheless, long term and insistent dedication was found to have been more important in the historical analysis. On the other hand, as learned from the past, creating the demand through deployment policies or direct public procurement was crucial for a visible manufacturing. Since the market was already created for the time frame examined in the quantitative analysis and it was not a primary concern inquired by the survey questions, this is not directly addressed in the policies below.

Another common finding of the expert interviews was non-functionality of the international precautions in terms of securing national manufacturing and leadership in PV technology or market. The attitude of the US at very early times against Europe which restricted the trade of PV devices that were being used in space vehicles caused Europe to develop its first commercial device to be used in the European satellite launched in 1970. Similarly, despite the anti-dumping precautions that were started against PV panels imported from China in the US in 2012 and in the EU in 2013, China developed its industry much faster. It might have even accelerated this process. This can be implicitly inferred from the econometric analysis where the years after 2011 were found to be more fruitful in terms of cost decline and it was somehow associated with the dominance of China in the PV value chain. Also, while none of the experts found them fully functional, some of the experts articulated that these policy measures stimulated Chinese effort. Therefore, policies were oriented to developing and maintenance of the local production rather than any kind of international precautions.

Table 6-2. Policy recommendations at national level

Policy Aim	**Policy Recommendation**	**Policy Instrument**
Making the innovation actors alerted and dedicated for a sustainable growth in the industry	Guide the industry and research with clear, long term and insistent targets	Roadmaps and action plans, clear targets in periodic government plans, long term programs, mobilized resources, facilitating regulations.
Creating supply security by considering knowledge development	Variate and increase number of entrepreneurial activities in the PV value chain	Design of programs that require joint activity of different firms that involve in different steps of value chain.
Boosting innovation through domestic knowledge flows	Build the medium that facilitate labor mobility	Promoting formation of PV industry clusters
Utilization of tacit knowledge embedded in national actors	Create mediums that facilitate agents informal contacts	Arranging or promoting social activities, information days that gather people interested in the field
Enabling as much as utilization of codified knowledge embedded in national actors	Create mediums that facilitate agents share scientific and technological knowledge	Arranging or promoting frequent conferences that were focused on specific topics
Raising skilled labor in the country	Create the specific education medium	Promote/allow design of PV programs/curriculums Support scientific and academic activities at the PV relevant university programs/research institutes
Familiarity of labor to global science and technology trends/attitudes for easy absorption of external knowledge	Enable international mobility of labor	Supporting abroad education or labor/student exchange in specific PV topics
Keeping skilled labor in the country in the long run	Create the required ecosystem and an appealing working medium	Tax support for the employee side of which proper implementation is audited as well as employment incentives for the employer side.

Table 6-2 (continued)

Policy Aim	**Policy Recommendation**	**Policy Instrument**
Increasing local products in the market to guarantee supply risks in terms of delivery, quality, price as well as to contribute to reduction of emissions arising from overseas freight	Promote domestic production and internal knowledge development rather than enacting international precautions	Supporting entrepreneurial activity: • through public risk-taking or purchase guarantees; • tax advantages to PV manufacturing equipment/material imports for a certain time accompanied by the incentives provided to their local production (machinery/tool/material) • by promoting Foreign Direct Investments (FDI) to revitalize the production medium i.e. create demand for spare products, contribute to employment and raise of skilled labor in the field; • public procurement of specific designs and purchase orders guaranteed for the developed products with desired specifications
Developing products close to commercialization and decreasing import ratios	Support collaborative projects between materials/machinery suppliers and manufacturing firms	Dedicating public resources at an appealing rate to industrial level projects between commercial actors that would otherwise not happen
Increasing diffusion of PV technologies that differentiate according to purpose of use or location of installations with better performance or lower cost	Support technologies validated at the intended environment (TRL5) at least until pre-commercialization step TRL 7/8	Mobilizing risk facilitating tools like public purchase guarantees

The main findings that underpinned the policies provided in Table 6-2 can be summarized as: enhancing and variating the supply chain enterprises by stimulating and facilitating the entrepreneurial activity; raising, attracting and keeping skilled labor in the field; allowing flow of national, and international knowledge from various sources like technology imports, national and international mobility of human capital, national level frequent knowledge dissemination activities, collaborative projects with international actors. From the success of Chinese firms, it can be inferred that the national strengths do not only arise from keeping all supply chain in hands but also from persistent internal and external interactions at any level. Therefore, national policies should still consider the knowledge flows that can be enabled by being integrated to the world through trade relations, research collaborations, labor mobility, etc. Finally, detailed underpinnings of the policy recommendations and the instruments seen in Table 6-2, identified or inspired from historical analysis, quantitative estimations and expert elicitations can be found in the concluding section of each chapter.

6.1.3. Firm Level

Strategic implications made for the PV firms are provided in Table 6-3. Since the quantitative analysis was based on company data, findings from the econometric estimations built the main foundation of the strategies below. In addition, the fruitful or non-functional traits of the firms in the PV industry that were articulated by the experts were considered. As a result, the overall findings were evaluated jointly for development of the firm level strategies provided in Table 6-3.

Table 6-3. Strategic recommendations for PV firms

Aim	**Strategy**	**Instruments**
Keeping the skilled labor motivated and dedicated to well-established targets	Define short- and long-term R&D targets, share with the employees, follow the progress frequently	Roadmaps, Strategic plans, Periodic follow up meetings
Boosting innovation abilities and capabilities to absorb external knowledge	Invest in R&D even if no radical improvements were expected internally	Allocating resources to research proportional to the revenue
Maintenance of the learning created and being updated	Make incremental and gradual upgrades in the production line without waiting for large extension plans or disrupting technologies	Following new technologies and related machinery through fairs and supply relations and making proper investing plans
Keeping the cost advantages and guaranteeing the continuity of production	Secure the supply chain with alternative solutions by covering internal and external stakeholders rather than relying on internally closed value chain.	Making strategic alliances with the domestic and foreign suppliers and establishing close collaborations with them by providing continuous feedback
Acquisition of the external knowledge outside the country	Extend and variate the knowledge sources	Hiring key people from other countries, being open to employing foreign experts and developing schemes for their attraction, attending all national and international dissemination activities and being involved in unions.
Utilization of domestic knowledge embedded in other firms	Allow two-sided labor mobility	Being located in clusters and avoiding strict rules for job change
Utilization of the knowledge and the capabilities within the firms as much as possible	Keeping skilled labor in the firm for at least 2 years	Contracts that do not restrict the transfer of people but making people committed by providing appealing conditions (salary, rewards, leaves, appreciation)
Exploiting the knowledge emanating from users	Involve in downstream applications	• Establishing close feedback communication with users • Installation of test systems with own products • Being directly involved in installation services as a segment of activity

Some of the firm level strategies may seem can be adaptable to many other industries. However, the criticality of continuous and frequent upgrades in manufacturing lines and the ease of knowledge flows through labor mobility indicate the upstream machinery bounded nature and tacit knowledge supported development of the PV industry, respectively. Moreover, even the PV technologies were more or the less settled, need of research within the PV firms cannot only be justified with a highly novel technology development focus but rather with the requirement for a certain level of absorptive capacity in terms of recognizing, assimilating and transformation of the external knowledge to be ultimately exploited in the company operations.

6.2. Conclusion

As understood from the overall findings that learning in PV is neither a story like "as time goes by..." nor a blind path dependency but rather is an intentional or unintentional process bounded by the existing capabilities of the firms/countries. Any factors including accumulated capacity could be left as manna from heaven or in other words black box. But in this case, they do not help us to understand what kind of channels enabled them to have been embodied by the actor. Furthermore, when too much attention was put on one factor, it causes underestimation of the others by suppressing the diversity of the mechanisms that might be at work in addition to accumulating experience based on repeating actions.

First, investigation of different dimensions of learning in PV industry was achieved based on the econometric study; then, the quantitative results attained were verified and elaborated through the qualitative analysis from learning and dynamic capabilities point of view and finally, the functional mechanisms and instruments that had been effective in the development of PV were revealed. Then all these findings and inferences were utilized in policy or strategic implications made for different levels. The featured conclusions that can be jointly made from the analyses carried out throughout the thesis are listed below:

- Chinese PV firms seem to have high level of dynamic capabilities which they improved through multiple learning sources.
- Making gradual and incremental equipment upgrades is identified as another crucial part of learning by doing in the PV industry while radical changes can deteriorate the learning accumulated.
- LBI enabled by the reckless knowledge flows through informal interactions seem to be one of the most prominent learning instruments of the PV industry flourished in China.
- Finance is crucial not only for making but also validating research-based innovations in PV. Risk taking funds or availability of resources for the verified technologies which address reliability and sustainability issues from TRL5 to at least until pre-commercialization stage can speed up commercialization of PV research aligned with the global green transition goals.
- Rather than vertical integration within firms, strategic alliances seem more advantageous since established communications and complementarity routines within firms seem to prevent internal innovations to emerge as fruitful as it happens by means of relations.
- When dense and frequent relations can be established, the availability of an ecosystem which covers all industrial actors from machine vendors to material suppliers is crucial.
- R&D labor is not only a contributor to research but it also functions synergistically with learning through accumulated production. According to quantitative findings it becomes effective after 2 years. Since the mobility of labor is desired as one of the fundamental sources of knowledge flows that facilitated the development of Chinese PV industry, the tradeoff between keeping skilled labor and creating a medium that allows its turnover should be considered.

- R&D labor, revenue proportional R&D expenditures i.e. R&D intensity, gradual equipment investments and either the formal or informal interactions all together contribute to improvement of absorptive capacity of PV firms which enable them acquire (sense), assimilate (understand), transform (combine with internal knowledge according to internal requirements) and exploit (utilize) the externally new knowledge.
- IP concerns, secrecy and lack of codes were seen as both barriers and facilitators of knowledge development in China. However, this can be a more sophisticated and long-term process rather than having a progress based on a recipe or know-how about a specific technology. By considering the persistently enhanced leadership of China in PV in the last 20 years, the capabilities that were stimulated and improved by means of labor mobility, informal interactions between individuals, open and fast communication among different stakeholders as well as conferences held at national level should be perceived from a broader perspective in terms of their role in this success rather than seeing them as just tools for easy spread of confidential knowledge.
- PV R&D should be more oriented to the issues that address environmental concerns and climate change directly or indirectly such as sustainability, abundance, environmental and C footprint of materials, longer utilization of product at high performance.
- The use of finance and competences in common at regional and global levels can increase the efficiency and speed of research in PV which seems to be shaping the future of energy globally in near future. Therefore, design of international collaboration programs and funds that do not disregard any region as well as establishment of regional research infrastructures open to international interactions at a certain extent can be functional.

There were certain limitations of the study. First one is related to number of observations utilized in the econometric analysis. It restricts the number of variables that can be investigated and the significance level of the variables examined. Accessing data of other companies which may not be listed in the Stock Exchange Markets but could provide similar information can be useful to improve the estimations.

Second, despite being novel and providing a different aspect to the LC literature, the LBI related implications made from the econometric results were indirect based on the joint significance of the internal and external factors. Hence, it was required to be corroborated by the expert elicitations. If any information regarding research collaborations or supply relations had been available, the inferences would have been more precise.

Third, by the vertical integration variable of which effect was investigated for the first time in the PV LC literature and evaluated as a barrier to dynamic capabilities opposed to the transaction cost theory, the four main steps after polysilicon production were covered since the partial integration like cell-module or wafer-ingot did not provide sufficient variation within time. A larger data set with longer time interval and cross-sectional observations can allow to investigate if being integrated in specific parts were effective on cost decline.

Four, not only specific to this study but as a general criticism to the LC theory, even if the handicaps that the global aggregate data own are overcome by firm level analysis, LBD is still an ambiguous parameter when it embodies the new investments. Because, the knowledge triggered by the potentially novel technologies cannot be distinguished from the repeated practices. When some control variables like capital investments are included, they have the risk of being highly correlated with the cumulative output since they will both increase when there is a continuous investment as it was in the sample employed in this thesis. If a survey-based data can be gathered, the investments in new technologies can be inquired and utilized as a control dummy.

Consequently, those drawbacks of the study were tried to be overcome by the expert elicitations. They were very useful in terms of understanding the non-quantifiable factors and corroborating the direct or indirect findings. However, it seems that a larger number of key knowledgeable is required and the questions should be more clear-cut for some technology specific parameters like the lag and depreciation of the PV technologies.

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APPENDICES

A. SOME ADDITIONAL SUMMARY STATISTICS

Table A-1. Summary statistics of the variables on yearly basis

	Mean			Minimum			Maximum		
Year	Cum.Mod. Ship. (MW)	R&D int. (%)	R&D Emp. (#)	Cum.Mod.Ship. (MW)	R&D int. (%)	R&D Emp. (#)	Cum.Mod. Ship. (MW)	R&D int. (%)	R&D Emp. (#)
2003	2	1.07	.	2	1.07	.	2	1.07	.
2004	10	21.42	.	0	0.42	.	28	63.29	.
2005	23	0.59	44	5	0.09	11	78	1.49	76
2006	69	1.22	76	21	0.58	15	200	1.66	202
2007	156	0.74	90	2	0.16	15	559	1.15	247
2008	342	0.52	113	4	0.26	25	1019	0.8	382
2009	511	1.12	134	13	0.38	43	1717	2.54	382
2010	1083	1	308	80	0.43	59	3272	3.01	1080
2011	2052	1.66	399	491	0.41	93	5299	4.78	1330
2012	2480	1.84	333	13	0.41	104	5980	4.55	1464
2013	3895	1.98	292	35	0.71	58	9214	4.81	1106
2014	5817	1.79	533	718	0.41	96	12575	4.44	1954
2015	9198	1.81	624	2022	0.49	121	17009	3.98	2588
2016	12689	1.63	292	3455	0.61	126	18509	2.93	697
2017	19266	1.15	548	5930	0.83	117	26366	1.65	1183
2018	25216	1.56	736	9231	1.18	572	37537	2.21	945
2019	46189	1.28	965	40634	1.09	515	51744	1.47	1415

Table A-2. Summary statistics of the variables on cross section basis

	Mean			Minimum			Maximum		
Firm ID	Cum.Mod. Ship. (MW)	R&D int. (%)	R&D Emp. (#)	Cum.Mod. Ship. (MW)	R&D int. (%)	R&D Emp. (#)	Cum.Mod .Ship. (MW)	R&D int. (%)	R&D Emp. (#)
1	772	1.32	61	1.6	0.41	0	2371	4.81	139
2	9647	0.65	215	2.2	0.09	15	40634	1.47	572
3	3897	1.36	159	5.2	0.4	11	17307	2.68	386
4	4786	0.9	116	3.3	0.16	26	20445	1.3	290
5	14156	0.94	442	14.4	0.38	43	51744	1.46	1415
6	1105	1.8	364	32.7	0.43	170	2038	2.92	870
7	3602	3.59	154	257.0	2.93	105	7923	4.78	234
8	3058	1.49	.	13.4	0.91	.	9231	2.15	.
9	1353	1.19	303	2.3	0.55	76	5299	1.71	450
10	3914	6.31	662	0.1	0.37	37	17009	63.29	2588
11	7827	1.89	767	16.6	0.43	25	21877	4.44	1464

Table A-3. Status of firms for being vertically integrated within years

Firm ID	1	2	3	4	5	6	7	8	9	10	11	Total
2003									0			0
2004		0							0	0		0
2005		0	0						0	0	1	1
2006		0	0						0	1	1	2
2007	0	0	0	0					0	1	1	2
2008	0	1	1	0					0	1	1	4
2009	0	1	1	0	1	0			0	1	1	5
2010	0	1	1	1	1	1	1		1	1	1	9
2011	0	1	1	1	1	1	1		1	1	1	9
2012	0	1	1	1	1	1	1	0		1	1	8
2013	0	1	1	1	1	1	1	1		1	1	9
2014	0	1	1	1	1	1	1	1		1	1	9
2015	0	1	1	1	1		1	1		1	1	8
2016		1	1	1	1		1	1			1	7
2017		1	1	1	1			1			1	6
2018		1			1			1			1	4
2019		1			1							2
Total	0	12	10	8	11	5	7	6	2	10	14	85

Table A-4. Change of polysilicon related variables within years

Year	pSi cost (2015 US$/W)	pSi spot price (2015 US$/kg)	pSi use (g/W)
2003	0.497	35.48	13.99
2004	0.723	55.53	13.02
2005	1.517	137.63	11.02
2006	2.900	290.41	9.99
2007	3.354	373.31	8.98
2008	3.202	399.48	8.02
2009	0.661	88.10	7.50
2010	0.462	65.32	7.08
2011	0.401	59.71	6.72
2012	0.143	23.02	6.21
2013	0.102	17.48	5.82
2014	0.112	20.70	5.40
2015	0.083	16.00	5.20
2016	0.071	14.84	4.78
2017	0.067	15.54	4.30
2018	0.046	12.33	3.75
2019	0.030	8.39	3.52

B. COMPLEMENTARY MFLC ESTIMATIONS

Table B-1. Benchmark of two MFLC models with LBD and time trend

VARIABLES	MFLC With LBD	MFLC With timetrend
lCumModShip	-0.240***	
	(0.042)	
timetrend		-0.151***
		(0.007)
lRDint	-0.099*	-0.069**
	(0.046)	(0.025)
L2.lRDEmp	-0.097***	-0.045
	(0.029)	(0.028)
y_2008	0.387***	0.419***
	(0.068)	(0.040)
after2011	-0.459***	-0.440***
	(0.061)	(0.042)
Constant	2.607***	2.034***
	(0.255)	(0.126)
Observations	80	80
R-squared	0.950	0.984
Number of firmID	10	10
Model	Fixed	Fixed
std err	Huber-White	Huber-White
Rsq within	0.950	0.984
Rsq overall	0.841	0.980
R sq BW	0.555	0.982
F	255.1	3607
p value of model	2.07e-09	0
rho	0.789	0.474
sd_res_panels	0.308	0.0841
sd_res_overall	0.159	0.0887

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

C. POST ESTIMATION ANALYSES

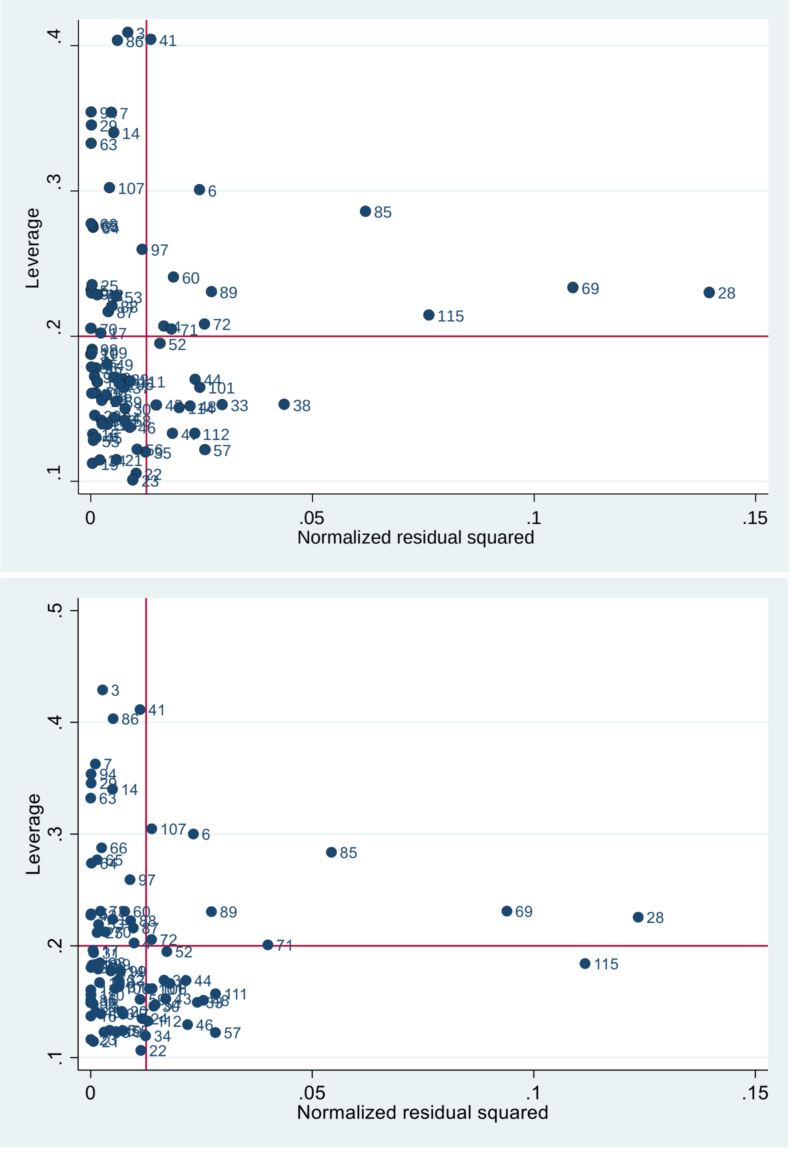
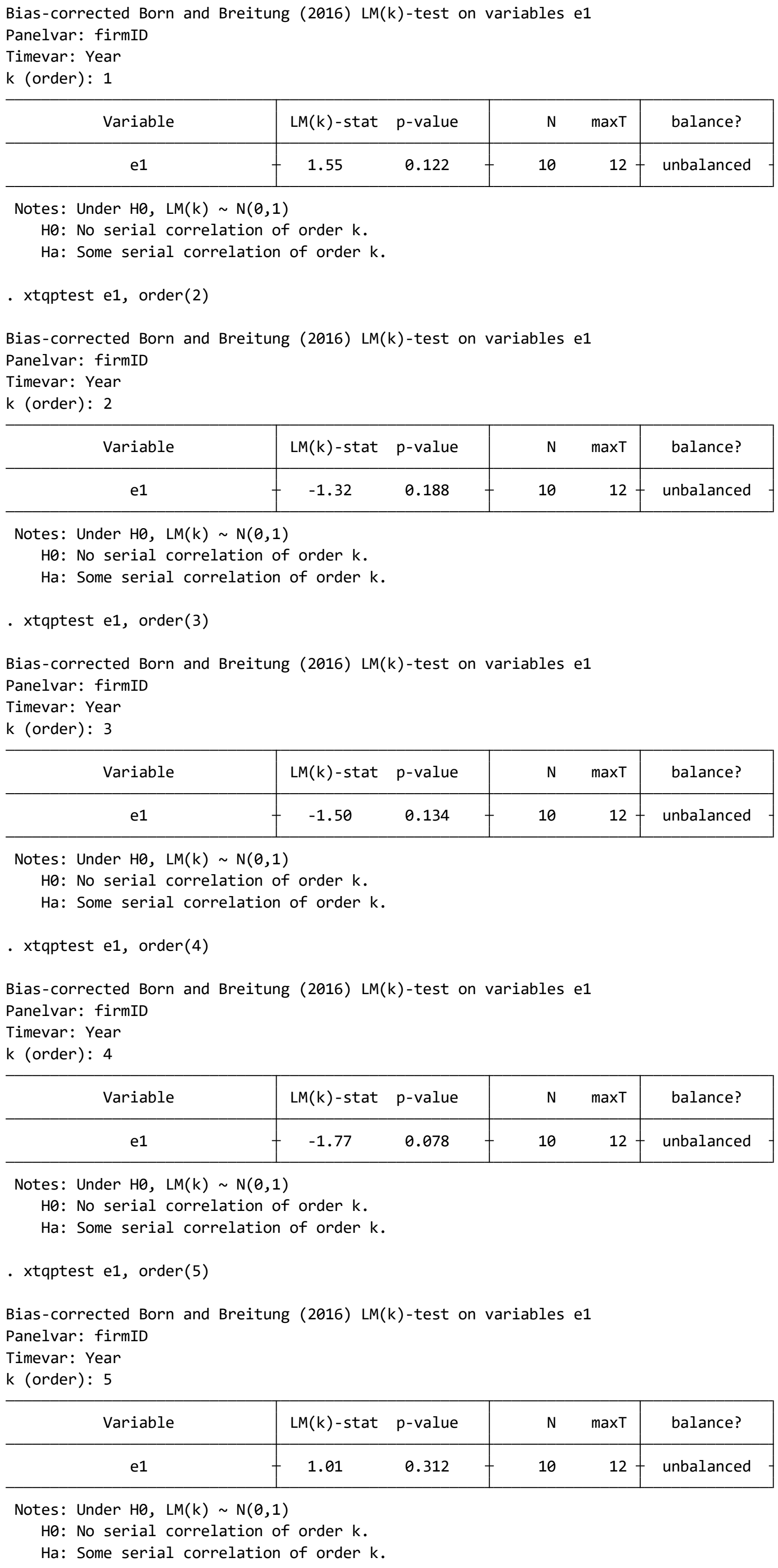


Figure C.1. The leverage vs residual plots of MFLC5 (above) and MFCL6 (below)

Table C-1. Heteroskdasticity test results of MFLCs after outliers are omitted

Breusch–Pagan/Cook–Weisberg test for heteroskedasticity		
Assumption: Normal error terms Variable: Fitted values of lASP_r H0: Constant variance		
	MFLC7	MFLC8
chi2(1)	3.32	2.42
Prob > chi2	0.0683	0.1200



```
Bias-corrected Born and Breitung (2016) LM(k)-test on variables e1
Panelvar: firmID
Timevar: Year
k (order): 1
------------------------------------------------------------------------
      Variable       | LM(k)-stat  p-value |     N    maxT |  balance?
------------------------------------------------------------------------
         e1          |   1.55       0.122  |    10      12 | unbalanced
------------------------------------------------------------------------
 Notes: Under H0, LM(k) ~ N(0,1)
    H0: No serial correlation of order k.
    Ha: Some serial correlation of order k.

. xtqptest e1, order(2)

Bias-corrected Born and Breitung (2016) LM(k)-test on variables e1
Panelvar: firmID
Timevar: Year
k (order): 2
------------------------------------------------------------------------
      Variable       | LM(k)-stat  p-value |     N    maxT |  balance?
------------------------------------------------------------------------
         e1          |  -1.32       0.188  |    10      12 | unbalanced
------------------------------------------------------------------------
 Notes: Under H0, LM(k) ~ N(0,1)
    H0: No serial correlation of order k.
    Ha: Some serial correlation of order k.

. xtqptest e1, order(3)

Bias-corrected Born and Breitung (2016) LM(k)-test on variables e1
Panelvar: firmID
Timevar: Year
k (order): 3
------------------------------------------------------------------------
      Variable       | LM(k)-stat  p-value |     N    maxT |  balance?
------------------------------------------------------------------------
         e1          |  -1.50       0.134  |    10      12 | unbalanced
------------------------------------------------------------------------
 Notes: Under H0, LM(k) ~ N(0,1)
    H0: No serial correlation of order k.
    Ha: Some serial correlation of order k.

. xtqptest e1, order(4)

Bias-corrected Born and Breitung (2016) LM(k)-test on variables e1
Panelvar: firmID
Timevar: Year
k (order): 4
------------------------------------------------------------------------
      Variable       | LM(k)-stat  p-value |     N    maxT |  balance?
------------------------------------------------------------------------
         e1          |  -1.77       0.078  |    10      12 | unbalanced
------------------------------------------------------------------------
 Notes: Under H0, LM(k) ~ N(0,1)
    H0: No serial correlation of order k.
    Ha: Some serial correlation of order k.

. xtqptest e1, order(5)

Bias-corrected Born and Breitung (2016) LM(k)-test on variables e1
Panelvar: firmID
Timevar: Year
k (order): 5
------------------------------------------------------------------------
      Variable       | LM(k)-stat  p-value |     N    maxT |  balance?
------------------------------------------------------------------------
         e1          |   1.01       0.312  |    10      12 | unbalanced
------------------------------------------------------------------------
 Notes: Under H0, LM(k) ~ N(0,1)
    H0: No serial correlation of order k.
    Ha: Some serial correlation of order k.
```

Figure C.2. Autocorrelation test results for MFLC7 up to order 5

```
Bias-corrected Born and Breitung (2016) LM(k)-test on variables e2
Panelvar: firmID
Timevar: Year
k (order): 1

              Variable    LM(k)-stat  p-value          N     maxT     balance?
                    e2       2.23       0.025         10       12    unbalanced

 Notes: Under H0, LM(k) ~ N(0,1)
    H0: No serial correlation of order k.
    Ha: Some serial correlation of order k.

. xtqptest e2, order(2)

Bias-corrected Born and Breitung (2016) LM(k)-test on variables e2
Panelvar: firmID
Timevar: Year
k (order): 2

              Variable    LM(k)-stat  p-value          N     maxT     balance?
                    e2      -2.57       0.010         10       12    unbalanced

 Notes: Under H0, LM(k) ~ N(0,1)
    H0: No serial correlation of order k.
    Ha: Some serial correlation of order k.

. xtqptest e2, order(3)

Bias-corrected Born and Breitung (2016) LM(k)-test on variables e2
Panelvar: firmID
Timevar: Year
k (order): 3

              Variable    LM(k)-stat  p-value          N     maxT     balance?
                    e2      -1.55       0.120         10       12    unbalanced

 Notes: Under H0, LM(k) ~ N(0,1)
    H0: No serial correlation of order k.
    Ha: Some serial correlation of order k.

. xtqptest e2, order(4)

Bias-corrected Born and Breitung (2016) LM(k)-test on variables e2
Panelvar: firmID
Timevar: Year
k (order): 4

              Variable    LM(k)-stat  p-value          N     maxT     balance?
                    e2      -1.39       0.165         10       12    unbalanced

 Notes: Under H0, LM(k) ~ N(0,1)
    H0: No serial correlation of order k.
    Ha: Some serial correlation of order k.

. xtqptest e2, order(5)

Bias-corrected Born and Breitung (2016) LM(k)-test on variables e2
Panelvar: firmID
Timevar: Year
k (order): 5

              Variable    LM(k)-stat  p-value          N     maxT     balance?
                    e2       1.74       0.083         10       12    unbalanced

 Notes: Under H0, LM(k) ~ N(0,1)
    H0: No serial correlation of order k.
    Ha: Some serial correlation of order k.
```

Figure C.3.Autocorrelation test results for MFLC8 up to order 5

Table C-2.Estimations of MFLC7 and MFLC8 with default standard errors

	With default standard errors	
VARIABLES	MFLC7	MFLC8
lCumModShip	-0.060***	-0.036**
	(0.017)	(0.015)
lRDint	-0.072***	-0.064***
	(0.023)	(0.019)
L2.lRDEmp	-0.043***	-0.034**
	(0.015)	(0.013)
y_2008	0.554***	0.485***
	(0.063)	(0.041)
after2011	-0.449***	-0.448***
	(0.036)	(0.030)
L.eff	-0.223***	
	(0.018)	
timetrend		-0.128***
		(0.008)
Constant	4.253***	2.000***
	(0.171)	(0.079)
Observations	70	73
R-squared	0.989	0.992
Number of firmID	10	10
Model	Fixed	Fixed
std err	Huber-White	Huber-White
Rsq within	0.989	0.992
Rsq overall	0.972	0.984
R sq BW	0.914	0.970
F	795.1	1242
p value of model	0	0
rho	0.698	0.645
sd_res_panels	0.110	0.0834
sd_res_overall	0.0727	0.0619

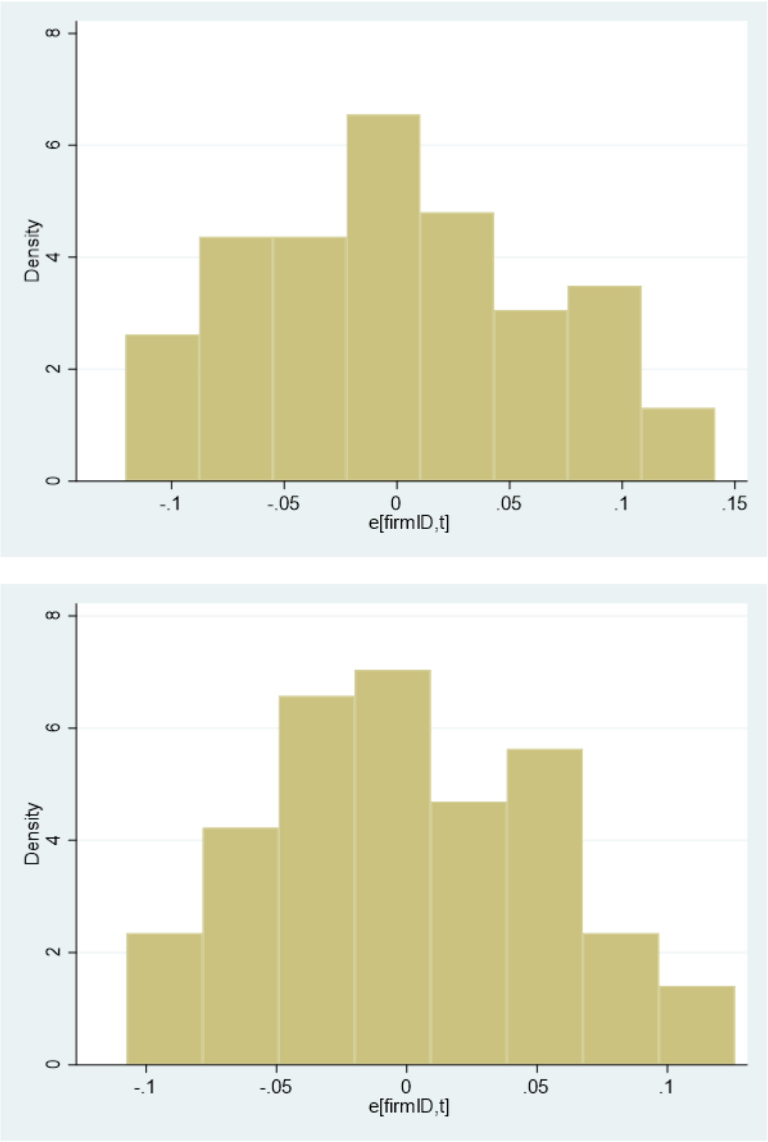


Figure C.4. Residual Histograms of MFLC7 (above) and MFLC8 (below)

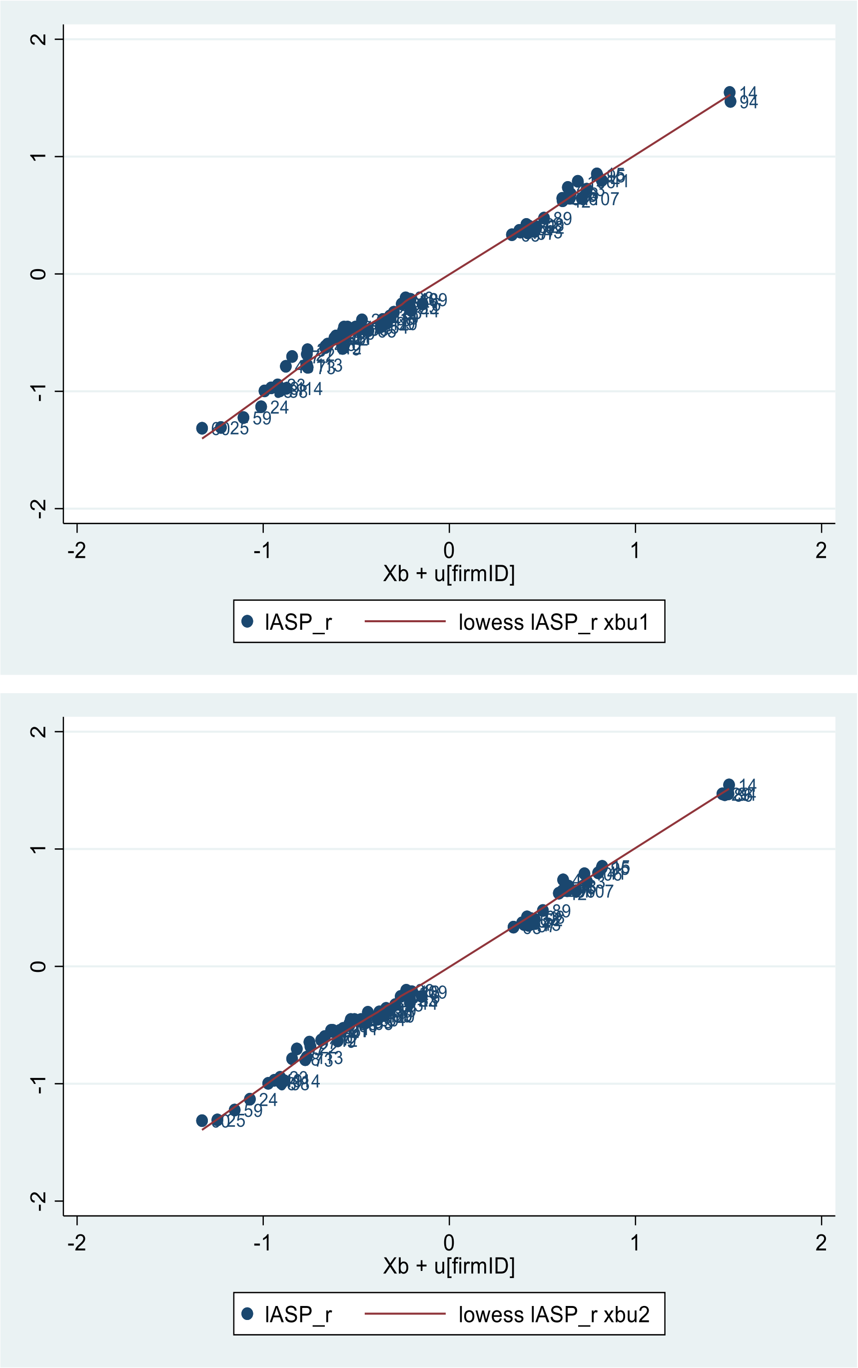


Figure C.5. Observed values of the dependent variable vs predicted for MFLC7 (above) and MFLC8 (below)

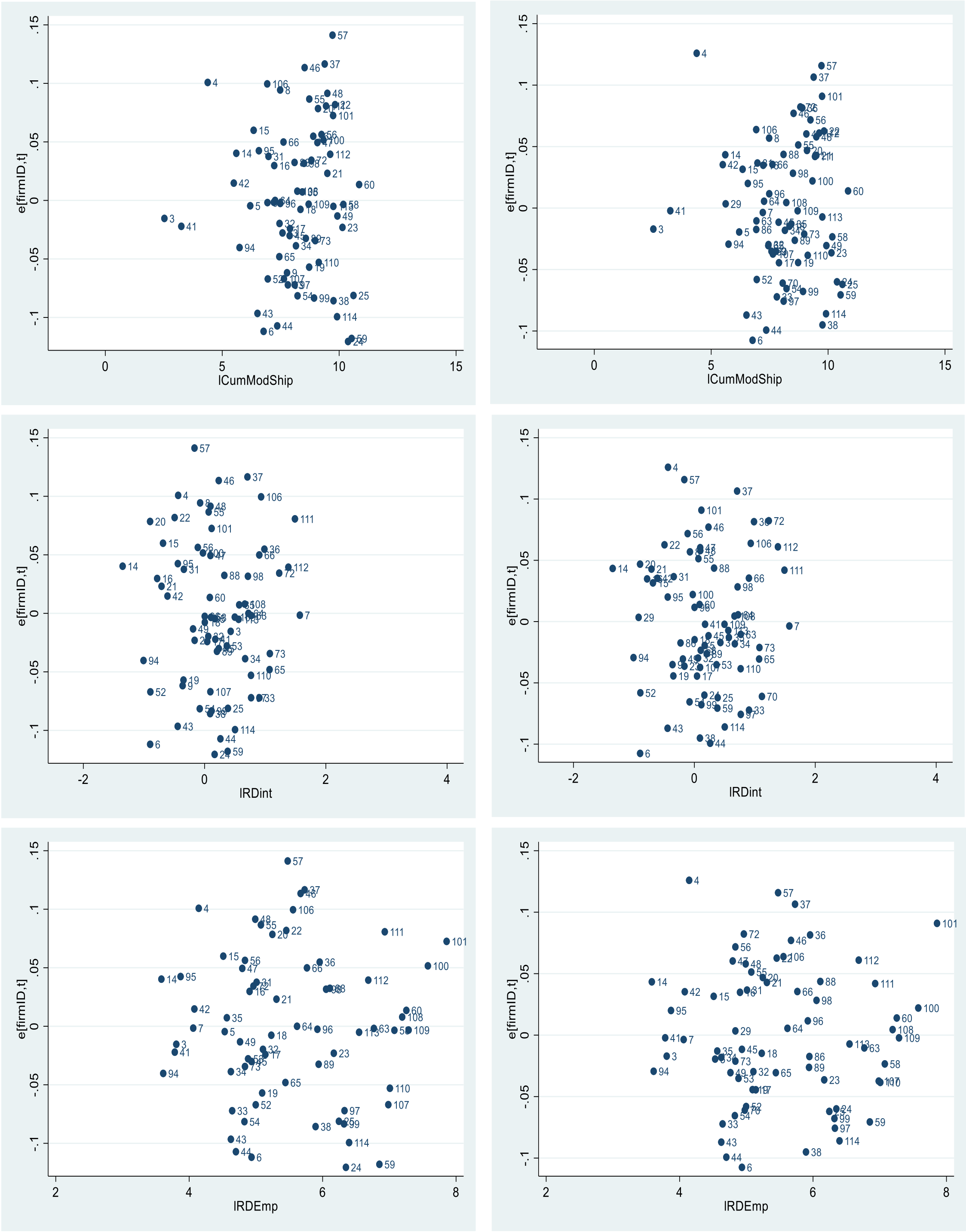


Figure C.6. Residual plots versus independent variables for MFLC7 (left) and MFLC8 (right)

Table C-3. Unit root test estimations

VARIABLES	1 lASP_r	2 lCumModShip	3 lRDint	4 lRDEmp	5 eff
L.lASP_r	0.961*** (0.0209)				
L.lCumModShip		0.796*** (0.0293)			
L.lRDint			0.0797 (0.123)		
L.lRDEmp				0.675*** (0.0922)	
L.eff					1.023*** (0.00870)
Constant	-0.193*** (0.00590)	2.128*** (0.191)	0.0989*** (0.00657)	1.894*** (0.473)	0.125 (0.131)
Observations	97	97	97	81	93
R-squared	0.919	0.964	0.012	0.537	0.987
Number of firmID	11	11	11	10	11

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table C-4. Granger causality test estimations for independent variables

VARIABLES	(1) Default s.e.
L.lASP_r	0.306**
	(0.114)
L2.lASP_r	-0.139
	(0.125)
L3.lASP_r	-0.120
	(0.118)
L.lCumModShip	-0.204***
	(0.0594)
L2.lCumModShip	-0.136*
	(0.0742)
L3.lCumModShip	0.195***
	(0.0422)
L.lRDint	-0.0651*
	(0.0379)
L2.lRDint	-0.0528
	(0.0406)
L3.lRDint	-0.0375
	(0.0392)
L.lRDEmp	0.00432
	(0.0313)
L2.lRDEmp	-0.0702**
	(0.0274)
L3.lRDEmp	-0.0351
	(0.0286)
L.eff	-0.137
	(0.170)
L2.eff	-0.342**
	(0.131)
L3.eff	0.262*
	(0.150)
Constant	5.124***
	(1.109)
Observations	59
R-squared	0.979
Number of firmID	10

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

```
. test l.lCumModShip=l2.lCumModShip=l3.lCumModShip=0

 ( 1)  L.lCumModShip - L2.lCumModShip = 0
 ( 2)  L.lCumModShip - L3.lCumModShip = 0
 ( 3)  L.lCumModShip = 0

       F(  3,    34) =   14.54
            Prob > F =    0.0000

. test l.lRDint=l2.lRDint=l3.lRDint=0

 ( 1)  L.lRDint - L2.lRDint = 0
 ( 2)  L.lRDint - L3.lRDint = 0
 ( 3)  L.lRDint = 0

       F(  3,    34) =    1.45
            Prob > F =    0.2449

. test l.lRDEmp=l2.lRDEmp=l3.lRDEmp=0

 ( 1)  L.lRDEmp - L2.lRDEmp = 0
 ( 2)  L.lRDEmp - L3.lRDEmp = 0
 ( 3)  L.lRDEmp = 0

       F(  3,    34) =    4.62
            Prob > F =    0.0081

. test l.eff=l2.eff=l3.eff=0

 ( 1)  L.eff - L2.eff = 0
 ( 2)  L.eff - L3.eff = 0
 ( 3)  L.eff = 0

       F(  3,    34) =    4.27
            Prob > F =    0.0116
```

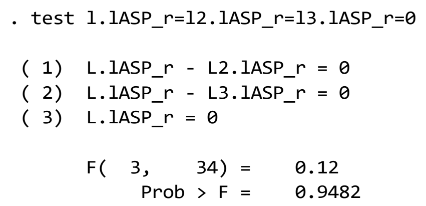
Figure C.7. Granger causality t test results for independent variables

Table C-5. Reverse causality test estimations of dependent variable on independent variables

	Default s.e.			
VARIABLES	lCumModShip	lRDint	lRDEmp	eff
L.lCumModShip	0.521***	-0.0678	0.116	0.115**
	(0.0945)	(0.253)	(0.329)	(0.0528)
L2.lCumModShip	-0.0575	0.533	-0.589	-0.0473
	(0.118)	(0.316)	(0.411)	(0.0659)
L3.lCumModShip	0.0869	-0.355*	0.301	-0.0194
	(0.0672)	(0.180)	(0.235)	(0.0375)
L.lASP_r	0.0155	-0.321	-0.648	-0.369***
	(0.182)	(0.486)	(0.644)	(0.101)
L2.lASP_r	0.0640	-1.129**	0.361	-0.271**
	(0.199)	(0.532)	(0.775)	(0.111)
L3.lASP_r	-0.107	0.712	0.397	-0.259**
	(0.188)	(0.504)	(0.683)	(0.105)
L.lRDint	-0.0360	-0.109	-0.0194	-0.00810
	(0.0603)	(0.161)	(0.233)	(0.0336)
L2.lRDint	0.0114	-0.0591	-0.260	0.0130
	(0.0646)	(0.173)	(0.270)	(0.0360)
L3.lRDint	-0.0696	-0.133	0.0546	-0.0138
	(0.0624)	(0.167)	(0.218)	(0.0348)
L.lRDEmp	0.120**	0.0131	0.651***	0.0162
	(0.0498)	(0.134)	(0.197)	(0.0278)
L2.lRDEmp	-0.0216	0.0114	-0.145	0.0503**
	(0.0436)	(0.117)	(0.163)	(0.0243)
L3.lRDEmp	-0.00562	-0.0405	-0.167	0.00254
	(0.0455)	(0.122)	(0.165)	(0.0254)
L.eff	0.224	-1.243*	1.067	-0.570***
	(0.271)	(0.726)	(0.951)	(0.151)
L2.eff	0.0678	0.422	0.0495	-0.00842
	(0.208)	(0.558)	(0.728)	(0.116)
L3.eff	-0.0562	0.644	-0.625	1.152***
	(0.239)	(0.640)	(0.832)	(0.133)
Constant	0.0146	2.704	-3.478	7.636***
	(1.765)	(4.729)	(6.163)	(0.985)
Observations	59	59	58	59
R-squared	0.989	0.448	0.665	0.997
Number of firmID	10	10	10	10

Standard errors in parentheses

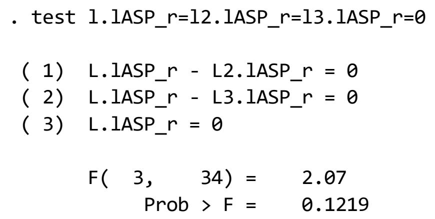
*** p<0.01, ** p<0.05, * p<0.1



```
. test l.lASP_r=l2.lASP_r=l3.lASP_r=0

 ( 1)  L.lASP_r - L2.lASP_r = 0
 ( 2)  L.lASP_r - L3.lASP_r = 0
 ( 3)  L.lASP_r = 0

       F(  3,    34) =    0.12
            Prob > F =    0.9482
```



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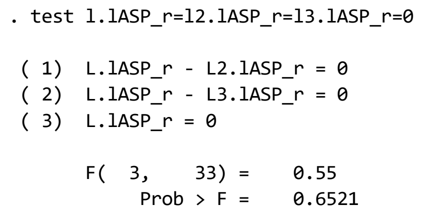
. test l.lASP_r=l2.lASP_r=l3.lASP_r=0

 ( 1)  L.lASP_r - L2.lASP_r = 0
 ( 2)  L.lASP_r - L3.lASP_r = 0
 ( 3)  L.lASP_r = 0

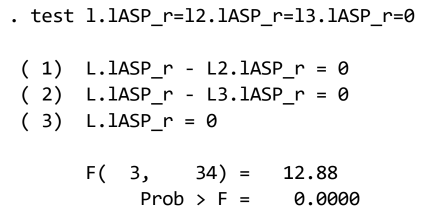
       F(  3,    34) =    2.07
            Prob > F =    0.1219
```



```
. test l.lASP_r=l2.lASP_r=l3.lASP_r=0

 ( 1)  L.lASP_r - L2.lASP_r = 0
 ( 2)  L.lASP_r - L3.lASP_r = 0
 ( 3)  L.lASP_r = 0

       F(  3,    33) =    0.55
            Prob > F =    0.6521
```



```
. test l.lASP_r=l2.lASP_r=l3.lASP_r=0

 ( 1)  L.lASP_r - L2.lASP_r = 0
 ( 2)  L.lASP_r - L3.lASP_r = 0
 ( 3)  L.lASP_r = 0

       F(  3,    34) =   12.88
            Prob > F =    0.0000
```

Figure C.8. Reverse causality t test results of dependent variable on independent variables

D. INTERVIEW QUESTIONS

INTRODUCTION:

Please answer the questions by regarding crystalline silicon (c-Si) photovoltaic (PV) technology if otherwise not indicated. If you have comments/views from another technology perspective, please indicate. If you have any confusion about the clarity of the questions or need more elaboration, please ask for more guidance.

INFORMATION ABOUT THE INTERVIEWEE:

- How long have you been experienced in PV and particularly in crystalline silicon PV technology?
- Currently, in which country do you perform your relevant work/studies?
- In which part of PV industry have you been involved?
    a. Manufacturing/production
    b. Quality
    c. Research and Development (R&D)
    d. Other:
- In which step(s) of PV value chain have you been involved? *(ingot/wafer/cell/module/PV plant)*
- How do you define the type of the organization you work for?
    a. University/R&D institute
    b. Private/public company
    c. Non-Governmental Organization (NGO)

QUESTIONS:

1. Technology Readiness Level (TRL) is crucial to understand the phase of a research and development effort. By referring to the European Commission's guideline (the table at the end of the page will be shown to the interviewee):
   a. What is the most common TRL that PV manufacturing companies start their product-based research activities?
   b. From that level to TRL 9, how many years does it take, either the research is conducted by the private company itself or in collaboration with Research Institutes (RI)? (If the interviewee has no idea about the starting level, it will be set as 4)
   c. How many years does it take for process improvement focused R&D? (again, directly by PV manufacturing companies or in collaboration with RIs)
   d. What kind of factors can affect this time period?
2. How long does it take a PV technology developed to become obsolescent? *(What is the duration for depreciation of a PV technology?)* Does it change in time/for different time periods?
3. What is needed to utilize PV R&D more efficiently in terms of technological advance and faster commercialization? *(e.g. skilled labor, more R&D personnel, infrastructure, expenditure, etc.)*
4. How can R&D contribute to decrease in cost of PV technology and where should it be directed more? Please elaborate it by referring to the representative options below.
   a. Decrease in Amount of Materials or Replacement of Some Materials
   b. Efficiency Increase by Process Optimization or Product Design
   c. Higher Process Yield by Process Optimizations
   d. Higher Process Throughput by New Machinery Designs
   e. Other
5. How do you think vertical integration along the value chain affect the performance of the PV companies/institutes?

6. Have you ever gained any beneficial feedbacks for your work from being an end-user of PV products or being involved in PV power plant applications? (Individually or in terms of corporate experience)
7. This question is about interactions that contribute to the improvement of PV technology, and it has 2 levels. I kindly ask you to answer the question first based on national level and then international level. Under each level, there are two different perspectives. First refer to the country you have carried out your professional PV activities for the longest time and then China if your first answer is not based on China. I will give some guiding examples but please feel free to elaborate and variate them.

   (e.g. collaboration with RI/universities; conferences; chamber/union organizations; user experiences; interactions within manufacturing value chain (supplier); collaborations with upstream machinery companies; market relations (via exports or national customers); government campaigns; outreach activities (public relations))

   a. What kind of national interactions are more fruitful for the improvement of PV technology?
   - Your country perspective
   - In China

   b. What kind of international interactions are more fruitful for the improvement of PV technology?
   - Your country perspective
   - In China
     a. In your opinion, which one is more critical?
8. How does labor force affect PV manufacturing costs?
9. By not considering extremely novel or very old-fashioned technologies, do you think that an average PV manufacturer can make a significant difference in cost or performance by changing the machinery?
10. Is there any difference you know between the quality of PV modules produced for (or sold to) Western markets and China? (From 2003 to 2018)

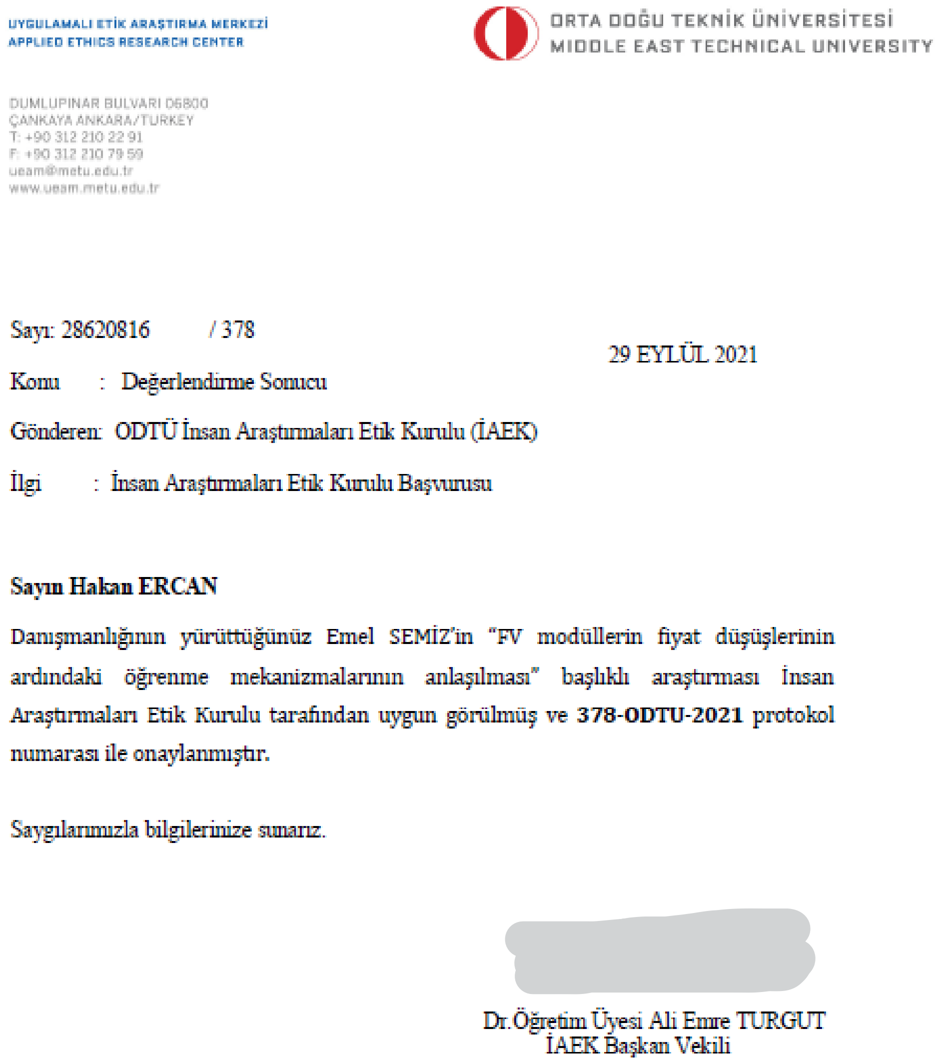
11. How do you think anti-dumping precautions help manufacturers outside China?
12. What do think for the future of different materials as a full replacement of or in combination with silicon in terms of their advantages and disadvantages? *(e.g. cost, durability, reliability, toxicity, need of rare materials, suitability for different kind of applications i.e. buildings, vehicles, off shore, fast consumable type)*

FINAL APPROVAL:

Do you approve use of your open identity information i.e. your name surname and name of the organization you are affiliated to in the interview participants list and acknowledgement?

TRL #	**Definition**	**Description**
TRL 0	**Idea**	Unproven concept, no testing has been performed.
TRL 1	**Basic principles observed**	Basic research. Principles postulated and observed but no experimental proof available
TRL 2	**Technology concept formulated**	Technology formulation. Concept and application have been formulated.
TRL 3	**Experimental proof of concept**	Applied research. First laboratory test completed; proof of concept
TRL 4	**Technology validated in lab**	Small scale prototype built in a laboratory environment ("ugly" prototype)
TRL 5	**Technology validated in relevant environment**	Large scale prototype tested in intended environment
TRL 6	**Technology demonstrated in relevant environment**	Prototype system tested in intended environment close to expected performance
TRL 7	**System prototype demonstration in operational**	Demonstration system operating in operational environment at pre-commercial scale
TRL 8	**System complete and qualified**	First of a kind commercial system. Manufacturing issues solved
TRL 9	**Actual system proven in operational environment**	Full commercial application, technology available for consumers

E. APPROVAL OF THE METU HUMAN SUBJECTS ETHICS COMMITTEE



UYGULAMALI ETİK ARAŞTIRMA MERKEZİ
APPLIED ETHICS RESEARCH CENTER

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29 EYLÜL 2021

Konu : Değerlendirme Sonucu

Gönderen: ODTÜ İnsan Araştırmaları Etik Kurulu (İAEK)

İlgi : İnsan Araştırmaları Etik Kurulu Başvurusu

Sayın Hakan ERCAN

Danışmanlığının yürüttüğünüz Emel SEMİZ'in "FV modüllerin fiyat düşüşlerinin ardındaki öğrenme mekanizmalarının anlaşılması" başlıklı araştırması İnsan Araştırmaları Etik Kurulu tarafından uygun görülmüş ve **378-ODTU-2021** protokol numarası ile onaylanmıştır.

Saygılarımızla bilgilerinize sunarız.

[redacted]

Dr.Öğretim Üyesi Ali Emre TURGUT
İAEK Başkan Vekili

F. THE OPEN IDENTITY PROFILE OF THE INTERVIEWEES

Table F-1. The open identity profile of the interviewees

Name Surname	Country	Organization	Position & Organization
Arthur Weeber	[redacted]	[redacted]	Program Manager Solar Energy at TNO/Full Professor of Applied Si Photovoltaics at TU Delft
Carlos del Canizo	[redacted]	[redacted]	Director of Solar Energy Institute/Full Professor at Technical University of Madrid
Christian Buchner	[redacted]	[redacted]	Vice President at SCHMID Group Business Unit PV
Fırat Es	[redacted]	[redacted]	R&D Manager at Kalyon PV
Gangadharo Rao	[redacted]	[redacted]	Director of AV Solar
Ivan Gordon	[redacted]	[redacted]	Manager PV Technology and Energy Systems at IMEC (Energyville) /Professor Digital Photovoltaics at TU Delft
Mehul Raval	[redacted]	[redacted]	Chief Engineer at RCT Solutions
Mete Günöven	[redacted]	[redacted]	Chief R&D Engineer at Kalyon PV
Paul Ni	[redacted]	[redacted]	Senior Vice President and Dean of the Academy of Solar Energy Research at AKCOME
Peter Fath	[redacted]	RCT Solutions/Kalyon PV/ The International Solar Energy Research Center (ISC) Konstanz / The Mechanical Engineering Industry Association (VDMA)	CEO of RCT Solutions/CTO at Kalyon PV/Member of Executive Board of Directors at ISC Konstanz/Chairman of the Executive Board of VDMA PV Equipment Supplier Division
Pietro P. Altermatt	[redacted]	[redacted]	Principal Scientist at Trina Solar/ Instructor at Oxford University
Raşit Turan	[redacted]	Center for Solar Energy Research and Applications (ODTÜ-GÜNAM) /Middle East Technical University (METU) Physics Department	Chairman of the Executive Board at GÜNAM /Full Professor at METU Physics Department
Stefaan de Wolf	[redacted]	[redacted]	Associate Professor in Material Sci.&Eng. and Interim Assoc. Director of Solar Center at KAUST

Table F-2 (continued)

Name Surname	**Country**	**Organization**	**Position & Organization**
Wolfgang Jooss	[redacted]	[redacted]	R&D Director at RCT Solutions/Instructor at ISC Konstanz
Lotfi Bounaas	[redacted]	[redacted]	[redacted] Partnerships at CEA
Pierre Verlinden	[redacted]	[redacted]	Founder, Managing Director (CEO/CTO) Amrock Pty Ltd and adjunct professor at UNSW (independent director of 2 PV companies & advisor to a couple of PV companies)
Yang Yang	[redacted]	[redacted]	CTO at Runergy
Arnulf Jäger-Waldau	[redacted]	[redacted]	Senior Expert at European Commission, JRC
Joseph Haase	[redacted]	[redacted]	Senior Vice President of Process & Technology PV at Centrotherm

G. CURRICULUM VITAE

PERSONAL INFORMATION

Surname, Name : Semiz, Emel

Date and Place of Birth [redacted]

e-mail [redacted]

EDUCATION

Degree	Institution	Start-Graduation
PhD	METU / Sci.&Tech. Policy Studies	2013-2023
MSc	Hacettepe Uni. / Chem. Eng.	2006-2008
BSc	Hacettepe Uni. / Chem. Eng.	2002-2006

WORK EXPERIENCE

Year	Organization	Position
[redacted]	[redacted]	[redacted]

FOREIGN LANGUAGES

English (advanced), German (beginner)

PUBLICATIONS

Journal Articles

1. Hisham Nasser, Fırat Es, Mona Zolfaghari Borra, **Emel Semiz,** Gamze Kökbudak, Efe Orhan and Raşit Turan, On the Application of Hole-Selective MoO x as Full-Area Rear Contact for Industrial Scale p-type c-Si Solar Cells, Progress in Photovoltaics: Research and Applications, 1-13. (2020) doi:10.1002/pip.3363.
2. Fırat Es, **Emel Semiz,** Efe Orhan, Ezgi Genç, Gamze Kökbudak, Gülsen Baytemir, Raşit Turan, Optimization of PERC Fabrication based on loss analysis in an industrially relevant environment: First results from GÜNAM Photovoltaic Line (GPVL), Renewable Energy, 146, 1676-1681. (2020). doi:10.1016/j.renene.2019.07.149

Conference Proceedings

1. Gamze. Kökbudak, Efe Orhan, Fırat Es, **Emel Semiz** and Raşit Turan, "Optimization of Silicon Nitride (SiNX) Anti-Reflective Coating (ARC) and Passivation Layers Using Industrial Plasma Enhanced Chemical Vapor Deposition (PECVD) for PERC Type Solar Cells," 2018 International Conference on Photovoltaic Science and Technologies (PVCon), Ankara, Turkey, (2018), pp. 1-5. Conference Proceedings, IEEE. doi: 10.1109/PVCon.2018.8523918
2. **Emel Semiz**, "Knowledge development in Turkish solar cell sectoral innovation system with functional dynamics approach", SolarTR 2014 Solar Conference and Exhibition, (2014) Izmir, Turkey.
3. **Emel Semiz**, Odabaş Sedat, Bişkin Erhan, “Magnetically Loaded Polycationic Nanoparticles For Plasmid DNA Isolation and Gene Transfer”, 4. Nanoscience and Nanotechnology Conference, Istanbul Technical University, (2008). Istanbul, Turkey.

Conference Presentations

1. M. Zolfaghari Borra, **Emel Semiz,** Ozan Aydin, Hisham Nasser, Ihor Pavlov, Firat Es, Rasit Turan “Emitter Formation on n-Type Crystalline Silicon Rear Side Using Aluminum Firing and Etching” EUPVSEC (2020) online (poster)
2. Ozan Aydın, Mona Zolfaghari Borra, **Emel Semiz**, Fırat Es, Metal Assisted Texturing on Micro Pyramids For Enhanced Anti Reflective Properties, PVSEC, Marseille, France (2019) (poster)
3. Hisham Nasser, Fırat Es, Mona Zolfaghari Borra, **Emel Semiz**, Efe Orhan, Gamze Kokbudak, Raşit Turan, Industrial Scale p-Type c-Si Solar Cells Featuring Hole-Selective MoOx Rear Contact with Efficiencies Above 17.6%, SiliconPV, Leuven, (2019). (poster)
4. Fırat Es, **Emel Semiz**, Raşit Turan, GÜNAM Photovoltaic Line (GPVL) - A Pilot Research Line for PERC/PERL/PERT Concepts, EUPVSEC, Brussels (2018). (poster)
5. Ezgi Genç, Deniz Türkay, Gamze Kökbudak, **Emel Semiz**, Fırat Es, Selçuk Yerci, Raşit Turan, Effects of Laser Parameters on Rear Contact Formation and Passivation of PERC Type Silicon Solar Cells, EUPVSEC, Brussels (2018). (poster)
6. Efe Orhan, Gamze Kökbudak, **Emel Semiz,** Fırat Es, Raşit Turan, Optimization Of Open-Tube Furnace Diffusion With BBr3 Liquid Source For Industrial P-Type Boron Doping Process, PVCON2018 International Conference on Photovoltaic Science and Technologies, Ankara – Turkey (2018). (poster)
7. Fırat Es, **Emel Semiz**, Efe Orhan, Ezgi Genç, Gamze Kökbudak, Gülsen Baytemir, Raşit Turan, Analysis Of The First Perc Type Cell Fabricated In GÜNAM Photovoltaic Line (GPVL), PVCON2018 International Conference on Photovoltaic Science and Technologies, Ankara – Turkey (2018). (poster)

8. Gamze Kökbudak, Efe Orhan, **Emel Semiz,** Fırat Es, Raşit Turan, Optimization of Silicon Nitride (SiNx) Anti-Reflective Coating (Arc) And Passivation Layers Using Industrial Plasma Enhanced Chemical Vapor Deposition (PECVD) For PERC Type Solar Cells, PVCON2018 International Conference on Photovoltaic Science and Technologies, Ankara – Turkey (2018). (poster)
9. **Emel Semiz**, "Knowledge development in Turkish solar cell sectoral innovation system with functional dynamics approach", SolarTR 2014 Solar Conference and Exhibition, İzmir, Turkey (2014). (oral)
10. Utkan, Güldem, Sayar, Filiz, **Semiz, Emel** ,Odabaş, Sedat, Bişkin, Erhan, “Magnetically Loaded Polymeric Nanoparticles for Plasmid DNA Purification”, International Congress in Medicine and Biology, Bionanomed 2009 Danube University, Krems, Austria (2009). (oral)
11. **Emel Semiz**, Odabaş Sedat, Bişkin Erhan, “Magnetically Loaded Polycationic Nanoparticles For Plasmid DNA Isolation and Gene Transfer”, 4. Nanoscience and Nanotechnology Conference, Istanbul Technical University, İstanbul, Türkiye (2008). (oral)

Theses

1. Emel Semiz, “Development of Magnetically Loaded Polymeric Nanoparticle Based Plasmid DNA Purification Kits”, MSc. Thesis, (2008)
2. Emel Semiz, “Learning Mechanisms Behind the Cost Decline Of Crystalline Silicon (c-Si) Solar Photovoltaic (PV) Modules”. PhD Thesis, (2023)

H. TURKISH SUMMARY / TÜRKÇE ÖZET

Giriş ve Arka Plan

İklim değişikliği önlemleri kapsamında 2016 yılında yürürlüğe giren Paris İklim Anlaşması ile birlikte, ulusal katkı beyanları kapsamında ülkelerin karbon emisyonlarını sıcaklık artışını 2ºC ve altında tutacak şekilde enerji dönüşümlerini gerçekleştirmesi gerekmektedir (UNFCCC, 2022a). Bu bağlamda, elektrik sektörünün karbonsuzlaştırılması büyük önem taşımaktadır. Küresel düzeyde nihai enerji tüketiminin %20'sini oluşturan elektrik enerjisi üretiminin daha çok yenilenebilir enerji kaynaklarına dayanması hızlı ve sürdürülebilir dönüşüm için elzemdir (IEA, 2021b). Diğer yandan, bu payın hem karayolu taşımacılığı, bina ısıtma, yüksek sıcaklıklı endüstriyel prosesler gibi enerji arzında farklı segmentlerin elektrifikasyonu hem de elektrik enerjisi kullanılarak üretilen yakıtların (örn. hidrojen) kullanımı yoluyla artması beklenmekte ve böylelikle yenilenebilir enerji (YE) kaynaklarının küresel ısınmayı önleme çabaları içinde kritik bir role sahip olacağı öngörülmektedir (IEA, 2021a, 2021b).

Enerji üretiminde kullanılan YE teknolojilerinin yaygınlaşması, yeşil dönüşüm ve iklim değişikliğinin hafifletilmesi amacıyla dekarbonizasyon politikalarıyla uyumlu olarak son 20 yılda hızlanmıştır. Bu arada, belirli enerji teknolojilerindeki kalıcı maliyet düşüşü, bunların genel enerji karışımındaki paylarında keskin bir artışa yol açmıştır. Bu anlamda güneş fotovoltaik (FV), son 10 yılda en hızlı kurulum oranına (IRENA, 2022a) ve en büyük maliyet düşüşüne sahip teknoloji olmuştur (IRENA, 2021). Ayrıca, 2050 yılına kadar, FV kurulu kümülatif kapasitesinin 2020 yılındaki değerinin 20 katına ulaşacağı tahmin edilmektedir (IEA, 2021a). Bu senaryoya göre güneş enerjisi, toplam enerji arzındaki %20'lik payı ile kapasite açısından en büyük kaynak olacak ve böylece küresel elektrik üretiminin %33'ünü sağlayabilecektir.

Yukarıdaki temel bilgiler ışığında, FV teknolojisindeki maliyet düşüşünü anlamak, yayılımını sürdürmek için çok önemlidir. Bu tez çalışmasının nihai amacı, piyasadaki FV modüllerinin %95'inin oluşturan kristal silisyum (k-Si) FV güneş modüllerinin (Fraunhofer ISE, 2022) maliyet düşüşünün ardındaki mekanizmaları belirlemek ve böylelikle daha etkili politika tasarımlarını mümkün kılmaktır. Buna yönelik olarak belirlenen temel araştırma sorusu şu şekildedir: "Kristal silisyum FV modüllerinin maliyetinin düşürülmesinde ne tür öğrenme mekanizmaları etkilidir?"

Bu sorunun cevabı, sırasıyla ekonometrik tahminlere ve uzman görüşmelerine dayanan hem nicel hem de nitel analizler kullanılarak sorgulanmıştır. Ana soru, bulguları detaylandırmak ve bunlardan çıkarılabilecek çıkarımları derinleştirmek için aşağıdaki alt sorular tarafından güçlü bir şekilde desteklenmiştir.

- Dahili öğrenme mekanizmaları, harici sektörel dinamiklerin kontrolü altında veya bunlarla kombinasyon halinde k-Si PV modüllerinin maliyetini ne ölçüde etkiler?
- k-Si PV endüstrisinde etkili veya etkisiz öğrenmenin altında yatan nedenler neler olabilir?
- k-Si PV endüstrisinde öğrenmenin başka yolları neler olabilir ve bunlar nasıl etkinleştirilebilir?

Yukarıdaki ilk alt soru nicel kısımda, farklı faktörlerle ilişkilendirilen birden çok değişkenin birim maliyet üzerindeki etkilerinin tahmin edilmesi ile ele alınmıştır. İkinci soru, ekonometrik bulgulara ve içsel öğrenme çabaları ile dış uyaranların ortak etkileri üzerinden açıklanan yenilik yetenekleri teorisine dayalı olarak kısmen cevaplanmıştır. Son olarak, ikinci alt sorunun hala detaylandırılması veya desteklenmesi gereken kısımları ve üçüncü alt soru, yarı yapılandırılmış uzman görüşmeleri yoluyla niteliksel bölümde incelenmiştir. Böylece, FV endüstrisinde öğrenmeyi tetiklemiş olabilecek potansiyel kanallar veya araçlar ve bunları kolaylaştırmış veya engellemiş olabilecek tutumlar aydınlatılmıştır.

Öğrenme eğrisi (LC) yaklaşımı, FV endüstrisinin gelişimine rehberlik eden birçok teknoloji yol haritası, sektör raporu gibi kaynaklarda (Feldman et al., 2021; Fraunhofer ISE, 2022; IEA, 2022; ITRPV, 2022). FV sistemlerinin veya FV modüllerinin maliyet eğilimini açıklamak ve tahmin etmek için yaygın olarak kullanılan bir araçtır. Bunun yanı sıra, FV teknolojisinin maliyet gelişimi, akademik düzeyde de birçok araştırmacı tarafından öğrenme eğrileri kullanılarak farklı yaklaşımlarla incelenmiştir (de La Tour et al., 2013; Gan & Li, 2015; Isoard & Soria, 2001; Kobos et al., 2006; Mauleón, 2016; Papineau, 2006; Pillai, 2015; Trappey et al., 2016; Wiebe & Lutz, 2016; Yu et al., 2011; Zheng & Kammen, 2014; Yi Zhou & Gu, 2019). Öğrenme eğrileri, kümülatif kurulum veya üretim her ikiye katlandığında bir teknolojinin birim maliyetinde sabit bir değişiklik olacağı varsayımına dayanır. Bu davranış, yıllar içinde biriken deneyimlerin getirdiği "yaparak öğrenme" etkisine atfedilir ve genellikle birikimli çıktı ile ilişkilendirilir (Arrow, 1962; Dosi & Nelson, 2010; Thompson, 2010).

Tarihsel olarak, ilk ilgili ampirik kanıt Wright tarafından uçak imalatında kümülatif çıktıya karşın artan emek üretkenliği olarak gözlemlenmiştir (Arrow, 1962; Dosi & Nelson, 2010; Thompson, 2010; Wright, 1936). İlerleyen yıllarda çeşitli teknolojiler için uygulanan öğrenme eğrilerinin birim maliyet tahmini için de geçerli olduğu gösterilmiştir (Berndt, 1991; Dutton & Thomas, 1984; Thompson, 2010). Bazı yazarların, firmalara yeni bilgi ve yetenekler sağlayanın statik çıktıdan ziyade kümülatif yatırım olabileceği tartışmalarına rağmen (Arrow, 1962; Thompson, 2010) yıllık çıktı miktarı sabit kalsa da yaparak öğrenme (LBD) etkisi gözlenmiştir (Alchian, 1949; Arrow, 1962; Berndt, 1991). Bu aynı zamanda, öğrenme etkisinin ölçek etkisinden ayrı birikimsel bir olgu olduğunu ortaya koymaktadır.

Deneyimin veya sözde öğrenme eğrisi fenomeninin daha derin bir şekilde anlaşılması çok önemlidir; çünkü firmaların, birikmiş çıktıyla birlikte gelen öğrenme avantajını kullanmak için pazara erken giriş yönünde kararlarını etkileyebilir (Berndt, 1991; Dutton & Thomas, 1984; Nemet, 2006; Rout et al., 2009). Ayrıca, zaman içinde diğer avantajlardan bağımsız olarak öğrenme yatırımları, yani kapasite eklemeleri yapmaya karar verebilirler (Dutton & Thomas, 1984; Rout et al., 2009). Öte yandan, hükümetleri veya diğer politika yapıcıları stratejilerini buna göre planlamaya ve uygun araçları tasarlamaya teşvik edebilir.

Öğrenme eğrilerinin en sık kullanılan versiyonu, yalnızca yaparak öğrenmeye bağlı olan tek faktörlü öğrenme eğrisidir (OFLC). Literatürde farklılıklar olsa da PV öğrenme eğrilerini kullanan sektörel yol haritaları veya trend analizi raporları, tahminlerini esas olarak bu temel versiyona göre oluşturur (Feldman et al., 2021; Fraunhofer ISE, 2022; IEA PVPS, 2022b; ITRPV, 2022). Küresel kümülatif üretimin veya kurulu kapasitenin her ikiye katlanmasına karşın toplam ortalama birim fiyattaki düşüşü (olgun bir pazarda maliyetin bir temsilcisi olarak) incelerler. Başka değişken içermeyen basit yapısı nedeniyle, veriler nispeten kolay erişilebilirdir ve öğrenme denkleminden çıkarılan öğrenme faktörüne kullanılarak geleceğe yönelik tahminler kolayca yapılabilir.

Ancak literatürde hesaplanan FV öğrenme faktörleri geniş bir aralıkta farklılık göstermektedir (Candelise et al., 2013; de La Tour et al., 2013; Neij, 2008; Nemet, 2009; Rubin et al., 2015; Samadi, 2018). Bunun nedeni, bağımlı değişkenin teknolojik kapsamındaki farklılıklar, kümülatif çıktı dışında başka açıklayıcı değişkenlerin kullanılması, farklı zaman dilimlerine veya coğrafi alanlara ait örneklemlerin seçilmesi gibi çeşitli faktörlerden kaynaklanabilir (Neij, 2008; Samadi, 2018). Ancak, bağımlı ve bağımsız değişkenler aynı kalsa bile, literatürde bildirilen öğrenme faktörleri geniş bir dağılıma sahiptir (de La Tour et al., 2013; Rubin et al., 2015; Samadi, 2018); bu da genel olarak analiz birimi küresel olan öğrenme hızlarının güvenilirliğini zayıflatır ve sonuçta politika tasarımında belirsizliğe yol açabilir.

Yalnızca kümülatif çıktı yoluyla deneyim birikimine dayanan öğrenme eğrilerinin bazı dezavantajları vardır. İlk olarak, tahmin tek değişken üzerinden gerçekleştirildiğinde, tespit edilen etkinin abartılı (gerçek değerinden fazla) olma riski taşır. Bu durum, sınırlı kaynakların yalnızca bir faktöre gereğinden fazla tahsis edilmesi sonucuna neden olabilir.

İkincisi, altta yatan farklı öğrenme mekanizmaları veya dış etkilerle ilgili olabilecek diğer nedenlerin keşfedilmesini engeller (Samadi, 2018; Wiesenthal et al., 2012; Yeh & Rubin, 2012) ve böylece diğer etmenler yeterli destekten yoksun kalırlar. Nihayetinde, bir faktöre dayalı tahminler, politika araçlarının ekonomik ve sosyal getirisini engelleyebilir.

Bazı yazarlar, Ar-Ge harcamaları, bilgi stoğu veya patentler gibi bilgiyle ilgili çeşitli parametreleri de modele dahil ederek bu sorunların üstesinden gelmeye çalışmışlardır (de La Tour et al., 2013; Kobos et al., 2006; Wiebe & Lutz, 2016; Zheng & Kammen, 2014). Bunlar literatürde genellikle iki faktörlü öğrenme eğrisi (TFLC) olarak adlandırılır. Ayrıca tesis ölçeği, hammadde fiyatı, enerji fiyatları, diğer girdi fiyatları, kırılma zamanları veya harici teknolojik ilerleme gibi diğer birçok değişkenin de TFLC modellerine (de La Tour et al., 2013; Wiebe & Lutz, 2016) veya yalnızca yaparak öğrenme parametresine ek olarak (Gan & Li, 2015; Isoard & Soria, 2001; Mauleón, 2016; Papineau, 2006; Pillai, 2015; Trappey et al., 2016; Yu et al., 2011) dahil edilerek incelendiği çalışmalar vardır. Bu tür modeller genelde çok faktörlü öğrenme eğrileri (MFLC) olarak adlandırılır.

FV öğrenme eğrisi tahminlerini ek değişkenlerle iyileştirme girişimlerine rağmen, seçilen örneklem çerçevesi, kullanılan değişkenler veya tahmin metodolojisinin yetersizliği nedeniyle tahmin sonuçlarının güvenilir ve/veya işlevsel olarak değerlendirilmesinin önünde hala bazı engeller vardır. Buna sebep olan başlıca nedenler aşağıda kısaca özetlenmiştir:

- Öğrenme eğrileri ilk olarak tesis veya firma seviyesinde gözlemlenmiştir (Berndt, 1991; Dutton & Thomas, 1984). Ancak, mevcut PV öğrenme eğrisi çalışmalarında, ülke (Kim vd., 2017; Papineau, 2006) veya firma düzeyinde (Pillai, 2015; Reichelstein & Sahoo, 2018) yapılan birkaç çalışma dışında, analiz birimi olarak küresel ölçekte toplulaştırılmış veri kullanılır. Bu yaklaşım, zaman içinde değişen ülke veya firmaya özgü dinamikler gibi mekânsal düzeydeki etkilerin yakalanmasına izin vermez. Sonuç olarak, bu tür çalışmalarla, ulusal politikalar veya şirket stratejileri açısından çıkarımlarda bulunmak mümkün değildir.

- Öte yandan, kesiti küresel düzeyde toplulaştırılmış verilerle yapılan zaman serisi tahminleri, nispeten yeni sayılabilecek bir endüstri olan FV teknolojisi için ilgili verilerin 1970'lerin ortasından önce mevcut olmaması nedeniyle, genellikle (Feldman et al., 2021; ITRPV, 2022; Samadi, 2018) düşük sayıdaki gözlemlere dayanmaktadır. Akademik yayınların pek çoğu 35'in altında veri sayısı ile tahmin yapmaktadır (Samadi, 2018); bu durum modelin serbestlik derecesini azalttığı ve sonuç olarak tahminlerin anlamlılığını etkileyebileceği için çok fazla değişken kullanımına izin vermemektedir.
- Yaparak öğrenme etkisinin fazla tahmin edilmesi ve diğer parametrelerin katkılarının gözden kaçırılması, teknoloji deneyim eğrilerinde yanlı sonuçlara neden olur (Samadi, 2018; Yeh & Rubin, 2012). Yukarıda bahsedildiği gibi, bu sorunları çözmek ve nihai olarak doğru ve faydalanılabilir çıkarımlar yapmak için çeşitli ek değişkenler kullanılır. Bu değişkenler yazarlar tarafından belirlense de modellerde seçimleri veya kullanımları, verilerin mevcudiyeti ve kalitesi ve ayrıca istatistiksel gereklilikler ile sınırlıdır.
- Ayrıca, veri kaynaklı sorunlar nedeniyle öğrenme eğrileri tarafından yakalanamayan veya kantitatif yöntemlerle nedenselliği kapsamlı bir şekilde anlaşılamayan bazı etkiler olabilir. FV öğrenme eğrilerinin sınırlamalarının üstesinden gelmek için alternatif veya tamamlayıcı bir yöntem olarak mühendislik değerlendirmeleri veya aşağıdan yukarıya maliyet tahmini yaklaşımı önerilmiştir (Candelise et al., 2013; Kavlak et al., 2018; Neij, 2008; Nemet, 2006). Bunlar maliyet değişimini esas olarak birincil teknik faktörlere ayrıştırırlar; ancak bunlar üzerinde etkili olabilecek veya bunlarla etkileşime girebilecek herhangi bir endüstriyel veya firma bazlı dinamik hakkında bir anlayış sağlamazlar.

Yukarıdaki kısa tartışmadan da anlaşılacağı gibi, farklı modeller ve tamamlayıcı yöntemlerle FV teknolojisinde maliyet düşüşünü etkileyen faktörleri araştırmak için hala bir alan mevcuttur. Özetle, emsal çalışmalarda muğlak kalan noktaların ele alınıp aydınlatılarak, firma düzeyinde FV modüllerin fiyat düşüşüne neden olan faktörlerin daha doğru şekilde anlaşılması ve öğrenme eğrileri yaklaşımının farklı öğrenme mekanizmalarının varlığını da dikkate alarak geliştirilmesi bu çalışmanın motivasyonunu oluşturmuştur.

İlerleyen bölümlerde, çalışmanın metodolojik çerçevesi kapsamında kullanılan yöntemler ve veriler, araştırma bulguları ve tartışma, bunlardan çıkarılan politika tavsiyeleri ve tezin kritik bulguları ile eksik yönleri ve gelecek çalışmalar için öneriler kısımları sunulmuştur.

Metodolojik Çerçeve ve Veri

Bu çalışma, birbirini sırasıyla takip eden nicel ve nitel araştırmalar ile gerçekleştirilmiştir. İlk olarak öğrenme eğrisi yaklaşımından yola çıkarak firma düzeyinde panel veriye dayalı ekonometrik tahmin çalışması yapılmıştır. Daha sonra, buradan çıkan bulguların etkisini doğrulamak, niceliksel olarak açıklamayan yönlerini anlamak ve modellere dahil edilemeyen farklı etkileri araştırmak için dünyanın çeşitli yerlerinden 19 FV uzmanı ile yarı yapılandırılmış mülakatlar yapılmıştır. Bu iki aşamadan elde edilen bulguların ortak değerlendirilmesi ve tezin 2. bölümünde değinilen FV endüstrisinin tarihsel incelemesinden faydalanarak da politika önerilerinde bulunulmuştur.

Yukarıda da bahsedildiği gibi literatürde bulunan FV öğrenme eğrilerine dayalı bulgular çok fazla değişkenlik göstermekte ve tek faktöre dayalı tahminlerden elde edilen sonuçlar ihmal edilen değişken sapması nedeniyle yanıltıcı olma ihtimali taşımaktadır. Tez çalışmasında, bu farklılıklar 4 ana analiz seviyesinde sınıflandırılarak incelenmiştir.

Teknolojik analiz seviyesi, bağımlı değişkenin kapsamını belirler. FV teknolojisi için bu kapsam, santral kurulumu için gereken tüm FV ve diğer elektronik/elektriksel, yapısal bileşenleri ve arazi, iş gücü ve diğer yumuşak masrafları içeren sistem maliyeti; sistem maliyetinin yaklaşık %50'sini oluşturan FV modül maliyeti (ITRPV, 2021) sistem maliyetinin yanında enerji üretimini de dikkate alan seviyelendirilmiş elektrik üretim maliyeti (LCOE) veya sadece FV modül dışındaki diğer tamamlayıcı bileşenleri ifade eden sistem dengeleyicileri maliyeti (BOS) olabilir. FV modüller, hem sistemin ağırlıklı maliyet unsuru olduklarından hem de diğer kapsamlarda birden çok bileşenin farklı etmenlerden etkilenen farklı öğrenme hızları olabileceğinden (Ferioli et al., 2009; Junginger et al., 2005) en uygun bağımlı değişken olarak değerlendirilmiştir. Daha da detaylı değerlendirildiğinde, FV modül türlerinin yaklaşık %95'ini oluşturan kristal silisyum teknolojisi (Fraunhofer ISE, 2022) üzerinden yapılacak öğrenme eğrisi çalışmalarını daha güvenilir olacağı düşünülmüştür.

Mekânsal analiz seviyesi ise alınan örneklemin fiziksel sınırlarını belirler. Veriye erişilebilirliğin kolay olması ve en uzun süreli verinin bu ölçekte bulunabilmesi sebebiyle FV öğrenme eğrileri genelde küresel toplulaştırılmış veriye dayanmaktadır (Elia et al., 2021; Samadi, 2018). Fakat bu durum, bölgeler arası farklılıkları veya firma düzeyinde etkili olabilecek öğrenme faktörlerini gölgeleyerek kısıtlı bilgi ile hatalı politika çıkarımlarına sebep olabilir. Zaman serisine dayalı çalışmalar yerine hem yatay kesiti hem de zamanı kapsayan panel veri analizine dayanan çalışmalar iki seviyeyi de kapsadığından hem gözlem sayısını artarak modele güvenilir şekilde daha fazla değişken dahil etmeyi (serbestlik derecesini yükselterek) hem de bölgesel/mekânsal düzeyde etkileri ayrıştırmayı mümkün kılar.

Literatürde modül maliyetlerinde düşüşü inceleyen birkaç çalışmada ülke (Papineau, 2006)ve firma düzeyinde (Pillai, 2015; Reichelstein & Sahoo, 2018; Watanabe et al., 2000) panel veri kullanılmıştır. Bu çalışmalardan birinde (Papineau, 2006) havuzlanmış panel veri kullanıldığından kesit etkisini ayırt etmek mümkün olmaz ve tahminler bu etkiden arındırılmadığında güvenirlilik sorunu oluşur. Japon firmalarının verilerine dayalı ve havuzlanmış panel veri kullanan diğer çalışma yaparak öğrenmeden ziyade bilgi stoğuna bir başka ifade ile araştırarak öğrenme kavramına odaklanan bir diğer çalışma (Watanabe et al., 2000) da hem modelleme türü nedeniyle benzer sorunları taşımakta hem de oldukça hızla değişen FV teknolojisi için yeterince güncel olmadığından geçerliliği iyi değerlendirilmelidir. Diğer yandan FV modül maliyetlerindeki değişimin öğrenme eğrisi yaklaşımına benzer şekilde firma düzeyinde panel veri ile ekonometri imceleme yapan iki çalışmadan birinde (Reichelstein & Sahoo, 2018) kullanılan değişkenler sadece yaparak öğrenme ve ölçeğe indirgenerek limitli tutulmuş, diğerinde ise (Pillai, 2015) araştırarak öğrenme gibi temel öğrenme türleri yine ihmal edilmiş ve kullanılan diğer öğrenme türleri ve dışsal etkiler nihai modellerden çoklu korelasyon nedeniyle çıkarılmıştır.

Zamansal analiz seviyesi ise öğrenme hızının teknolojinin farklı evrelerinde değişkenlik gösterebilmesi nedeniyle tespit edilen öğrenme hızlarının sabit olmamasına neden olabilir (Ferioli et al., 2009). Buna yanı sıra, verinin erişilebilirlik sorunu nedeniyle öğrenme eğrilerinde, birim maliyetin temsilcisi olarak sıklıkla birim fiyatın bağımlı değişken tercih edilmektedir (Ferioli et al., 2009; Junginger et al., 2005; Rubin et al., 2015; Samadi, 2018). Fakat pazarın gelişim sürecinde değişkenlik gösteren farklı bileşenleri de içerdiğinden maliyette sabit bir düşüş olsa fiyattaki değişim pazarlama stratejisi, talep eğilimleri, endüstriyel yapı, sübvansiyonlar gibi nedenlerle bunu takip etmeyebilir (Candelise et al., 2013; Junginger et al., 2005; Rubin et al., 2015). Diğer yandan, gelişme dönemi, ardından kâr marjının yüksek tutularak pazar avantajının değerlendirildiği fiyat şemsiyesi evresi ve sarsılma sürecini takiben gelen kararlılık (stabilite) dönemi ile olgun pazarda marjın sabitlenerek fiyat ile maliyetin benzer hızda azaldığı varsayımı yapılır (Ferioli et al., 2009; Junginger et al., 2005; Neij, 2008).

Metodolojik analiz seviyesi ise kullanılan veri ve model yaklaşımını tanımlamaktadır. Yukarıda bahsedildiği gibi ülke veya firma ölçeğinde veri kullanmak teorik olarak hem açıklayıcı değişken çeşitliliği hem de kullanılan verinin boyutları açısından avantajlar sunduğundan farklı tahmin yaklaşımları ile daha geniş yelpazede değişkenler incelenebilir. Birden çok ülke veya firma ile zaman serisini birleştiren panel veri analizinin gözlem sayısına ve değişken çeşitliğine olan katkı sağlar. Buna ek olarak, birikimsel kapasiteden doğan yaparak öğrenme dışında, farklı öğrenme türlerinin gelişime ve yeniliğe yol açabileceğini dikkate alan modeller daha güvenilir ve politikalar açısından daha faydalı sonuçlar verebilir. Farklı öğrenme şekilleri ve bunların dinamik yetenekler ile olan bağlantısı aşağıda kısaca özetlenmiştir.

Yaparak Öğrenme (Arrow, 1962): Yukarıda da bahsedildiği gibi öğrenme eğrilerine temel olan ilk öğrenme şekli budur. En basit hali ile tekrar eden rutin işlemler sırasında farklı durumlarla karşılaşma ve buna istinaden biriken deneyim etkisi olarak tarif edilebilecek bu öğrenme tipi genellikle birikimli çıktı ile ilişkilendirilir (Arrow, 1962; Dosi & Nelson, 2010; Thompson, 2010).

Araştırarak Öğrenme (Cohen &Levinthal, 1989): Ar-Ge etkinliklerinin yeni şeyler keşfetme dışında öğrenme boyutu ve özümseme kapasitesine katkısı olarak tarif edilebilir. Özümseme kapasitesi nihayetinde yenilik ile sonuçlanan dinamik yeteneklerin bir bileşenidir.

Kullanarak Öğrenme (Rosenberg, 1982): İlk olarak kompleks teknolojilerin nihai kullanıcılar tarafından faydalanılma fonksiyonu olarak tanımlanmıştır. Daha açıkça, gerçek kullanım ortamımda uzun dönem performansı ve sunulan ürünün sınırlılıklarını kullanıcılar açısından anlama ve gerekli değişiklikleri yapma veya üreticiye yeni öneriler sunma işlemini anlatır (Kahouli Brahmi, 2008).

Etkileşerek Öğrenme (Lundvall, 1988): Başarılı bir yenilik için, kullanıcıların ihtiyaçlarını bilmek, yeni teknolojik fırsatları tanıtmak kadar önemli görülmüş ve bunun aynı kuruluş içindeki bireyler ve farklı departmanlar arasında organizasyon içi etkileşimleri ve bilgi paylaşımını gerektirdiği ifade edilmiştir. Bunlara ek olarak, ortak kodlar ve güvenin bu öğrenme türünde belirsizliği azaltacağı ve yenilik sürecini daha verimli hale getireceği öne sürülmüştür (Lundvall, 1988). Ayrıca, yaparak öğrenme sürecinde karşılaşılan yeni sorunlara çözüm aramanın, farklı öğrenme modellerini tetikleyebileceği ve dolayısıyla birçok aktörle etkileşime girmeyi gerektireceği ifade edilmiştir (Nielsen ve Lundvall, 2003). Bu öğrenme şekli üretici-kullanıcı düzlemi dışında, üreticiler, tedarikçiler, kullanıcılar, araştırma enstitüleri, politika yapıcılar gibi çeşitli paydaşlar arasındaki gayrı resmi ilişkiler, ağ oluşturma veya işbirlikçi faaliyetler yoluyla bilgi alışverişiyle sağlanan çok daha geniş bir kavramı ifade eder (Kahouli Brahmi, 2008; Mauleón, 2016; Rout et al., 2009; Yu et al., 2011).

Bu öğrenme türleri, doğrudan veya dolaylı olarak dinamik yetenekler kavramının zemini oluşturur. Dinamik yetenekler firmaların dış bilgiyi algılayıp özümseyip dönüştürecek içsel yetenekler geliştirerek yenilik yapma ve rekabet avantajı elde etme potansiyelini anlatır (Teece & Pisano, 1994). Kaynak tabanlı stratejiden ilham alan dinamik yetenekler yaklaşımı, firmaların varlıklarını uyarlama, bütünleştirme ve yeniden yapılandırma yeteneklerini tanımlar; daha geniş bir bağlamda, değişen teknolojik koşullar altında iktisadi oyuncuların ayırt edici kaynaklarından, süreçlerinden, örgütsel becerilerinden ve işlevsel yeterliliklerden oluşur (Teece et al., 1997; Teece & Pisano, 1994; Wang & Ahmed, 2007). Kurum için entegrasyonun sağladığı yerleşik hale gelmiş rutin ve iletişimler ve dezavantajları, genel olarak öğrenme başlığı ile ifade edilen tekrar eden pratikler ve denemeler, yeniden yapılanma ve dönüşüm kabiliyetleri organizasyonel ve yönetimsel belirleyiciler; teknolojik, tamamlayıcı, finansal ve mekânsal değerler pozisyonel belirleyiciler; patika bağımlılığı ve teknolojik fırsatlar da patika belirleyicileri olarak ifade edilebilir (Teece & Pisano, 1994). Farklı boyutlardaki bu belirleyiciler, yukarıda bahsi geçen tüm öğrenme türlerine değinir. İçsel etkileşimin yanı sıra, bunun getirdiği işletme körlüğünü aşacak ve yeni bilgiyi algılamaya izin veren dış iletişim; öğrenmenin belli bir olgunluğa gelebilmesi için rutinlerdeki değişim hızını patika bağımlılığının getirdiği faydaları değerlendirecek düzeyde tutma davranışı; diğer yandan araştırma ve geliştirme çabaları ile dışsal bilgiyi özümseme kapasitesi gibi tutumlara işaret eder.

Dinamik yeteneklerin bir bileşeni olarak açıkça kabul eden bir çalışmada özümseme kapasitesi, firmanın mevcut ve potansiyel rekabet avantajını birlikte belirleyen bilgiyi edinme (algılama), benimseme (anlama), dönüştürme (yeni bilgi ile mevcut bilgiyi birleştirerek yeni rutinler yaratma) ve kullanma (yeni rutinleri operasyonlarında değerlendirme) gibi dört yetenek boyutuyla yeniden kavramsallaştırılmıştır (Zahra & George, 2002). Bu yetenekler sayesinde dışarıdaki yeni bilgi kazanılır ve içsel bilgi ile birleştirilerek işlevsel bir forma dönüştürülür. Özümseme kapasitesinden bahseden ilk çalışmada Ar-Ge şiddeti (Ar-Ge harcamasının şirket büyüklüğü ile normalize edilmiş değeri) belirleyici olarak kullanılmış (Cohen & Levinthal, 1989a); fakat literatürdeki daha sonraki yaklaşımlarda, özümseme kapasitesini mümkün kılan faktörler, teknolojik bilgi, Ar-Ge personeli, Ar-Ge departmanı faaliyetleri, nitelikli personel, personel eğitimi, bilimsel çıktılar ve patentler, makineler, yani sermaye yatırımlarıyla gelen yeni bilgiler, ağlar yani ortaklıklar/bağlı kuruluşlar, etkinliklere katılma, araştırma ittifakları, organizasyon yapısı ve içinde bulunulan çevredeki koşullar olarak genişletilmiştir (Ayala et al., 2015).

Çalışmanın ilk ampirik basamağını oluşturan ekonometrik çalışmada, Amerikan borsasında işlem gören 11 FV firmasının 2003-2019 yılları arasındaki faaliyet raporlarından çekilen veriler kullanılmıştır. Sabit etkiler modeli kullanılarak gerçekleştirilen panel veri analizinde firmaların gözlemlenemeyen spesifik özelliklerinden arındırılmış tahmin yapılır. Dolayısı ile bunların yaratacğı yanlılık bertaraf edilmiştir. Kullanılan panel veride gözlemler dengesizdir. Bir başka deyişle mevcut yıl aralığında her firmanın faaliyeti söz konusu değildir; daha açıkça bazı firmalar sonradan faaliyete geçmiş, bir kısmı incelenen dönem içinde borsadan çekilmiştir. Bu sebeple, OFLC ve TFLC olarak ilk tahminler 115 gözleme dayalı olarak yapılmıştır. Bu modellerde LBD etkisi göstergesi olarak firmaların kümülatif modüle çıktıları (güç değeri-MW) ve araştırarak öğrenme (LBR) göstergeleri olarak Ar-Ge şiddeti ve Ar-Ge çalışan sayısı incelenmiştir. Bunlar açıkça temsil edilebilen iç öğrenme mekanizmaları iken; MFLC modellerinde, FV modül veriminin endüstri ortalaması ve zaman trendi gibi dış teknolojik gelişimi ve genel ilerlemeyi temsil eden firmadan bağımsız etkiler ve bir başka dışsal etki olan polisilisyum hammaddesinin modüldeki birim maliyeti (2015 ABD/W) ile firmanın dikey entegrasyonunu gösteren kukla değişkenin çarpımından oluşan etkileşim değişkeni k-Si PV modüllerinin maliyet düşüşü üzerindeki etkileri açısından incelenmiştir.

İlk grup genel ilk bakışta hem öğrenme eğrileri teorisi hem de dinamik yetenekler yaklaşımı ile açıklanabilirken; ikinci grup farklı çalışmalarda da değişik formlarda incelenmiş kontrol değişkenleridir (Mauleón, 2016; Papineau, 2006; Pillai, 2015; Trappey et al., 2016; Yu et al., 2011). Fakat bu tezin özgün katkılarından biri olarak ikinci gruptaki değişkenlerle ilk gruptaki değişkenlerin aynı modelde incelenmesi ve birlikte anlamlı çıkarak müşterek bir etki göstermeleri durumunda dinamik yetenekler teorisi kapsamında oldukça önem atfedilen etkileşim kavramının varlığını değerlendirmesidir. Daha açıkça, LBD ve LBR mekanizmalarının dışsal gelişmeler ile birlikte FV modül maliyetleri üzerinde negatif etkilerinin olması yani maliyet düşüşüne neden olmaları; firmaların içsel çabalarının özümseme kapasitelerini geliştirmesinin ve buna bağlı olarak dışsal bilgiyi fark etme/tanıma, anlama, iç bilgi ile birleştirerek yeni rutinlere dönüştürme ve bunları kendi operasyonlarında değerlendirme/kullanma faaliyetlerini gerçekleştirebilmelerinin göstergesi olabilir. Bu yaklaşımla ilk defa bu tez kapsamında, öğrenme eğrilerinde etkileşerek öğrenme kavramı incelenmiş ve dolaylı olarak da olsa varlığının ekonometrik çalışma ile gösterilmesi hedeflenmiştir.

Buna ek olarak ekonometrik modellerde kullanılan değişkenlerin bir kısmı farklı çalışmalarda değerlendirilmiş olsa da bir arada kullanımları ve bazıları modele dahil edildikleri yapı itibariyle ilgili literatürde ilktir. Ayrıca, aynı öğrenme türlerini temsil eden ve diğer çalışmalarda henüz rastlanmamış olan firma içi farklı karakteristiklere dayalı değişkenlerin etkisi de incelenmiştir. Araştırarak öğrenme, yaparak öğrenmeden sonra enerji teknolojileri öğrenme eğrileri literatüründe en çok incelenen öğrenme türüdür (Elia et al., 2021; Rubin et al., 2015; Samadi, 2018; Wiesenthal et al., 2012). Bu öğrenme türünü temsilen literatürdeki çalışmalarda sıklıkla kullanıldığı görülen göstergeler şunlardır: kümülatif araştırma harcamalarının cari yıl Ar-Ge harcamalarına belirli bir zaman gecikmesi ve yıpranma faktörleri dikkate alınarak eklenmesiyle hesaplanan bilgi stoku (Kobos et al., 2006; Watanabe et al., 2000; Yi Zhou & Gu, 2019), belirli bir gecikme ile kümülatif Ar-Ge harcaması (Wiebe & Lutz, 2016), kümülatif patentler (de La Tour et al., 2013), PV modüllerinin güç dönüşüm verimliliği (Pillai, 2015). Bu çalışmada ise, firmaların yıllık Ar-Ge harcamalarının net satışlarına oranı kullanılmış ve böylece temelde LBD üzerine kurulu modelde kümülatif çıktı ile korelasyonu olmayan bir LBR değişkeni FV öğrenme eğrileri için ilk defa kullanılmıştır. Ar-Ge şiddetine ek olarak özümseme kapasitesinin bir diğer göstergesi sayılan Ar-Ge çalışan sayısının etkisi de incelenmiştir.

Bunlar dışında, başka bir açıklayıcı değişken olarak firmaların dikey entegrasyonunu temsil eden kukla değişken ile temel hammadde olan polisilisyumun birim maliyetinin çarpımından oluşan bir etkileşim parametresi kullanılmıştır. Polisilisyum birim fiyatı fiyatının ($/kg) küresel PV modülü maliyetleri üzerindeki etkisi, LBD ve ölçek ve çeşitli kontrol değişkenleriyle birlikte (de La Tour et al., 2013; Gan & Li, 2015; Pillai, 2015; Yu et al., 2011) daha önce denenmiş olsa da firmanın üretim yapısını bu kadar net gösteren bir değişken etkileşimli olarak ilk defa incelenmiştir.

Ayrıca dışsal faktörler olarak değerlendirilen zaman trendi, FV modül veriminin endüstri ortalaması ve Çin'in FV değer zincirinde küresel ölçekte %50'den fazla pay ile baskın hale geldiği dönemi kapsayan 2011 sonrası yılları gösteren kukla değişkenin modeldeki diğer parametrelerle birlikte modül maliyetine etkisi araştırılmıştır. Özellikle son ikisi, yapılan araştırmaya dayalı olarak ilgili literatürde daha önce tarif edilen hali ve tanımı ile kullanılmamıştır.

Daha sonra nicel bulgular, daha derin bir analiz için nitel bir araştırmayla tamamlanmıştır. Uzman çıkarımları, PV LC tahminleri için iyi bir tamamlayıcı yöntem olabilir. Ancak genellikle ön analizde, yani nicel tahminler için veri girdisi sağlamak amacıyla kullanılırlar. Bazı yazarlar, belirli Ar-Ge senaryoları kapsamında gelecekteki maliyetleri tahmin etmek için doğrudan uzman görüşlerine (Bosetti et al., 2012; Verdolini et al., 2015), bazıları dolaylı bir yol izleyerek uzman görüşlerini, araştırma çabalarının aşağıdan yukarıya maliyet tahminlerinde kullandıkları seçilmiş bilimsel/teknolojik parametreler üzerine etkilerini belirlemek için kullanmıştır (Nemet & Baker, 2009). Ayrıca, nitel analiz yoluyla PV teknolojisinin maliyet düşüşünün ardındaki etkenleri bulmaya odaklanan çalışmalar da mevcuttur (Lam et al., 2018; Nemet, 2019). Diğer yandan, önemli ekonometrik bulguların arkasındaki nedenselliği anlamak ve modellere dahil edilemeyen veya dahil edilse de etkisi net olarak anlaşılamayan diğer faktörleri araştırmak için nicel PV öğrenme eğrisi tahminlerini nitel bir analizle ardışık olarak tamamlayan herhangi bir çalışmaya rastlanmamıştır.

Bu tez çalışmasında, dünyadan 19 FV uzmanı ile yarı yapılandırılmış mülakatlar yapılarak temelde ilk olarak nicel bulguları doğrulamak ve açıklanamayan nedenleri ve bu öğrenme türlerine yol açan araçları tespit etmek; ikinci olarak da modele dahil edilemeyen veya etkisi net anlaşılamayan faktörleri açıklığa kavuşturmak amaçlanmıştır. Uzmanlar bilgi yoğun yanıtlar alabilmek adına amaçsal örneklem ile uyumlu olarak anahtar bilir kişiler olarak değerlendirilebilecek nitelikte kişiler arasından seçilmiştir. Görüşmeler Skype ve Zoom gibi online görüşme uygulamaları üzerinden gerçekleştirilmiştir. Katılımcı tarafından kaydedilmesine izin verilmeyen 1 görüşme dışında 19 görüşmeden 18'i kayıt altına alınmıştır. Görüşmelerden biri teknik sorunlar nedeniyle ses kaydına alınmış, 17 görüşme ise hem ses hem de görüntü kaydına alınmıştır. Hazırlanan sorular üç grup altında incelenebilir.

Bu amaçla Ar-Ge odaklı soru grupları dışında, ekonometrik analize temel oluşturan öğrenme türleri ve dinamik yetenekler teoriler ile benzer bir temele dayanarak kullanarak öğrenme, dikey entegrasyon, yeni yatırımlar, iş gücü gibi iç etmenlerin yanı sıra, FV modüllerin sevkiyat bölgesine göre kalite farklılıkları, Çin'de üretilen modüllere uygulanan gözetim vergileri, kristal silisyum teknolojisinin geleceği gibi farklı boyutları da aydınlatması düşünülen yardımcı sorular sorulmuştur.

Bulgular ve Tartışma

Ekonometrik bulgular, öncelikle iki faktörlü öğrenme eğrisi yaklaşımı ile LBD göstergesi olan birikimsel modül çıktısı ve LBR parametreleri olarak hem Ar-Ge şiddeti hem de Ar-Ge personel sayısının 2 yıl gecikmeli değerinin birim modül maliyeti üzerine aynı anda negatif etkisi olduğunu göstermiştir. Bu bulgular, dinamik yetenekler yaklaşımı ile uyumlu olarak firmaların bu araştırma çabalarının, rutinlerini tekrar etme ile uyumlu ve sinerjik bir katkı sunduğuna işaret eder. Aynı zamanda yaparak öğrenme parametresinin, mevcut örneklem için genellikle yıllık bazda artan çıktı ile biriken bir yapıda olması, bu etkinin sadece rutin tekrara bağlı değil, yeni makine-ekipman yatırımının uyarıcılığından da (Arrow, 1962; Thompson, 2010) kaynaklanabileceğini düşündürmüştür.

Bunlara ek olarak, FV değer zinciri boyunca külçe büyütmeden başlayarak modül aşaması dahil dikey entegre olmaları halinde, firmaların modül maliyetlerinin polisilisyumun birim maliyetine bağlı olarak, entegre olmama durumuna göre anlamlı şekilde arttığı bulunmuştur. Model, polisilisyum krizi olarak görülen 2008 yılı ile (Bernreuter Research, 2022b) kontrol edildiğinde bu değişkenin anlamlılığı ortadan kalkmış, dolayısı ile kriz yıllarına özel olarak dikey entegrasyonun, firma maliyetlerini artırma yönünde etkilediği anlaşılmıştır.

Ayrıca dışsal etki olarak kullanılan 2011 yılı sonrası Çin'in FV değer zincirine hâkim olma durumu, modül verimi endüstri ortalaması ve zaman trendi gibi değişkenlerin, diğer tüm firma içi çabaları dolayısıyla öğrenme kanallarını da içeren bir modelde, hep birlikte anlamlı çıkmaları firmaların etkileşerek öğrendiklerine ve gelişen dinamik yeteneklerine veya bir başka deyişle dışarda var olan yeni bilgiyi özümseme kapasitelerinin varlığına işaret eder. Bu iki değişken de kümülatif kapasite ile yüksek düzeyde korelasyona sahip olup benzer yönde etki gösterirler. Bu nedenle, modele dahil edildiklerinde yaparak öğrenme etkisinin azaldığı görülmüştür. Yine de anlamlı çıkmaları, ağırlıklı olarak Çin'de üretim yapan örneklemin içsel ve dışsal etkileşimlerinin etkinliğine ve maliyet düşüşüne olan katkılarına işaret eder.

Diğer yandan, yürütülen niteliksel çalışmadan toplanan veriler mülakatlarda uzmanlar tarafından ortak veya benzer şekilde kullanılan belli anahtar ifadelere dayalı olarak kodlanmıştır. Aynı zamanda bu ifadeler Teknolojik Yenilik Sistemlerinin (TIS) incelenmesi için bir çerçeve sunan fonksiyonel dinamikler yaklaşımının yedi fonksiyonu altında da değerlendirilmiş ve TIS içinde kolaylaştırıcı ve engelleyici etmenler tespit edilmeye çalışılmıştır.

Uzman görüşmelerinden çıkarılan bulgular ekonometrik sonuçlarla uyumludur. Yaparak öğrenmenin yanında FV üretim hatlarında radikal teknolojik dönüşümlerden ziyade sık ve artımsal yatırımların maliyet açısından önemli olduğu; Ar-Ge harcamaları kadar idarenin Ar-Ge'ye olan adanmışlığı, bir anlamda yön belirleyici olarak kaynakları araştırmaya tahsis etme istekliliği; işgücü FV hatlarının yoğun otomasyon ile çalışması nedeniyle son yıllarda etkisiz bir faktör gibi görülse de yeni bilgiye ihtiyaç duyulduğunda nitelikli işgücünün FV'de hala çok kritik olduğu; dikey entegrasyonun FV sektörü için uzmanlaşma gerektiren basamaklar, iç rekabetin dış tedarikçilerde olduğu kadar etkin olmaması ve firma içi iletişimin verimli ve etkin bulunmaması gibi sebepler ile çok da etkili olmadığı, diğer yandan tedarikçilerle sıkı ilişkiler, uzun dönem ortaklıklar ile daha iyi yönetilebileceği; bilgi paylaşımında ve gelişiminde, ilk olarak tedarik zinciri aktörleri arasındaki ilişkilerinin, sonrasında Çin'deki FV endüstri kümelenmelerinde içinde çalışan hareketliliğinin ve aktörler arasında resmi olmayan iletişimlerin ve son olarak yurtiçinde sık olarak düzenlenen FV içindeki farklı gelişmelere odaklanan tematik konferansların yurtiçindeki en önemli etkileşim kanalları olduğu; FV alanında yurtdışı akademik eğitimlerin, yabancı ülkelerden anahtar FV uzmanlarının istihdamının, FV alanındaki yurtdışı konferanslara etkin katılımların, cihaz ithalatının ve Avrupalı FV ekipman üreticileri ile olan ilişkilerin uluslararası teknolojik gelişmeyi özümseme için en etkili bulunan etkileşim yolları olduğu gibi bulgular elde edilmiştir.

Sonuç olarak ekonometrik tahminlerdeki LBD ve LBR için elde edilen bulgular ve çıkarımlar doğrulanmış; diğer yandan 2011 sonrası Çin'deki FV değer zincirinin tüm basamaklarında (polisilisyum oranı hariç) %50 sınırını aşarak büyümesinin ekonometrik sonuçlarda maliyet üzerinde anlamlı seviyede azaltıcı etki olduğu bulgusu, yurtiçindeki tedarik zinciri aktörleri ve girişimlerin artmasına, alanda çalışan bireyler arasında formal ve formal olmayan yoğun iletişimlerin eşlik etmesi ile açıklanmış; dikey entegrasyonun avantajlarına rağmen FV sektöründe ilgili alt basamakların farklı uzmanlıklar gerektirmesi nedeniyle firmaların gelişimini engelleyebileceği anlaşılmış; dış teknolojik gelişmelerle içsel öğrenme çabalarının modelde bir arada anlamlı olması, uluslararası alanda bilgiye, bilgi yayılım etkinliklerine katılım, nitelikli işgücünün FV alanında bilgi gelişiminde ileride olan ülkelerde eğitim yoluyla yetiştirilmesi, ekipman ithalatı ve ilgili yurtdışı firmalarla bilgi paylaşımı yollarıyla erişildiği açıklanmıştır.

Özetle, yapılan mülakatlar, ekonometrik analizlerde açıkça incelenen öğrenme türleri dışında, dolaylı olarak çıkarımı yapılan özümseme kapasitesi ve dinamik yetenekler kavramlarının Çin FV firmalarında güçlü şekilde var olduğunu ve bu durumun sektörünün yaklaşık son 15 yıllık gelişiminde büyük rol oynadığı sonucuna varılmıştır.

FV sektöründe öne çıkan araştırma temaları, gözetim uygulamalarının etkili ve anlamlı olmaması, gibi tamamlayıcı bulgular da üstteki çıkarımlara ek olarak politika tasarımı için dikkate alınmıştır.

Politika Önerileri ve Sonuç

Tez çalışmasının nihai çıktısı olarak küresel ve ulusal seviyelerde politika önerilerinde bulunulmuştur. Ayrıca firma ölçeğinde yapılan çıkarımlardan da strateji tavsiyeleri oluşturulmuştur. Bu düzeylerde öne çıkan öneriler politika önerileri kısaca aşağıda özetlenmiştir.

Küresel ölçekte, FV teknolojisinin iklim değişikliğine olan katkısı ve bunun en etkin biçimde değerlendirilmesi politika önerilerinin temel motivasyonunu oluşturmuştur. Bunlar aşağıdaki gibi özetlenebilir.

- Kullanılan malzemelerin sürdürülebilirliğini hedeflenmesi ve FV modüllerinin ömrünün ve sahadaki güvenirliliğinin artırılması ve bu amaçla kaynakların modül verimi artışlarından ziyade malzeme azaltımı, mevcut malzemelerin daha sürdürülebilir malzemeler ile ikamesi gibi araştırma programlarına tahsis edilmesi.
- TRL5 olarak gösterilmiş olan ve daha iyi performans veya daha düşük maliyetle, kullanım amacına veya kurulum yerine göre farklılaşan FV teknolojilerinin giderek yaygınlaşması için özel sektörün uzun dönem saha güvenirliliği nedeniyle çekimser kaldığı finansman temin sorununun, kamu risk garantileri gibi risk kolaylaştırıcı araçlar kullanılarak çözülmesi ve bu teknolojilerin hızla ticarileşme aşamasına (TRL7/8) taşınması.
- Fikri Mülkiyet Hakkı kaynaklı sorunları aşmak ve enerji dönüşümüne hızlandırmak amacı ile araştırmaya tahsis edilen kaynakların etkin kullanımı için paydaşların kazançları oranında bağışta bulunacağı ve uygun şekilde çıktılarından faydalanacağı ortak araştırma merkezlerinin kurulması.
- Yine benzer amaçla Batı'daki bilimsel bilgi yoğun kuruluşlardaki araştırma faaliyetlerini finanse eden ve Doğu'daki endüstriyel olarak güçlü ticari aktörlerin az gelişmiş bölgeler (elektrik enerjisine ve suya erişimde sorun yaşayanlar veya elektrik sistemlerinin yeşil dönüşümü için desteğe ihtiyaç duyanlar) için ürün (PV modülü) bağışları karşılığında bu bilgileri kullanmalarına izin veren mevcut küresel fonların tasarımı veya kullanımı.

Ulusal ölçekte ise en öne çıkan politikalar aşağıdaki gibi özetlenmiştir:

- Tedarik zincirinin güvenliğini sağlarken bilgi gelişimini ve endüstrinin sürekliliğini de amaçlayarak FV sektörünün değer ve tedarik zincirindeki aktörlerin sayısını ve çeşitliliğini artırmaya yönelik farklı aktörlerin ortak faaliyetlerini gerektiren programlar tasarlamak.

- Yurtiçindeki bilginin etkin akışını kolaylaştırmak için FV alanında öne çıktığı görülen zımni bilgi paylaşımını tetikleyen iş gücünün hareketliliğini kolaylaştırmaya yönelik olarak FV endüstri kümeleri oluşumunun teşvik edilmesi.
- Ülkede nitelikli işgücünü yetiştirmek üzere FV alanında özelleşmiş eğitim/öğretim programlarının/müfredatlarının tasarlanması ve uluslararası eğitim olanaklarının FV alanında gelişmiş ülkelerde enstitülerle ikili anlaşma gibi yollarla sağlanması.
- Nakliye emisyonları, tedarik zinciri ile ilgili kalite/fiyat/temin sorunları gibi konuları aşmak için yerli üretimin artmasını teşvik etmek amacıyla yeni girişimleri çeşitli politika araçlarıyla desteklemek. Yeni yatırımlar için kamu risk garantileri; bir yandan yeni yatırımları hızlandırmak ve kolaylaştırmak için yerli üretime (makine/araç/malzeme) sağlanan teşviklerin yanında, FV üretim ekipmanları/malzeme ithalatına belirli bir süre için vergi avantajları sağlamak; üretim ortamını canlandırmak (yedek parça talebi yaratmak, istihdama ve sahada vasıflı işgücünün artmasına katkıda bulunmak dahil) veya bir başka ifadeyle üretimde kritik kütleyi oluşturmak adına belli bir süre Doğrudan Yabancı Yatırımları (FDI) teşvik etmek; istenen özelliklerde geliştirilen ürünlerin alımını garanti eden kamu ihaleleri ile hem bilgi gelişimini hem de yatırımların devamlılığını teşvik etmek olarak örneklenebilir.

Firma düzeyinde önerilen stratejilerin öne çıkanları ise aşağıda listelenmiştir.

- Oluşturulan ve güncellenen öğrenmenin sürdürülmesi amacıyla büyük genişletme planlarını veya kırılma yaratan teknolojileri beklemeden, üretim hattında artımlı ve kademeli yükseltmeler yapmak ve bunun için teknolojileri ve ilgili makineleri takip etmek ve uygun yatırım planları yapmak.

- Harici bilgiyi özümsemek için inovasyon yeteneklerini ve yeteneklerini artırmak için dahili olarak hiçbir radikal gelişme beklenmese bile Ar-Ge'ye yatırım yapmak ve bunu gelirle orantılı olarak artırmak.
- Geri dönüş alabilmek için nitelikli iş gücünü en az 2 yıl elde tutmak ve hareketliliğinin getirdiği bilgi akışından faydalanmak arasındaki dengeyi korumak adına kişilerin transferini kısıtlamayan ancak cazip koşullar (maaş, ödül, izin, takdir) sağlayarak kişilerin adanmışlığını artıran sözleşmeler yapmak ve diğer yandan çalışan geçişini kolaylaştırmak için endüstriyel kümelenmeler içinde yer almak.
- Kullanımdan kaynaklı uzun süreli saha bilgisinden yararlanmak için FV uygulama süreçlerinde bir şekilde (örn. kullanıcılarla yakın geribildirim iletişimi kurmak, kendi ürünleri ile test sistemlerinin kurulumu yapmak, bir faaliyet alanı olarak kurulum hizmetlerine doğrudan dahil olmak) yer almak.

Son olarak tez çalışmasından elde edilen genel sonuçlar şu şekilde özetlenebilir. İlk olarak, ekonometrik çalışmaya dayalı olarak FV endüstrisinde öğrenmenin farklı boyutlarının araştırılmış; daha sonra, elde edilen nicel sonuçlar, öğrenme ve dinamik yetenekler açısından nitel analizlerle doğrulanmış ve detaylandırılmıştır ve son olarak, FV'nin geliştirilmesinde etkili olan işlevsel mekanizmalar ve araçlar ortaya çıkarılmıştır. Daha sonra tüm bu bulgular ve çıkarımlar, farklı düzeyler için yapılan politika veya stratejik çıkarımlarda kullanılmıştır. Tez boyunca yapılan analizlerden ortaklaşa çıkarılabilecek öne çıkan sonuçlar aşağıda listelenmiştir:

- Çinli FV firmaları, çoklu öğrenme kaynakları yoluyla geliştirdikleri yüksek düzeyde dinamik yeteneklere sahiptir.
- Kademeli ve artımlı ekipman yükseltmeleri yapmak, PV endüstrisinde yaparak öğrenmenin bir başka önemli parçası olarak tanımlanırken, radikal değişiklikler birikmiş öğrenmeyi bozabilir.
- Gayri resmi etkileşimler yoluyla pervasız bilgi akışlarının sağladığı etkileşerek öğrenmenin, Çin'de gelişen FV endüstrisinin en önemli öğrenme araçlarından biri olduğu gösterilmiştir.

- Sahada uzun dönem güvenilirlik ve sürdürülebilirlik özelliklerine katkısı doğrulanmış FV modül teknolojileri yatırımlarının, TRL5'ten en azından ticarileştirme öncesi aşamaya (TRL7/8) kadar risk alma fonları veya benzer kaynaklarla desteklenmesi böylelikle küresel yeşil geçiş hedefleriyle uyumlu olan FV alanındaki araştırma çabalarının ticarileşmesini hızlandırabilir.
- Firmalar içindeki yerleşik iletişim ve tamamlayıcı rutinler, yeniliklerin ortaya çıkmasını engelleyebilir. Bu nedenle, firmalar içindeki dikey bütünleşmeden ziyade, FV imalat değer ve tedarik zincirinde stratejik ittifaklar daha avantajlı görünmektedir.
- Yoğun ve sık ilişkiler kurulabildiğinde, makine satıcısından malzeme tedarikçisine kadar tüm endüstriyel aktörleri kapsayan bir ekosistemin varlığı çok önemlidir.
- Ar-Ge emeği sadece araştırmaya katkı sağlamaz, aynı zamanda birikmiş üretim yoluyla öğrenme ile sinerji içinde çalışır. Kantitatif bulgulara göre Ar-Ge iş gücü 2 yıl sonra etkili olmaktadır. Diğer yandan, işgücünün hareketliliği, Çin FV endüstrisinin gelişimini kolaylaştıran temel bilgi akış kaynaklarından biri olarak tespit edilmiştir. Bu nedenle vasıflı işgücünü elde tutmak ve onun devrine izin veren bir ortam yaratmak arasındaki denge dikkate alınmalıdır.
- Ar-Ge emeği, gelirle orantılı Ar-Ge harcamaları, yani Ar-Ge yoğunluğu, kademeli ekipman yatırımları ve resmi veya gayri resmi etkileşimlerin hepsi birlikte, PV firmalarının dış bilgiyi özümseme kapasitesinin geliştirilmesine katkıda bulunur.
- Fikri mülkiyet endişeleri, gizlilik eksikliği, Çin'de bilgi gelişiminin hem engelleri hem de kolaylaştırıcıları olarak görülmüştür. Ancak bu, belirli bir teknoloji hakkında bir reçete paylaşımı veya know-how'a dayalı bir ilerlemeden ziyade daha sofistike ve uzun vadeli bir süreç olabilir. Çin'in son 20 yılda FV alanında sürekli artan liderliği göz önüne alındığında, işgücü hareketliliği, bireyler arasındaki gayri resmi etkileşimler, farklı paydaşlar arasında açık ve hızlı iletişim ve ulusal düzeyde düzenlenen konferanslar yoluyla teşvik edilen ve geliştirilen yetenekler sadece gizli bilginin kolayca

yayılmasına yarayan araçlar olarak değerlendirilmek yerine bu başarıdaki rolleri açısından daha geniş bir perspektiften algılanmalıdır.

- FV Ar-Ge'si, sürdürülebilirlik, bolluk, malzemelerin çevresel ve karbon ayak izi, ürünün yüksek performansta daha uzun süre kullanılması gibi çevresel endişeleri ve iklim değişikliğini doğrudan veya dolaylı olarak ele alan konulara daha fazla odaklanmalıdır.
- Finans ve yetkinliklerin bölgesel ve küresel düzeylerde ortak kullanımı, yakın gelecekte küresel olarak enerjinin geleceğini şekillendiriyor gibi görünen FV araştırmalarının etkinliğini ve hızını artırabilir. Bu nedenle, herhangi bir bölgeyi göz ardı etmeyen uluslararası iş birliği programlarının ve fonlarının tasarlanması ve belirli ölçüde uluslararası etkileşime açık bölgesel araştırma altyapılarının oluşturulması işlevsel olabilir.

Diğer yandan çalışmanın sahip olduğu belirli sınırlılıkları vardır. Bunlardan birincisi, ekonometrik analizde kullanılan gözlem sayısı ile ilgilidir. Az gözlem, araştırılabilecek değişken sayısını sınırlar ve değişkenlerin anlamlılık derecesini sınırlar. Bu da bulguların güvenilirliğini belirsiz kılar. Borsa Piyasalarında işlem görmeyen ancak benzer bilgileri sağlayabilecek diğer şirketlerin verilerine ulaşmak gözlem sayısını artırarak tahminlerin iyileştirilmesinde faydalı olabilir.

İkincisi, yeni olmasına ve öğrenme eğrisi literatürüne farklı bir yön sağlamasına rağmen, ekonometrik sonuçlardan yapılan etkileşerek öğrenme ile ilgili çıkarımlar, iç ve dış faktörlerin ortak önemine dayalı olarak dolaylıdır. Bu nedenle uzman görüşmeleri ile açıklığa kavuşturulmuştur. Araştırma iş birlikleri veya tedarik ilişkileri hakkında herhangi bir verinin ekonometrik modellere dahil edilmesi ile daha kesin çıkarımlar yapılabilir.

Üçüncüsü, etkisi PV LC literatüründe ilk kez araştırılan ve işlem maliyeti teorisine karşı dinamik yeteneklere bir engel olarak değerlendirilen dikey entegrasyon değişkeni ile kısmi entegrasyondan bu yana polisilisyum üretiminden sonraki dört ana adım kapsanmıştır. Hücre-modül veya dilim-külçe gibi ikili entegrasyon adımlarına yönelik örnekleme dayalı gözlemlerde zaman içinde yeterli varyasyon yoktur. Daha uzun zaman aralığı ve kesitsel gözlemlere sahip daha büyük bir veri seti ile belirli bölümler arasında entegre olmanın maliyet düşüşü üzerinde etkili olup olmadığını araştırmak faydalı olabilir.

Dört, sadece bu çalışmaya özgü değil, aynı zamanda öğrenme eğrisi teorisine genel bir eleştiri olarak, küresel toplu verilerin sahip olduğu handikaplar firma düzeyinde analizle aşılmış olsa bile, LBD yeni yatırımları bünyesinde barındırdığından hala belirsiz bir parametredir. Çünkü potansiyel olarak yeni teknolojilerin tetiklediği bilgi, tekrarlanan uygulamalardan ayırt edilemez. Sermaye yatırımları gibi bazı kontrol değişkenleri, bu tezde kullanılan örnekte olduğu gibi sürekli bir yatırım olduğunda kesin olarak artacağından, modele dahil edildiğinde kümülatif çıktı ile yüksek oranda ilişkili olma riski taşır. Anket tabanlı bir veri toplanabilirse, yeni teknolojilere yapılan yatırımlar sorgulanabilir ve bir kontrol kuklası olarak kullanılabilir.

Sonuç olarak, çalışmanın bu sakıncaları uzman görüşleri alınarak giderilmeye çalışılmıştır. Uzman mülakatları ölçülemeyen faktörlerin anlaşılması ve doğrudan veya dolaylı bulguların desteklenmesi açısından çok faydalı olmuştur. Bununla birlikte, daha fazla sayıda anahtar bilir kişi daha fazla ve farklı boyutlar ortaya çıkarabileceği ve soruların, FV teknolojisine dair bazı durumların tespiti için soruların daha spesifik olması gerektiği düşünülmüştür.

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<u>**TEZİN ADI /** TITLE OF THE THESIS</u> (**İngilizce** / English)**: LEARNING MECHANISMS BEHIND THE COST DECLINE OF CRYSTALLINE SILICON (c-Si) SOLAR PHOTOVOLTAIC (PV) MODULES**

<u>**TEZİN TÜRÜ**</u> **/** <u>DEGREE**:**</u> **Yüksek Lisans** / Master ☐ **Doktora** / PhD ☒

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