TRANSFORMATION PATHWAYS TOWARD A SUSTAINABLE ENERGY SYSTEM IN TURKEY

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ABSTRACT

TRANSFORMATION PATHWAYS TOWARD A SUSTAINABLE ENERGY SYSTEM IN TURKEY

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The important factors for designing and implementing a sustainable energy system consist of a sufficient, affordable, secure, and environmentally sound energy supply along with the efficient use of energy. Given its high dependency on foreign energy resources, the current energy system in Turkey is far from satisfying the criteria of a sustainable energy system. In addition, relying solely on fossil fuels is no longer a proper alternative mainly due to its impact on climate change and vastly diminishing resources. As the economy is expected to grow, proper planning and transformation pathway towards a more sustainable energy system is deemed necessary. This will involve a complete change in energy system's structure over the next decades. The system involved is quite complex, with new technologies, multiple agents, and new policies and actions. In order to realize a sustainable energy configuration, fossil fuel consumption would need to be reduced while significant proportion of renewable energy should be integrated to current energy system. In this study, several scenarios that reflect a sustainable energy system in Turkey will be developed, quantified, and assessed with the application of a Turkish energy model. Next, necessary actions in order to bring structural transitions in the current energy system will be proposed. The results of the study may contribute new insights on probable sustainable energy system in Turkey. The study will also provide pathway suggestions on how the transformation to such an energy system would be realized.

Keywords: Turkish Energy System, Sustainable Development, Climate Change, Energy Modeling, Energy Economics, Renewable Energy

ÖZ

TÜRKİYE’DE SÜRDÜRÜLEBİLİR ENERJİ SİSTEMİNEDOĞRU DÖNÜŞÜM YOLLARI

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Sürdürülebilir bir enerji sisteminin uygulanabilmesi; yeterli miktarda, ekonomik, güvenli ve çevreyle uyumlu enerji tedariği ile verimli enerji kullanımı gibi önemli faktörleri içermelidir. Türkiye’nin enerji sistemi büyük ölçüde fosil yakıta bağımlı ve sürdürülebilir enerji sisteminin özelliklerini karşılamaktan oldukça uzak bulunmaktadır. Bununla birlikte, sadece fosil yakıtlara bağımlı olmak, bu yakıtların iklim değişikliğine olan etkisinden ve kaynakları oldukça fazla azalttığından dolayı uygun bir seçenek değildir. Ekonominin hızla büyümesi öngörülürken, uygun planlama ve sürdürülebilir enerji sistemine doğru bir dönüşüm yolu oldukça gereklidir. Bunun için de enerji sisteminin yapısının önümüzdeki 10 yıllarda tamamen değişmesi gerekmektedir. Bu sistem yeni teknolojiler, birçok temsilci, yeni politika ve eylem içerdiğinden oldukça karışıktır. Sürdürülebilir enerji yapısının hayata geçirilebilmesi için, yenilenebilir enerjinin önemli miktarda mevcut enerji sistemine entegre edilmesi; fosil yakıt tüketiminin de eş zamanlı azaltılması gerekmektedir. Bu çalışmada, Türkiye’nin sürdürülebilir enerji sistemini gösteren çeşitli senaryolar, Türkiye’nin enerji modeline uygulanarak geliştirilecek, hesaplanacak ve değerlendirilecektir. Daha sonra, mevcut enerji sisteminde yapısal değişiklikler için gerekli eylem önerileri sunulacaktır. Bu çalışma, Türkiye’de uygulanacak muhtemel

bir sürdürülebilir enerji sistemi için yeni kavrayışlar kazandırarak katkıda bulunacaktır. Diğer bir yandan çalışma bu gibi enerji sistemlerine dönüşümün nasıl gerçekleştirilebileceğinin de özellikle üzerinde duracaktır

Anahtar Kelimeler: Türkiye Enerji Sistemi, Sürdürülebilir Kalkınma, Iklim Değişikliği, Enerji Modellemesi, Enerji Ekonomisi, Yenilenebilir Enerji

Dedicated to my beloved parents, Joeliaty and Asep Sufwana

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ABBREVIATIONS	
AD	Anno Domini
BaseCase	Base Case Reference Scenario
BCE	Before Common Era
CGE	Computable General Equilibrium
CMP	Common Measuring Points
COP	Conference of the Party
EAPI	Energy Architecture Performance Index
ESI	Energy Sustainability Index
FullRE	Full Utilization of Renewable Energy Scenario
GDP	Gross Domestic Product
GHG	Greenhouse gas
GTAP-CGE	GTAP-Computable General Equilibrium Model
GW	Gigawatt
HDI	Human Development Index
INDC	Intended Nationally Determined Contributions
IAM	Integrated Assessment Model
IEA	International Energy Agency
IO	Input-Output

INDC	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
LEAP	Long-range Energy Alternatives Planning Model
MaxLocal	Maximization Local Resource Scenario
MinGHG	Minimization GHG Emissions Scenario
MtCO2e	Million tonnes of CO_2 equivalent
MW	Megawatt
OPEC	The Organization of Petroleum Exporting Countries
Power-LP	Power Linear Program Model
R&D	Research and Development
SAM	Social Accounting Matrix
SESI	Sustainable Energy System Index
SDGs	Sustainable Development Goals
TWh	Terawatt-hour
UN	United Nations
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
WCED	World Commission on Environment and Development

CHAPTER 1

INTRODUCTION

1.1. Background

Traditionally, the use of energy is attributed to pursue solely the economic growth. However, as the demand of energy keeps increasing (along with the raise in population, income and changes in lifestyles), coupled by the intensifying pressure to the environment and diminishing resources, that mindset is deemed to be obsolete. The future energy system should not only be able to meet economic objectives, but simultaneously achieve environmental and social goals. In short, the energy system should be able to realize a sustainable development.

The current development pathway, however, produces and consumes energy in ways that could not be sustained. Thus, a quick shift to a more sustainable energy system is crucial. In this framework, the transition would require a complete socio-techno transformation within the energy system. In order to achieve that, two main tools are recognized: integration of new and renewable alternative energy supply and enhancing efficiency of energy use in all sectors.

Although the solutions are already known, the complexity of the energy system (i.e., the constraints in political/institutional, economic, social, and technological dimensions) makes it challenging in practical applications. By proposing a novel energy-economic modeling framework and the application of the resulting energy-economic model, the proposed study seeks to develop and compare energy system transformation pathways to realize a sustainable energy system. Turkish electricity system will be the case of the analysis.

1.2. Statement of the Problem

Energy system of the future should be sustainable. On one hand it should allow a secure and uninterrupted energy supply, on the other hand it should be able to meet the goal of the society without putting pressure on environmental sustainability.

The indicator-based measurement system has long been used to evaluate the sustainability of energy system. Some of the examples of such measurement are Energy Architecture Performance Index (EAPI) (World Economic Forum, 2017), Energy Sustainability Index (ESI) (World Energy Council, 2018) and Sustainable Energy System Index (SESI) (Fathurrahman, 2016). Although each index differs in terms of its calculation approach as well as set of indicators, the indicators generally reflect on three sustainable development dimensions: economic, social and environmental. For Turkey, none of the above-mentioned indexes favors a very strong sustainability in Turkish energy system. EAPI and ESI for instance, put a great concern on Turkish energy dependency on foreign supply. While SESI marks environmental sustainability as lowest score for the sustainability of Turkish energy system.

Hence, it is modest to argue that the current situation of Turkish energy system is still far from sustainable. In this study, as also put forward in Biresselioglu (2012) and Karagöz & Bakirci (2009), our points of departure are as follows: First is the huge dependency on fossil fuel-based resources. And second one is the high share of energy imports.

High dependency on foreign supply is putting energy security at risk as the energy supply is depended upon the foreign countries. Over the course of 1990-2017, Turkish energy imports (as a % of total energy use) has grown from 54% to 77% (GDEA ,2019) . Energy imports in 2011 were 113.4 Mtoe and has increased to 145.3 Mtoe in 2017, an annual growth rate of 4%. Without any significant changes in current energy system, the energy dependency is expected to reach 82% in 2020 (Sözen, 2009).

Geopolitical dynamics and fluctuation of energy prices are common risks that accompanied the country which depends too much on imported energy resources.

Furthermore, even though Turkey is blessed in its geographical position, i.e., located in-between fossil-fuel rich countries, the region is also subject to unstable geopolitical situation.

The portfolio of energy supply structure of Turkey is still dictated by fossil fuel resources. Based on Turkish energy balance table (GDEA, 2019), about 88% of total primary energy supply in 2017 is coming from fossil fuels. This is responsible for 379.9 million tonnes of CO_2 equivalent (MtCO2e), or corresponds to 72.2% of total greenhouse gas (GHG) emissions of Turkey in 2017 (TurkStat, 2019a). The continuing practice of fossil-fuel usage in energy sector is no longer desirable, mainly due to its impact on climate change and vastly diminishing resources. In Turkey, climate change will possibly decrease water resource, increase aridity and drought and increasing heat waves, which ultimately allow adverse impact to well-being of the people (Şen, 2013; Huhne & Slingo, 2011; MEU, 2018).

At the time of 21st session of the Conference of the Party (COP) to the United Nations Framework Convention on Climate Change (UNFCC) held in Paris, Turkish government submitted Intended Nationally Determined Contributions (INDC) to combat global warming. The document shows Turkish commitment to decrease GHG emissions up to 21% from the reference base level by 2030. This is equivalent to 929 MtCO2e in 2030. However, this figure is seen as a quite less ambitious target. According to Yeldan, Voyvoda, Berke, Şahin, & Gacal, (2015), under the climate policy package scenario[1], in 2030, it is possible to realize GHG emissions level of 506 MtCO2e. This level is also considered less ambitious compared to Turkey's fair share allocation[2]. Based on fair share allocation, in 2030 Turkey's GHG emissions should reach 265 MtCO2e.

[1] In the study (Yeldan et al., 2015) 'Climate Policy Package' refers to introduction of three policy instruments: taxing carbon emissions, investment fund of renewable energy and enhancement of energy efficiency.

[2] Fair share allocation refers to Turkey's equitable share of carbon budget with the aim to keep earth's temperature rise up to 2°C. The fair share is calculated using Climate Equity Reference Calculator, a tool created by the Stockholm Environment Institute and EcoEquity, accessible through

In order to deal with the problems, the design of a sustainable energy system need to be put forward. Since the energy system transition is a complex and capital-intensive process with a long-term nature. The desirable long-term future needs to be assessed and the possible pathways should be considered for the transition to happen.

1.3. Objectives and Research Questions

The central purpose of this study is to develop a hybrid energy-economic model to assess energy system pathways in realizing a sustainable Turkish energy system. In doing so, the study will also accomplish the following sub-objectives:

- Assessing the development of Turkish energy system and identify key challenges and constraints in terms of realizing sustainable development.
- Reviewing comparatively the studies in the field of energy system modeling.
- Improve understanding on how different pathways may have different economic costs and GHG emissions in different manner.
- Providing insight to policymakers in setting up long-term energy policy targets.

Furthermore, the main question of the study is 'How can the transition to a sustainable energy system in Turkey be attained?' In addition, the following sub questions will also be addressed:

- How is the development of Turkish energy system?
- What are the relevant long-term sustainable energy goals for Turkey?
- How can the long-term energy goals be achieved through several pathways?
- How does each pathway differ in terms of its economic costs and GHG emissions?

https://calculator.climateequityreference.org/. The basis of the calculations are demographic and macroeconomic indicators, historical responsibility in emissions, and present national capacity.

CHAPTER 2

ENERGY TRANSITION AND SUSTAINABLE ENERGY SYSTEM

2.1. Introduction

In the modern world, energy resources have become one of the most vital necessities to sustain human needs. Energy use has not only become a requisite to enjoy the good lifestyle we are having now, but also provided the basis for our civilization to grow and develop to the point where it was unimaginable before. Over time we observed that food production increased, the production of goods and services became more efficient, technological advancement accelerated, economy kept growing, and so forth, mostly due to the use of energy resources. Unfortunately, we have not only enjoyed benefits of energy consumption, but energy resources have also played an important role (and is still playing) during some unpleasant periods over conflict and war (Månsson, 2014; Mercille, 2010), economic crises (Commoner, 1976), unjust distributions (Spreng, 2005) and maybe the most importantly: severe environmental problems (Dincer, 1999).

These opposing consequences of energy utilization then raise challenges: Is it possible to keep getting the full advantages from the use of energy without harming the economy, society and the environment? Could the well-being that has been achieved be continued in the next generations? At least a part of the answers to these challenges involve transitioning to a sustainable energy system. Although applying the concept is believed to be technically possible (Hertwich et al., 2015; Barton et al., 2017; Schandl et al., 2016) and affordable (European Commission, 2016), this will require a complete change in the structure of the whole system over the next decades. Moreover, the energy system structure is quite complex and dynamic with new technologies, multiple agents, and new policies and actions emerging over time.

The chapter aims to present an insight of sustainability in the context of the energy system. It aims to give the reader overview on the historical evolution of the idea, and provide definitions and the theoretical framework. Furthermore, the three pillars of sustainable development and the forward-looking sustainable energy system will be introduced.

2.2. The Changing Role of Energy

This sub-chapter describes the historical development of human utilization of energy resources. It is characterized by the dynamic changes in the resources being used, advances in the technological, economic and social dimensions as well as in the various institutions involved in shaping our current energy system. History holds valuable leads for constructing subsequent energy transition policies. Through the wealth of historical evidence, we would hope to acquire knowledge on how similar transitions in the past happened, what the drivers and the implications to those changes are. There could be important lessons to foster our current goal at transitioning to sustainable energy system.

2.2.1. Energy Transitions in Human History

The use of energy has been changing dynamically throughout the human civilization. There are distinctive features in all of the eras which could be divided into several episodes. However, note that the typology of energy episodes over time does not mean to be viewed as a rigid categorization. Such effort would be unrealistic due to the complex system (involving spatial and temporal differences in the course of energy utilization by the human kind) and also the evolutionary nature of energy transitions itself (Smil, 1994).

The characteristics of the energy episodes is due to the variations of the impact of energy use and resources in human development. Smil (2004) argued that there were at least 4 major energy eras distinguished by the major transitions which were happening in the history of human civilization. The first era, the era of nomadic Homo Sapiens, started in the prehistorical time more than around 300,000 years ago and lasted until the societies started to settle in around 10,000 years ago. At first, the utilization of energy is limited only by human muscle and some inefficient use of fire to cook and to get warm. The activities to increase the output of gathering (and consuming) food was thus very important for survival. Following the hunting-gathering period, gradual shifting to agriculture were driven by a number of reasons such as increase in the population, energy-related issues, nutritional and social factors (Smil, 2004).

As the society started cultivating and farming, domestication of draft animals became necessary due to the increasing size of fields and trade which makes the tasks more demanding. This resulted in the substitution of human by animal muscle power and was noted as the first great energy transition in prehistoric times (Smil, 2004). As the society evolves, the use of fire was also extended to remove vegetation, produce bricks and smelt metals. The advances in using fire open up the new era of Copper Age followed by later, Iron Age. Most of traditional smelters and stoves were using biomass-based energy resources: firewood and charcoal. Since this early industry was small-scale and highly wood-intensive, the society could not smelt enough metal to make it as preeminent material in everyday use and produce simple machines (Smil, 2004).

The second great energy transition was started in around the 1st century BCE. The advance of agriculture technique as well as the increased need to produce and process agricultural products has enabled the mechanization that become possible through the invention and utilization of waterwheels and windmills. The substitutions of muscle by these machines has made the agriculture output to increase and work more efficiently, further reducing the human labor in agriculture sector (Smil, 1994). By the 11th century AD, the use of these technologies was common in Europe. The technologies become more common due to its applicability in multiple tasks such as grain milling, wood sawing, oil pressing, as well as mechanization of some manufacturing processes: wire pulling and tile gazing (Smil, 2004).

The third energy transition started several centuries ago, around 16th century AD. It is regarded by a period known as ‘Industrial Revolution’. The energy transition was then related to substitution of muscle-based (animal and human) and some simple mechanical works by engines and biomass and by fossil fuels. The best documented case of this transition occurred in England. Increasing demand for charcoal led to extensive deforestation, and the substitution to coal become necessary (Allen, 2009). Furthermore, the invention of steam engine has made the use of coal more common. Radical shift (from wood to coal) become unprecedented due to coal’s abundant availability and deforestation problems (Allen, 2009; Smil, 2004), low price (Fouquet & Pearson, 2006) and also boosted by advancement in steam engine technology that suitable to use for many different tasks (general purpose technology) (Bithas & Kalimeris, 2016). The shifting to coal has improved the development in industries such as coal mining, agriculture, metal-smelting and transportation (Allen, 2009). For example, this energy era features the intensifying use of metals. It became possible when the technology for smelting advanced, where coke-based large-scale smelting began producing inexpensive iron. Additionally, in transportation sector, coal-powered steam train could go 10 times faster and provide more comfort than the traditional horse-drawn carriages (Smil, 1994).

It is then apparent to say that Industrial Revolution opens the door for the bigger transition of the use of fossil fuel. Steam engine was the prime mover technology, which enabled other innovative technologies, harnessing different energy sources and with different purposes to support human civilization. The transition in this era was observed in all industrialized countries and in some developing countries by the 20th centuries AD.

The latest energy transition starts with the first electricity generation plant becoming commercial. Since early 1880s, the invention of a viable and commercial system of electricity generation, transmission, and distribution was started by Thomas A. Edison and his colleagues. Around a decade later, as soon as late 1890s, the whole system was standardized and developed to the point that it is still applicable until today (Smil, 1994). Since then, all modern economy has increased its fossil fuel consumption, partly in order to generate its final form of energy: electricity.

Industrial production is one of the many sectors getting revolutionary consequences through electrification. Steam engines, which transmitting energies through rotating shafts and belts, result a considerable amount of energy loss and risk of accident. The electricity poses a huge benefit as a substitute: working without shafts, belts, noise and provide lesser risk of accidents (Smil, 1994). Furthermore, electricity accommodates flexible individual control of power and precision.

Furthermore, electrification is one of the main drivers of our modern computer and information era. Since World War II, electricity begun powering the new computer age and paved the way for information and telecommunication sectors. In households and personal wellness, the use of electricity boosted the invention of lots of household gadgets and machines. Air conditioning for example, which was initially patented in 1902 by William Carrier, already spread rapidly in large numbers among residentials in tropical and subtropical regions by 1980s (Smil, 2004).

2.2.2. Insights from the Past Energy Transitions

In its most general context, the transitions in energy resource use can be distinguished to several stages: the utilization of human and animal muscle, increasing use of biomass and finally the shift to fossil fuel-based resources. There are several known features of the last energy transition:

Rapid economic growth and changes in economic activity, social and demographic structure accompany the transition of energy use.

Different energy era, as discussed earlier, are in agreement within recognizable waves of economic growth (Bithas & Kalimeris, 2016). The most classic example can be seen in the era of Industrial Revolution. The shifting of energy resource use (from biomass to coal) coincide with emerging of Industrial Revolution allows higher industrial output which translated to the growth in the economy. During the Industrial

Revolution, in 1800, the world's Gross Domestic Product (GDP) is estimated around 175.24 billion of 1990 International US$, a decade later its output had increased six-fold to the level 1102.96 billion of 1990 International US$ (DeLong, 1998). In addition, since Industrial Revolution, the structure of the economy tends to shift, from agriculturally based to industrial based economy (Rühl, Appleby, Fennema, Naumov, & Schaffer, 2012). While in the last energy era, as the mechanization and automation of works become possible, due to electrification, the economic structure tends to again shifting to more service-based sector.

The energy transition also coincides with the change in social and demographic structures. The increase in population, as well as the concomitant technological development, has changed the way people live. In the prehistoric times for example, the shifting of human muscle with draft animal changes the way of nomadic living to become a settled society with agriculture and domestication of draft animals (Smil, 2004). In the more modern world, during Industrial Revolution, travelling become faster and more convenient due to the availability of coal as fuel for trains and steamboats. The movement of people, either from rural to urban or cross the border (between kingdoms/nations/states), not only increased trade but also allowed cultural and religious exchange between different societies (Smil, 1994).

All of the changes accompanying the energy transitions suggest that the ongoing sustainable energy transition would also drive the economic growth and radical social and demographic transformation. For instance, full scale utilization of electricity vehicles could result an adjustment in the way we live. A system that enables recharging the batteries easily will be needed. In this way, this transformation would also wipe out some support service industries, for example fossil-fueled vehicles. How are we going to employ current car mechanics that specialize on repairing fossil-fueled vehicles? What will happen to the petrol stations and people working there? Other example, smart transportation gets more wide spread, vehicles will drive themselves. What will the taxi or bus or truck drivers do? Those kinds of concerns have to be dealt along with energy transition.

Quantity improvement: Major increase in energy consumption following the transition to new sources

The use of new energy sources, accompanied by new technology and change of energy use patterns, and increase in income result in considerable rises in energy consumption (Grubler, 2004). The global energy transitions can be seen in Figure 2.1 which shows the absolute global primary energy use by source from the year 1800 to 2000. If we look at the trend, energy transitions have resulted to a more rapid growth in energy use. Consequently, there were also changes in the energy mix where the new energy improved significantly, while conventional sources grew more slowly.

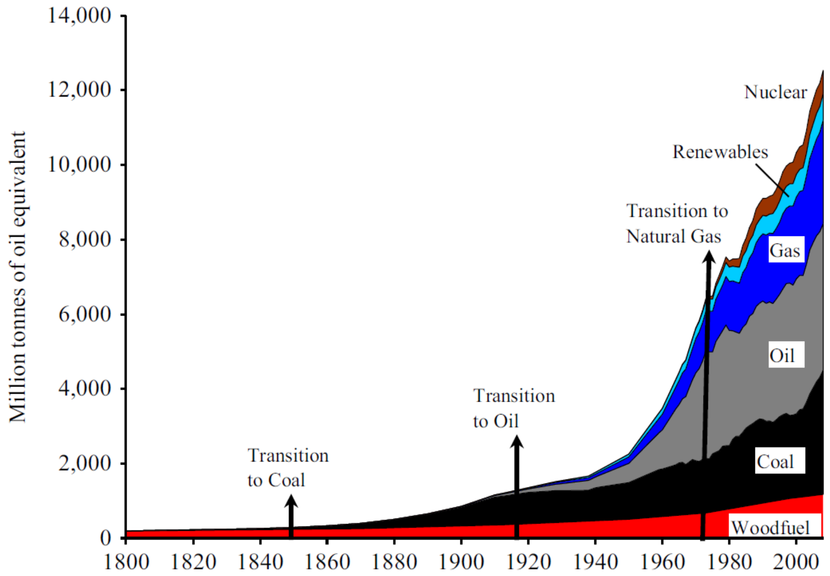

Figure 2.1. Global Energy Transitions, 1800-2010
Adopted from: Fouquet (2009)

Given this fact, we would expect that, although renewable energy (as new energy sources) emerges as a significant substitute for fossil fuels, it would not necessarily drive the use of fossil fuel for energy generation down to zero in a short period of time. Instead, such changes may drive overall increase in energy consumption. This is due to the coupling of energy and the economy. The new technology is usually associated with overall increase in the economy which subsequently follow the rise in energy use.

Quality improvement

Past energy transitions also show a pattern of improvement in the quality of producing and consuming energy. The energy consumption has become more productive and efficient following up the energy transitions. One of the indicators for energy quality is Hydrogen/Carbon (H/C) ratio. The past transitions (from fuelwood to coal and a shift from coal to oil and gas) can be summarize as gradual shift from low H/C fuels to higher H/C fuels (H/C for fuelwood, coal, oil, and natural gas respectively 0.1, 1, 2 and 4) (Grubler, 2004).

Shift in energy quality fosters the improvement of technology and the efficient use of energy. Past trend shows that the efficiency of energy use (indicated by energy per GDP) has typically follow similar trends: increasing during industrialization, then peaking and finally declining as the economy shifts to more service-based (Rühl et al., 2012). Furthermore, the development of urban energy structure (i.e., from the agricultural settlements to the modern metropolis) follow a trend of the improvement in energy use efficiency in order to fulfil urban energy service demand (Rutter & Keirstead, 2012).

Those past trends are likely to continue in the future, as the technology becomes more advanced, so does more efficient means on using the energy. In the long-run, the efficiency of energy use in different parts of the world is likely to converge (Rühl et al., 2012; Csereklyei, Varas, & Stern, 2016).

Temporal scale of the transitions could last decades, but also could be shorter

The temporal scale and dynamics of energy transitions is one of the most critical elements to consider. Speeding up the transition to sustainable energy system is what we would hope. Experience from past transitions may shed some light on the temporal space of transitions in the past in the hope that it is relevant to our present time.

In this context, two different trends are noticeable: relatively long transitions before electric era and fast transitions in the era after. In the first and second era of energy transitions, we experience very long periods of transition. During Industrial Revolution, in general, the transitions at individual sector and service took between 40 - 130 years, while full-scale transitions (involving entire economy) took longer period (Fouquet & Pearson, 2012). The reason is, energy transitions require major change not only in the energy sources but also in the supply network as well as the services it's provided. This whole process required new agents (producers, distributors, retailers) and often capital-intensive infrastructure investments (e.g. railways, electricity networks, etc.) (Fouquet, 2010).

During modern times, the post- electricity era, the transitions are happening relatively faster in various places. The speeding process in the transitions is due to factors such as availability of domestic resources, the internal market size for energy services, trade relations and appropriate policy decisions. In other study, Sovacool (2016) presents various evidence that energy transitions could be faster for some energy-end-use services as well as in the whole energy system. Some factors that can influence the speed of transitions can be endogenous factors, such as radical planning from stakeholders and market-driven, or exogenous factors, such as military conflict, significant energy-related accident, or some global crisis (e.g. the oil shocks of the 1970s) (Sovacool, 2017). In addition, social acceptance of new technologies being applied is also crucial to safe guard the transition.

Technological innovation is not the only driver of the transition.

Past energy transitions always linked closely with technological advancement. The scientific and technological developments are believed to give rise to the energy system transitions. In every energy era, the first steps of the transitions relate significantly with the beginning of important innovation movements (Smil, 2004). However, they are not the only drivers of transitions. Allen (2009) presented evidence based on the Industrial Revolution, factors such as high wages, cheaper energy price and capital and availability of specific markets—were creating new demands for technologies that could progress on the new fuel and improve productivity. That means, both producers and consumers need price incentives to respond to the new state of the system. Scarcity of resources (e.g. during the oil embargos in 1970's) also trigger transitions (Sovacool, 2017). Furthermore, political influences have played significant roles in deciding the nature of the past transitions (Rubio & Folchi, 2012).

The transitions of the energy system in fact, is quite complex phenomenon with a lot of agents, drivers and dimensions. Although technological advancement is believed to be an important factor driving transitions, factors that trigger the technological shifts also play a significant role. The energy transitions are not merely the technical ability to implement new systems, but it goes beyond how the interplay between technological innovation, economic affordability (and resources availability), political will and sociocultural acceptability is functioning.

2.3. The Changing Perspective of Energy Use

The emergence of sustainable development concept which later tried to be adopted to various sectors (including energy), cannot be separated from the course of history. The concept can be traced back to the early 20th century, when the perspective of the world society (industrialized countries in particular) towards the use of energy has evolved due to stressed being done to the environment through rapid industrialization (Hall & Ashford, 2012). Consequently, society was responding to such problems with various efforts from upgrading knowledge on economic, social and environmental impacts to local, regional and global policy actions. Some of the key events and publications that shape the gradual shift in energy use can be seen in Figure 2.2.We have discussed earlier that major energy transitions (i.e., from traditional biomass to fossil fuel) occurred during Industrial Revolution. Following the transition, output production, standard of living (and hence, population) and energy demand increases tremendously. This period was also marked by the general view of energy supply (and use) as the substantial driver of the economic growth. Discovery of new fossil fuel resources such as oil and gas, made the substitution between fossil fuels become possible. At this point, the economy became very dependent on the supply of energy, making the exploration and exploitation of fossil fuel resources crucial for continuous development. No wonder that the main focus of energy policy at the time was to find and acquire energy resources as much as possible. World energy council, one of the oldest multilateral energy organ founded in 1923, released its first publication about identification and estimation of world's energy resources (Wright, Shin, & Trentmann, 2013). It is pointing out the clear dire need of the industrialized world to exploit energy sources.

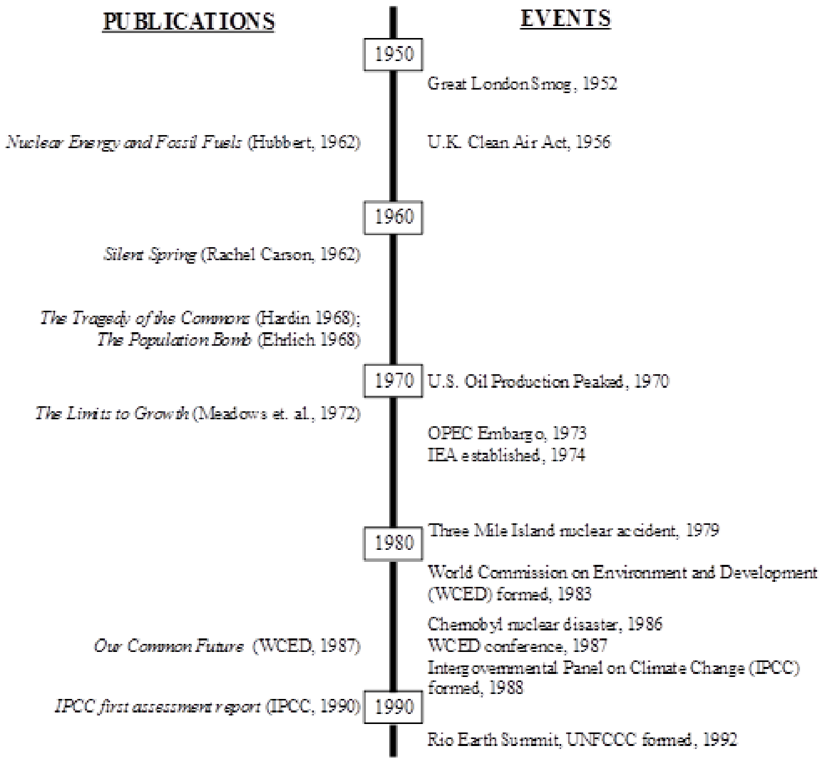

Figure 2.2. Timeline of Some Key Events and Publications

The problem of resources, in fact, has been circling around since 18th century. Thomas Malthus, a political economist, pointing out the problems of population growth and resources (food production) in his *Essay on the Principle of Population* (Malthus, 1798). The problem of hunger (lack of food supply) and poverty is naturally occurred due to unchecked population growth. In other words, scarcity (of resources) is a natural way to 'check' population growth through so-called the Malthusians processes (i.e., war, famine, pestilence and death). Malthus thought scarcity was due to population growth.

Over time, arguments cautioning the problems related with the current development pathway of rapid economic growth and industrialization come to surface. In the 20th century, these concerns are actualized in classic publications such as *The Population Bomb* (Ehrlich, 1968) and *The Tragedy of the Commons* (Hardin, 1968). Ehrlich (1968) pointed out that, the needs for over increasing population might not be satisfied by a fixed resource based, causing the problem of scarcity. While, Hardin (1968) discussed the impact of overpopulation and tendency of individuals to overuse public/environmental commons to their own benefits while disadvantageous to others, to the point that can no longer support the economic activity. All of those ideas and concerns over population, industrialization (and economic growth) and subsistence to support them became delineated in *Limits to Growth* (Meadows, Meadows, Randers, & Behrens, 1972). By using computer simulations, Meadows et al. (1972) show that the development pattern of the era coupled with finite resources would potentially lead to negative consequences in the quality of life, even declining number of human population. During the same period, geologist M. King Hubbert predicted that oil production of the United States (U.S.) would reach its peak in 1970 (Hubbert, 1956). Although his predictions at that period were neglected, the oil production of the U.S. at that time in fact peaked in 1970 and natural gas in 1973. However, the latest advancement in oil and gas extraction (hydraulic fracturing) has made the U.S. oil and gas production surpass its 1970s production level in 2017.

In the time of scarcity of the domestic resources, the search of finding resources beyond border sometimes was causing geopolitical problems. In order to maintain continuous supply, resources are sometimes taken by any means necessary, including the rise of arms and bloodshed-similar to what Malthus had predicted. During the third quarter of 20th century, in the backdrop Arab-Israeli war, marked as the first time in history where energy was used as a ‘weapon’. The Organization of Petroleum Exporting Countries (OPEC) members forced an embargo against the U.S. and other countries (including the Netherlands, Portugal and South Africa) in retaliation for their support to Israeli military. It is also used to gain advantage in the post-war peace negotiations. The embargo both banned the exports of petroleum as well as oil production cuts. The result was apparent: oil scarcity occurred, pushing the price higher creating a devastating economic impact in the U.S. The GDP declined while inflation and unemployment rose (Hall & Day, 2009).

In a way to find solution to energy problem during the embargo, industrialized countries formed an energy alliance namely International Energy Agency (IEA) (Scott, 1994). With the main objective to secure the energy supply. It is translated into several actions such as: finding alternative energy sources, promote energy efficiency, and enhance cooperation and R&D (Scott, 1994). The formation of IEA as well as its accompanying objectives and policy recommendations, marked the foundation of the changing perspective on energy use in industrialized countries. At the same time, several countries affected by the embargo put forth policy responses such as increasing domestic supply to decrease dependency on energy imports.

This period of development is identified by Dernbach (1998) as a “conventional development” which focuses on inter-connected ideas: national governance that secures peace, economic and social developments. The focus has been extended (from previously limited to economic growth-oriented development), but the concern over environmental protection is not yet regarded (Dernbach, 1998). The inclusion of environmental protection goals to the conventional development as well as recognition of the well-being of future generations, are necessary ‘ingredients’ to form the sustainable development concept (Hall & Ashford, 2012).

The inclusion of environmental protection to development concept is a gradual process of growing environmental awareness in the face of rapid industrialization. For example, in 1952, the air in the city of London covered with heavy smog, from the burning of coal, resulting thousands of people to die and many others to suffer respiratory illnesses. In the U.S., over the similar period, the air was much polluted in

Pittsburgh, causing white-collar workers to change their shirts at midday due to dirt from soot (Hunter, Salzman, & Zaelke, 1998). Cuyahoga River in Ohio was one of the most polluted rivers, the pollution was so severe it caught fire in 1969. Having observed severe environmental pressure, Rachel Carson published *Silent Spring* (Carson, 1962) which is recognized by many analysts as the wake-up-call on the negative impacts of industrialization on the environment (Hunter et al., 1998; Gudmundsson, Hall, Marsden, & Zietsman, 2016). In other industrialized countries, many environmental issues are also related to air and water pollution, some of which naturally could raise transboundary issues. Although some countries later put in place its environmental law, the transboundary impact of the pollution motivated the talks in an international roundtable. UN Conference on the Human Environment held in Stockholm in 1972 was the result of those emerging environmental concerns. The Stockholm Conference brings nations to discuss around the topics of biological diversity, ecosystem integrity, the ecological and resource limits problems and human health (Hunter et al., 1998). However, its most important impact is its role as a stimulant for growing environmental discourses that raised the world's awareness on the environment (Gudmundsson et al., 2016).

Following the Stockholm conference, the concept of sustainable development was crystalized during the World Commission on Environment and Development (WCED) conference in 1987. The Commission produced a publication titled *Our Common Future* or also commonly known as Brundtland Report (Brundtland, 1987), which coining and popularizing the concept of Sustainable Development. The report consists of what has become the most popular and accepted definition of sustainable development:

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. (Brundtland, 1987)*

Within the notion of sustainable development, the Commission intended to provide link between economic and social developments with the consideration towards environmental protection and a forward-looking of intergenerational equity. The report also emphasizes on the major role of science and technological innovations and institutions to address various development problems.

The Brundtland Report also addresses the topic about energy use. Explicitly, it laid out the challenge faced by energy use and the importance of maintaining sustainability through reconciliation of 4 key elements (Brundtland, 1987): adequate supply of energy to meet human needs, efficient use of energy and conservation measures, public health and protection of the natural environment. Although the transition to low carbon energy system is not precisely proposed, the problem of climate change and local air pollution is presented as well as the opportunity to utilize the untapped potential of renewable energy resources. Furthermore, regarding the concern over past nuclear incidents and accompanying risks, the Commission recommended moving out of nuclear energy generation (Brundtland, 1987).

By the end of 20th century, the growing knowledge of climate change and its likely link to human activities have allowed the establishment of Intergovernmental Panel on Climate Change (IPCC). Its main task is to present the scientific perspective on climate change and its potential impacts to the world community (Houghton, Jenkins, & Ephraums, 1990). Its first assessment report cautioned the world of the possible danger of climate change due to anthropogenic GHG emissions to the atmosphere (Houghton et al., 1990). Energy systems are by far the most significant activities responsible for the release of GHG to the atmosphere accounting for two-thirds of anthropogenic GHG emissions (UNDP, 2000).

International communities respond to the depressing pressure on local, regional and global environment by organizing the Rio Earth Summit in 1992, which aimed to examine the state of environment and social development after the Stockholm Conference (Hunter et al., 1998). At least two important results were achieved: the establishment of UNFCCC to specifically address global climate change problem and the publication of Agenda 21, a ‘blueprint’ for sustainable development in 21st century. Within the chapters of Agenda 21 (UNCED, 1993), though there was no special coverage on energy, all chapters address the need for the transition from unsustainable to sustainable energy management. Agenda 21 also emphasizes the negative externalities that might arise from unsustainable energy production and consumption.

At this stage, the perspective of development in general and energy production and use in particular, again evolved to include the sustainable development concept. Although the practical application of the concept seems burdensome[3], the threat of global climate change makes it necessary to work together for realizing the transitions.

The Sustainable Energy System

An energy system consists of energy supply and energy demand (end-use) sectors. The main objective of energy system is to deliver the benefits that energy can give to various consumers. These benefits are usually termed as ‘energy services’. Energy services, for example, in the transportation sector include the gasoline that drives the car, electricity that drives trains, etc. Energy services are used in every human activity, from production of goods and services to household needs and personal entertainment and welfare needs. The example of energy system chain-from energy supply to end-use energy service- is shown in Figure 2.3.

Energy services can be provided through the chain of processes which require primary energy, capital investment (technology and infrastructure), labor and other materials. Each stage involves different types of processes and technologies and has embedded costs within itself. Consumers of energy services are often unaware of these upstream processes; they would only consider the benefits of an energy service and its price (economic value).

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[3] especially to the developing countries which still have a lot to do for economic and social development compared to the developed countries (Hunter et al., 1998).

The term sustainable energy is basically the coupling between sustainable development concept and the energy system. It is widely used and implied, however, there is no generally accepted definition. The sustainable development definition by the Brundtland Commission has been referred to by many authors as the starting point for defining sustainable energy, while other authors offer implicit definitions by showing relevant aspects (Peura, 2013). In its most general form, sustainable energy often corresponds to terms such as energy security, energy equity and environmental sustainability (Fathurrahman, 2016). Although all three terms are also sometimes ill-defined, generally the energy security is correlated with uninterruptable supply of energy, energy equity refers to equal access of energy for all people, while environmental sustainability is mostly related to mitigation of climate change and air pollution control. Regardless of the definitions, there exists overall commonality that, integration of renewable energy and efficient use of energy are two fundamental ways to realize sustainable energy (Fathurrahman, 2016; Peura, 2013).

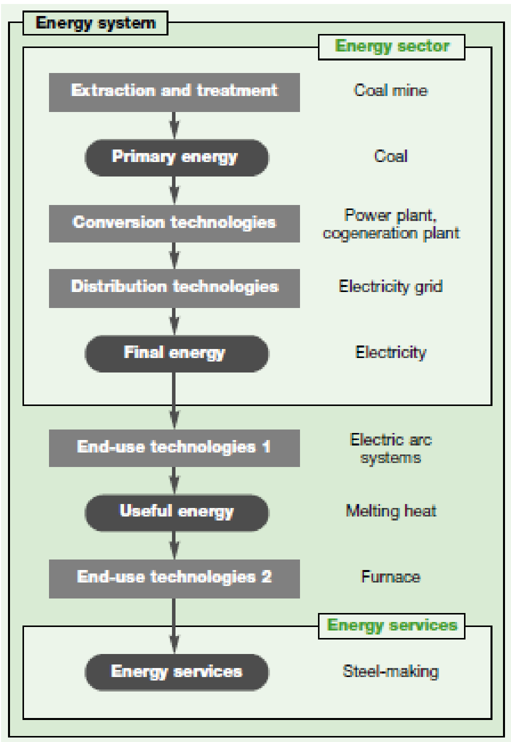


Figure 2.3. Energy System Chain
Adapted from: UNDP (2000)

In the global policy discourses, the sustainable energy concept and its practical means were also evolving. Ad Hoc Open-ended Intergovernmental Group of Experts on Energy and Sustainable Development point out the key energy issues including: energy access, efficiency in energy use, renewable energy, advanced fossil fuel and nuclear energy technologies, rural energy and energy issues in transportation (UN, 2000). In another report, Commissions on Sustainable Development (UN, 2001) emphasizes that the future energy development should be more reliable, economically affordable, socially acceptable, and environmentally secure and benign manner. In addition, the World Summit on Sustainable Development, which was held in 2002, proclaimed for a change in unsustainable energy system practice (UN, 2002).

In Rio+20, the Earth Summit of 2012, ideas circulating around for the successor of Millennium Development Goals. The Post-2015 development goals are deemed necessary to continue the world development in the right directions. Open Working Group on Sustainable Development Goals (SDGs) was formed and later submitted the proposal for the sustainable development goals. In 2015, The SDGs was adopted, which contains 17 "Global Goals" with total 169 targets (UN General Assembly, 2015). Energy goal is available as sustainable development goal number 7. The energy goal has an objective to “ensure access to affordable, reliable, sustainable and modern energy for all” (UN General Assembly, 2015).

2.4. Energy and the Three Pillars of Sustainable Development

In the literature, the framework of the sustainable development concept is not clearly defined (Peura, 2013). However, commonly, sustainable development is translated and represented into three pillars: economic, societal and environment (see Figure 2.4). This implies that all the three pillars need to progress in order for sustainable development to work. The economic development, environmental preservation and regeneration and social well-being should go hand-in-hand (Gudmundsson et al., 2016). The intersection of those three pillars make up sustainable development.

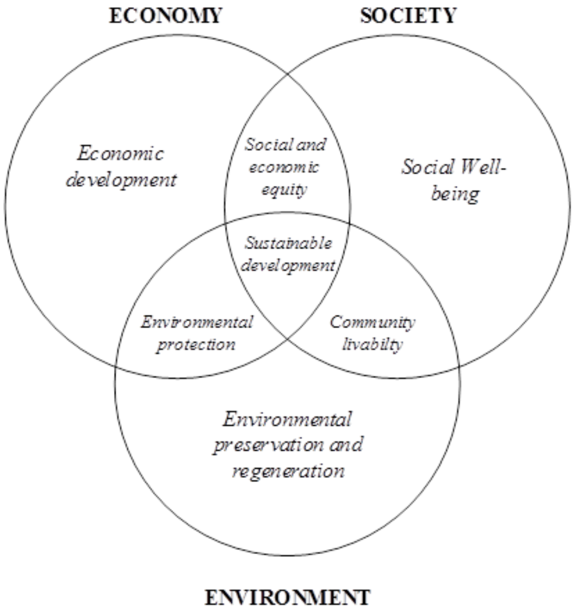


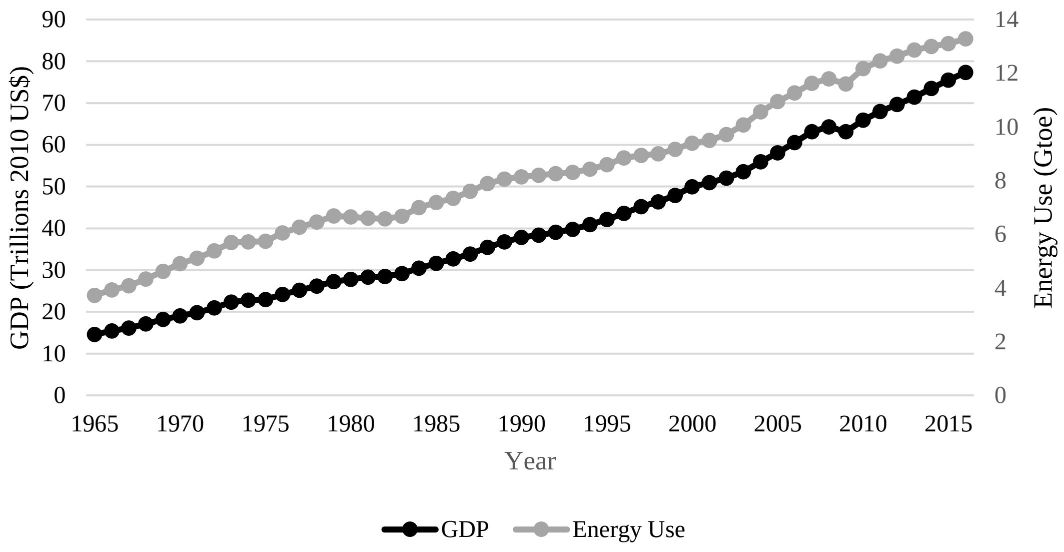
Figure 2.4. Three Pillars of Sustainable Development
Adapted from Gudmundsson et al. (2016)

In light of the importance of these elements, this section is devoted to discuss the relationship between energy and each of the pillars.

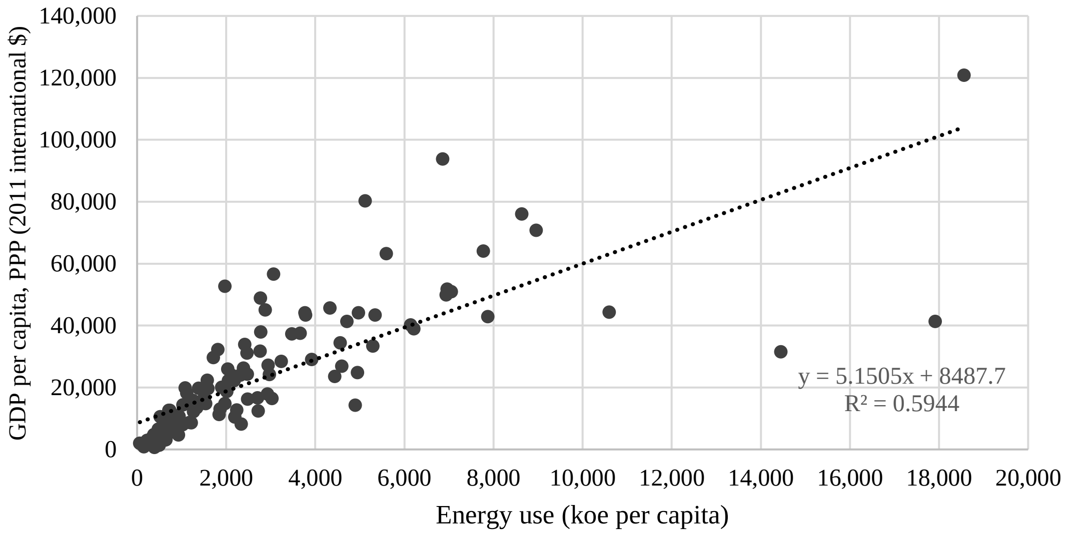
Energy and the Economy

We have already briefly introduced in the earlier subchapters some of the interactions between energy and economy. Historically, the increased use of energy has been attributed to economic growth. This coupling effect of both variables can be clearly seen in Figure 2.5.a. It shows time series of world energy use and GDP from 1965-2016. The trend in GDP growth coincides almost perfectly with the trend in energy consumption which suggests a close link.

Another way to look at the linkage between economic growth and energy use can be seen by the high correlation between per capita average of GDP and energy use (Figure 2.5.b). The correlation between the variables for 130 countries is at 0.77, and the linear regression explains 59% of variance. This kind of link can also be found in single country studies (Smil, 2003).



(a) 1965-2015 Time Series of GDP[1] vs Energy Use[2]



(b) Panel Countries Energy per Capita[1] vs Income per Capita[1] in 2014

Figure 2.5. Energy Use and GDP
Own calculations based on data from: [1] World Bank (2019) [2] BP (2018)

The straightforward explanation of these findings are the fact that energy is an input to produce of goods and services. Over time, the link can be strengthened or weakened due to factors such as: the change in technology, substitution between energy and other inputs, shifts in the mix of the energy input and transitions in the composition of economic output (Stern & Cleveland, 2004). Although in some developed countries there seems to be a decoupling, the general trend in the past four decades globally still shows strong coupling effect between economic growth and energy consumption (Csereklyei et al., 2016). This decoupling happens due to energy efficiency improvement as well as shifting of economy from highly energy-intensive industrial economy to less energy-intensive service sectors economy.

The coupling link between energy and economy looks apparent and less disputed. However, there has been a wide discussion in terms of the direction and causal relationship between energy and economy (Isa, Sayed, & Kun, 2015). This is a very important aspect, as the policy implications of this relationship depends on the type of the causality link between those two. The causal relationship can be categorized into 4 types (Ozturk, 2010; Isa et al., 2015):

1. No causality: Also known as 'neutrality hypotheses'. It implies that no correlation exists between energy use and economic growth. Hence, neither energy conservation nor expansion policies will have effect to economic growth.

2. Uni-directional causality from economic growth to energy consumption: Also called 'conservation hypotheses'. That means, the increase in economic output causes increase in energy consumptions. Thus, energy conservation policy will have less to minimum effect to the economy.

3. Uni-directional causality from energy consumption to economic growth. Sometimes also called 'growth hypotheses'. Where, an increase in consumption of energy causes improvement in economic output. As opposed to previous one, energy conservation strategy might harm the economy growth. Thus, uninterruptable energy supply will be crucial for economic growth.

4. Bi-directional causality: Or a ‘feedback hypothesis’. That means, both energy consumption and economic growth affected each other.

Energy and the Society

The social dimension of sustainability deals with the well-being of the society. The issues such as poverty, inequality, employment opportunity, education, healthcare, etc. are the ones related to this dimension. It has been a general understanding that high use of energy is attributed to the good standard of living and welfare. That is because, energy is used for economic activities and such activities contribute to wealth and well-being. At some point it is true, however, this only partially address the issue. Well-being is not exclusively determined purely by wealth or income, but also other factors: healthcare improvement, access to education, employment opportunity, political freedom, hygiene and sanitation, etc. rather than only indicated by wealth or income.

To get a closer look at the link between energy and well-being of the society we can see from Figure 2.6. Here, well-being is represented with Human Development Index (HDI), a composite index developed by UNDP to measure the rate of development and well-being. Figure 2.6 shows the relation between HDI and energy use in 130 countries. Several things can be concluded from the graph:

1. Positive logarithmic relationship exists between those two, with the fit line explaining 69% of the variance. That is, increase of energy uses also coincidently increase the well-being logarithmically. Country with lower energy consumption rate tend to have smaller HDI, it is also valid vice versa.
2. No country reaches very high HDI with less than 1,500 koe/capita energy use. It is suggested that there are certain minima for energy use to reach a decent quality of life.
3. The HDI relate to average per capita energy use with clear sharp accent at between 400 and 1,500 koe/capita, followed by lower returns and no additional HDI gains above energy consumption 5,595 koe/capita (Norway). The U.S.,

Canada, Iceland, Qatar consume more energy per capita than Norway, however, no-country match up Norway's quality of life.

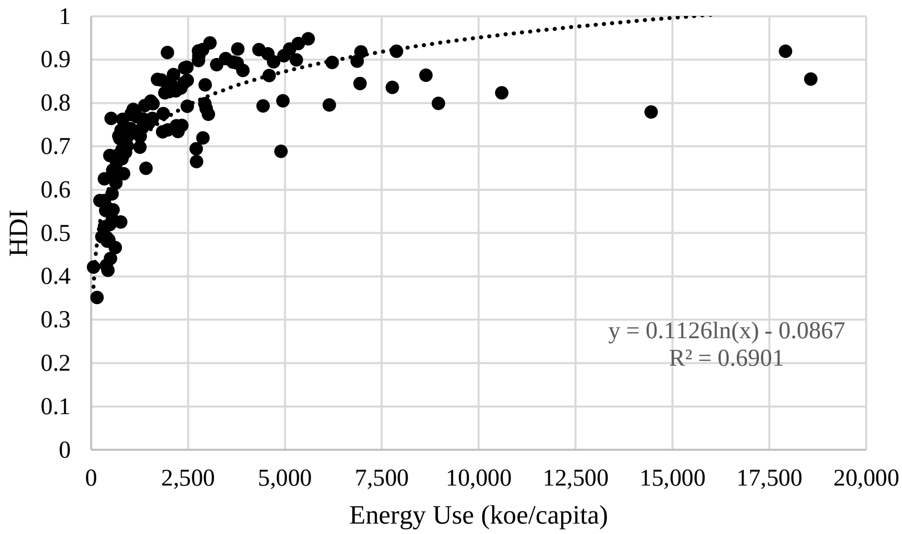


Figure 2.6. Plot between HDI and Energy Use for the Year 2014

The link between energy and well-being of society focuses on energy services rather than the supply of energy itself. That is, how society can have options regarding their energy services they would like to get. Then, it comes to the dilemma in the society regarding with the issue of unequal distribution of energy, i.e., the inability for some of the community to access energy services. Some people enjoy too much access to energy services, while the others suffer the lack access of energy services. This phenomenon is usually termed as 'energy poverty'. It is defined as: "..the absence of sufficient choice in accessing adequate, affordable, reliable, high-quality, safe, and environmentally benign energy services to support economic and human development" (UNDP, 2000). This issue is one of the main challenges related to energy faced by the society. No wonder that one of the energy targets in energy SDG is to increase access to energy (target 7.1) (UN General Assembly, 2015).

Energy poverty has been a challenge in realizing sustainable energy development, especially in developing countries (Fathurrahman, 2016). Over 1.4 billion people across the world still live without electricity and 2.7 billion people are without clean cooking facilities, most residing in developing countries (OECD/EIA, 2010). Lack of access to modern energy services hinder them from attaining a higher well-being. For example, the utilization of traditional energy (e.g., dung, fuel wood, crop residue) is contributing to indoor air pollution (health hazard), at the same time, the collection of fuel wood is usually performed by women and school-going children, taking time away from other productive activities (Barnes, Khandker, & Samad, 2010) and creating and widening gender inequalities. Therefore, replacing traditional fuel with more efficient modern energy can result in time savings and better opportunities. Electricity use can expand household members’ efficiency in more productive economic activities and participation to workforce and thus contribute to productivity improvement (World Bank, 2002).

Energy and the Environment

The use of energy always leaves a considerable amount of environmental footprint. Energy sector is the most significant sector responsible for human made GHG emissions that contribute to global warming. In addition, local, regional and national environmental problems also arise due to energy use.

The current pattern of fossil fuel-based economy is contributing significantly to environmental degradations. In the past, as already discussed previously, the emerging environmental problems are mainly local or regional ones, such as air and water pollution in a city. The great London Smog is the early example how devastating the impact of energy could be to the local environment. In fact, the environmental issues resulting from fossil fuels is attributed to all phases of their production cycle, from extraction to its use/combustion. Table 2.1 presents the environmental problems that can be caused from several energy supply technologies.

Table 2.1. *Environmental & Risks from Various Energy Supply Technologies Adapted from Tester, Drake, & Driscoll (2012)*

Production Phase	Coal	Oil	Natural Gas	Nuclear
Extraction	Mining accidents, Lung damage	Drilling spills	Drilling	Mining accidents, Lung damage
Refining	Refuse piles	Water pollution	-	Milling tails
Transportation	Collision	Spills	Pipeline explosion	-
On site:	-	-	-	-
Thermal	High efficiency	High efficiency	High efficiency	Low efficiecny
Air	Particulates, SO2, Nox	SO2, Nox	Nox	Low radiation
Water	Water treatment chemicals	Water treatment chemicals	Water treatment chemicals	Water treatment chemicals
Aesthetic	Large plant transmission lines	Large plant transmission lines	Large plant transmission lines	Small plant transmission lines
Wastes	Ash, slag	Ash	-	Spent fuel transportation, Reprocessing waste storage
Special problems	-	-	-	
Major accident	Mining	Oil spill	Pipeline explosion	Reactor cooling failure, Nuclear weapon proliferation

Production Phase	Hydro	Solar PV	Wind	Geothermal
Extraction	Construction	Mining accidents	-	-
Refining	-	-	-	-
Transportation	-	-	-	-
On site:	-	-	-	-
Thermal	-	Low efficiency, Ecosystem change	-	-
Air	-	-	-	H2S
Water	Destroy prior ecosystem	Water treatment chemicals	-	Brine in streams
Aesthetic	Small plant transmission lines	Poor large are	Locally visible	Large area
Wastes	Fish killed	Spent cells	-	Cool brine
Special problems	Population, Agricultural displacement	Construction accidents	Sitting structural failure	-
Major accident	Dam failure	Fire	-	-

We can see from Table 2.1, that renewable-based energy supply also has its adverse impact to the environment. The energy related pollutants can be in various form such as gases, liquids, solids, or mixed phases. Whatever technology we choose, some adverse impact on the environment is always present. Then the remaining question is: How can we provide energy services with minimum level of environmental degradation?

Tester et al. (2012) argued that there are three main challenges that make the control of environmental risk difficult: 1. various environmental services do not attain economic value, thus prone to negative externalities which finally will distort the market. 2. The adverse effect to the environment is very diverse in terms of its length and time scale. 3. The pollutants often come from very complex interaction of various different chemical and physical factors. All of these challenges can be seen in the case of global climate change problem.

From the main stream economists' perspective, climate change phenomena are seen as a market failure problem, where GHG emissions are seen as negative externalities. The costs and/or benefits of externalities are ignored when making short run decisions in markets. Hence, to deal with the problem, 'internalization' of costs and/or benefits is required. Existing climate policy instruments such as taxes, subsidies, emissions limit, carbon trading, and so on, are meant to internalize the costs and benefits of GHG emissions.

The problem gets complicated as the impact of global warming itself is not immediately observed, but it is rather gradual. People with no concern for the future generations may still feel that there is nothing wrong to pollute the atmosphere with GHG emissions. Up until now, the technologies to curb the GHG emissions (e.g. carbon capture and storage) appear to lag behind desired levels, thus all efforts to minimize the GHG emissions are through substitutions to 'cleaner' technologies, such as that energy services derived from renewable sources.

2.5. Energy System Transition

Energy system of the future should be sustainable. On one hand it should allow a secure and uninterrupted energy supply, on the other hand it should be able to meet the goal of the society without putting pressure on environmental sustainability. But then, the remaining question is 'how can these be achieved?' In the past decades we experienced a radical transition of the energy system. Assuring the sustainability of the future energy system requires the next transition to be completed over the next few decades to come.

From our previous discussion regarding sustainability and energy transition, the sustainability of energy system can be achieved mainly via two fundamental ways: renewable energy based technology application in the supply side and improvement of energy efficiency in production and end-use. Fossil-fuel based energy services can no longer be the main option as it has persistent impact on the local, regional and most importantly global environment. The shift to renewable energy is indisputably favorable as the resources are limitless. However, there are various challenges in terms of technical, economic, social and political aspects. Technically, the problem of intermittency is a longstanding constrain on the integration of the renewable energy to current conventional system. In addition, the potency of renewable energy resources is dependent on its geographical situation.

For the economic aspect, various renewable energy technologies are still non-competitive with the fossil-based energy. However, the costs of these technologies have been decreasing. As the technology becomes more favorable and mature, the economics of scale may bring down the cost to a more competitive level.

Social challenges include: social acceptance of renewable energy sources, re-training and employment of people working in fossil fuel sectors, social innovation and changing life styles etc.

In the political sphere, the disparity between developed and developing country as well as its perspective on the issue such as climate change, will make it challenging for renewable energy to be applied globally. Developing countries in general, has not equipped with enough political will and awareness to move to such transitions. The main reason is, their development priority is still focused on catching up the development to their developed countries counterpart (Hunter et al., 1998). However, transition to sustainable energy is proven by many studies, could be able as a way to leapfrog the development of those developed country has achieved. With the correct policy measures, it’s inevitable that such transitions could happened.

CHAPTER 3

REVIEW OF ENERGY MODELS FOR POLICY PLANNING

3.1. Introduction

Developing and implementing a sustainable energy policy is important for the society, since it has significant economic, environmental, and social impacts. Some of these impacts are positive (i.e., economic growth) and some are negative (i.e., pollution). Policy makers face challenges due to this conflicting nature of energy use and its accompanying trade-offs. On the one hand it plays an important role in economic growth and employment, on the other hand, fossil fuel consumption is one of the biggest sources of environmental degradation. Thus, in order to achieve higher economic and social welfare without causing irreversible environmental degradation alternative policy options must be assessed. These policy options require at least some level of energy transition from conventional fossil fuel resources to renewable and more environmentally friendly energy sources. Managing the transition process by itself is a challenge. The sustainability of energy policy is vital to safeguard a smooth energy transition. It is necessary to see how related dimensions surrounding energy system interact and what the implications of applied policy will be for the society and the environment. Researchers have been continuously searching for new insights regarding this multidimensional problem using energy models.

Models are representations of real systems. It is necessary for modeling practice to be done in order to answer from general to specific problems faced by the systems. Energy system modeling is also the most practical way to govern future transitions (Johnson, 2001). Energy modeling is employed as the analysis of energy related problems such as technical and economic issues in the energy sector. Such problems include planning and investment analyses of different phases starting from production to end-use (Kavrakoğlu, 1987). From an economic perspective, the energy model is the representation of economic theory about energy sectors (Searl, 1973). In the simplest term, however, energy models are all models that deal with problems related to energy (Charpentie, 1976). Regardless of the definitions, main issue is: modeling is practical means in solving the energy related problems.

Energy models relevant with this study is in the class of 'policy models' which usually have following purposes (Samouilidis & Mitropoulos, 1982):

- *Descriptive*: Replicate some of the relevant features of the reference system, by giving information about the behavior of past and present energy system.
- *Predictive*: Forecast future aspects and features of the reference system.
- *Planning or normative*: Projecting how the reference system should develop overtime with a given objectives and constraints.

The chapter aims to review energy models which have been used for various energy policy challenges. It discusses the early methods and application of energy models and its development as well as addressing the typology of each modeling genre. Further discussion will be given to the two most distinguished approaches of energy modeling (i.e., top-down and bottom-up). In addition, the recent approach of linking both models into a 'hybrid' model is necessary to fill the gap between those approaches. Finally, the modeling challenges those still need to be resolved will be discussed in the end of the chapter.

3.2. Early Application and Development of Energy Models

Energy models have been employed since 1960's but started to boom after the 'oil crisis' in 70's (Kavrakoglu, 1987a; Kavrakoğlu, 1987b). Prior to oil crisis, the number of publications was around hundreds (Voss, 1984), however, following the oil crisis it increased to thousands (Kavrakoglu, 1987a).

The earlier energy models (i.e., before oil crises) were documented in Charpentie (1975, 1976). Most of the models focused on the supply and demand of only one kind of fuel (e.g. electricity or oil or natural gas or coal). In the compilation of models in Charpentie (1976) for example, most single fuel energy models at the time were focused on electricity expansion strategy and new nuclear power installments.

Charpentie (1976) was clearly showing the main energy problems at that time: increasing demand for electricity and penetration of nuclear power technology. For example, faced with the need of nuclear power plant deployment to satisfy electricity demand, Iliffe (1973) developed energy model which aims to find the optimal structure of installing nuclear power plants. The system was optimal from the point of view of the total energy production cost. In terms of electricity sector, a large number of models tried to find the optimal mix of power system expansion required to fulfil increased electricity consumption (e.g. Anderson, 1972; Jenkin, 1973; Lencz, 1969). The optimal mix is usually determined under the objective of discounted sum of total cost minimization (which typically includes capital, fuel, as well as operating costs) over the planning horizon.

These models focused on the supply side, i.e., aimed to answer the question on how to satisfy increasing demand. Demand for energy was treated as an exogenous input to the models, often estimated through econometric demand models. The main limitation of such a single fuel model was the negligence of the possibility of *inter-fuel substitution* (related to: e.g. changing energy prices, technological development or environmental considerations), thereby ignoring many alternative ways to satisfy various type of energy service demands (Rathnagel & Voss, 1981; Voss, 1984).

Hoffman & Jorgenson (1977) argued that the model for energy policy have to include detail representation of each specific technology and must incorporate the policy impacts assessment on overall economic activities. Furthermore, Charpentie (1976) noted some challenges in the earlier energy models which include: refinement of methods in projection and optimization models, formulation of demand relations, modeling R&D impact and integration of energy models to the economy-wide model and the links between models.

Answering the challenges, the development of energy model started to consider the whole energy system and also its economy-wide link. Holistic view of energy systems is usually represented with energy balance figure, which describes the flow of energy from different primary energy sources going through conversion and utilization at different end use demands (Voss, 1984). The network in energy balance is used to evaluate various options in the energy system to satisfy exogenously defined end-use demands. In addition to these accounting-based energy system models, the optimization of whole energy system also has been done. The main aim was to find the optimal allocation of energy supply to satisfy the demand. The most notable example is a well-known energy system model, MARKAL (Loulou, Goldstein, & Noble, 2004). Figure 3.1 shows the simplified representation of energy system in MARKAL.

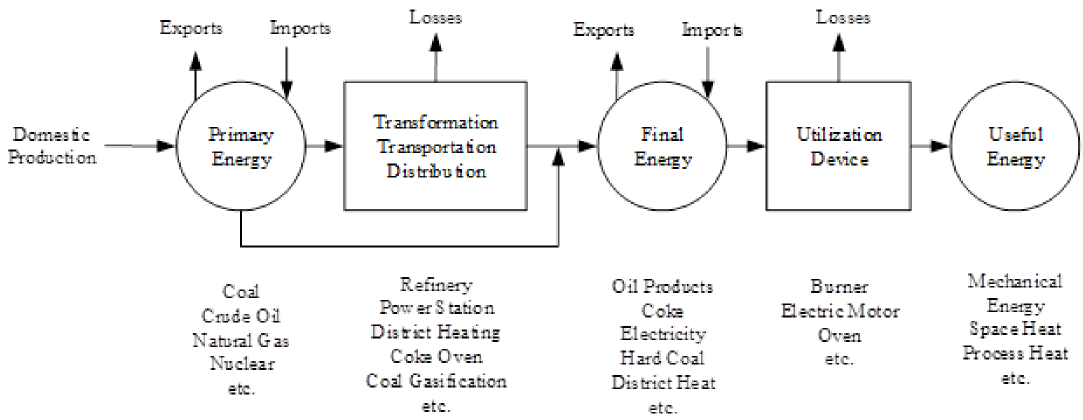


Figure 3.1. Energy System Model in MARKAL
Adapted from Voss (1984)

MARKAL finds the optimal solution through minimization of discounted costs (such as: primary fuel cost, operating and maintenance, transportation cost, investment cost of adding new capacity) over the planning horizon, subject to satisfying several constraints (e.g. demand, supply, capacity, resource, implementation and environmental) (Loulou et al., 2004).

Both accounting and optimization models treat demand as an exogenous input, and neglect the demand adjustment due to changing economic variables such as higher energy price or growth rate. Tackling this problem is the motivation of the development of energy-economy type models.

Summarized in Table 3.1, Samouilidis & Berahas (1983) proposed a general framework for energy-economy models. The basic elements (modules) of these models consist of: Macroeconomic growth model, consumption models, supply models, energy demand models and energy supply models. In order to treat the energy sector in detail, the energy demand and supply models (IIa and IIIa) were used which comprise particular cases of the consumption and supply models (II and IIII) respectively. The authors also noted that although not all the elements need to participate in a formal energy model (explicitly), their function is necessary and can be entered through the inputs implicitly.

Table 3.1. *Elements of Energy-economic Models*
Adapted from Samouilidis & Berahas (1983)

Element/Module	Approach/Methodology	Functions	Policy Area
I. Macroeconomic Growth Model	• Theory of growth • Optimal control • General equilibrium approach	• Integrating mechanism • Relates present and future states of the system	Impact of energy policies to economic growth
II. Consumption Models	Econometrics	• Describes consumption patterns of final consumers • Disaggregates final demand into the economic sectors of I/O models	• Consumption patterns • Allocation of aggregate demand to products and services
III. Supply models	Econometrics	• Accounting mechanism • Determines output of each sector in the economy	Production patterns
IIa. Energy demand model	• Engineering process analysis • Econometrics	Relates energy demand to income, energy prices, energy efficiencies	• Price and tax effects • Energy conservation • Regulations • Energy efficiency
IIIa. Energy supply model	• Linear/Nonlinear optimization • Simulation • System dynamics	• Relates energy supply to policy objectives • Determines requirements of the energy sector	• Structure of energy system • Impacts of new energy technologies

The growing concern over the environmental impacts of the energy sector made the inclusion of environmental criteria inevitable. The application of energy models extended from energy-economic specific problems to environment-related issues. The earlier applications can be traced back for example in Kopac & Hazuka (1974). Local air pollution problems induced by energy sectors motivated the authors to study SO_4 and fly ash pollution from energy use. This kind of study can estimate how energy consumption activities (hence, economic activities) may harm the environment through pollutions. However, in earlier models, the environmental problems practically inserted in the form of a simple multiplication of the amount of energy produced by specific pollution factors. This approach yields the aggregate volume of emissions but does not consider feedback effects of such pollution on the welfare (Charpentie, 1976).

Up to 1981, as shown in Table 3.2, there were several highly notable energy models which serve as foundation of the later models. In the following periods, as concern over climate change started to grow, climate change variables begun to be incorporated in many models. Climate change is the result of complex interactions between several earth systems, thus, including climate change criteria to the models means also including complex interactions within the earth system. In addition, although the earlier models were unable to account for the feedback effect between environmental degradation and welfare, new type of models called 'Integrated Assessment Model' (IAM) emerged to accommodate these needs.

IAMs are multidisciplinary models which try to combine knowledge from a wide range of disciplines. The main aims of these models are to explore interaction between human and natural system, formulate policies, and set priorities for research (Cline et al., 1996).

Despite their potential use in policy formulation, the IAMs also incite criticisms. The result of an IAM model can be misleading as the knowledge over the nature and the degree of impact on the climate outcome is still highly uncertain (Pindyck, 2017; Pindyck, 2013). (Ackerman, DeCanio, Howarth, & Sheeran, 2009) argue that, there are at least three principal areas where IAMs have a limit in terms of climate policy applications: the discounted utility framework, the characterization and monetization of the benefits of mitigation, and the projection of mitigation costs, all of which rest on assumption about the pace and nature of technical changes. Current knowledge is not enough to justify estimation of such parameters (Pindyck, 2013), which produce divergent results in IAM models (Ackerman et al., 2009).

Table 3.2. *Notable Early Energy Models*
Adapted from Rathnagel & Voss (1981)

		Model	Methodology	Application
ENERGY SYSTEM MODELS		BESOM (Kydes, 1980)	Linear optimization	Evaluation of energy technologies for US R&D policy
		EFOM (Grohnheit, 1991)	Linear optimization	Originally built to develop energy scenarios for France
		MARKAL (Loulou et al., 2004)	Linear optimization	Optimization of end-use and supply side
		MESSAGE	Linear optimization	Energy model applied to 7 world regions
ENERGY-ECONOMIC MODELS	Integrated Models	ETA-MACRO (A. S. Manne, 1978)	Nonlinear optimization, informal econometric	Studies of nuclear and alternative energy system in the US
		PILOT (Conolly, Dantzig, & Parikh, 1977)	Dynamic linear optimization	Exploration of energy and economic growth in the US
		HUDSON-JORGENSEN (Hudson, 2014)	Econometric	Long-term energy and economic growth analysis of the US. Taxing policy in the US
		ESPM (Carasso, 1975)	Accounting	Framework for energy supply planning and accounting of industrial, capital, labor, and material requirements.
		PIES (MIT Energy Laboratory Policy Study Group, 1975)	Process representation, Linear optimization, econometric	Analysis of alternative strategies for the national energy plan in the US
	Model Sets	DRI-BROOKHEAVEN (combination of Hudson-Jorgenson and BESOM models) (Tessmer, Hoffman, Marcuse, & Behling, 1975)	Linear optimization, econometric	Studies of economic impact of alternative energy futures in the US
		CEC (Combination of macroeconomic growth, energy demand, IO and energy supply models) (Fontela & Rubin, 1980)	Linear optimization, econometric	Application to member countries of the European Communities for Energy System Studies
		IIASA (combination of macroeconomic, energy demand, energy supply and energy impact model) (Basile et al., 1982)	Linear optimization, econometric	Applied to studies of the energy-economic growth of 7 world regions. Investigation about energy strategy impacts

3.3. Typology of Energy Models

There are various ways to classify energy models. Van Beeck (1999) provides a thorough classification of energy models based on nine distinguished features: purposes of the model, structure of the model, analytical approach, underlying methodology, mathematical approach, geographical coverage, sectoral coverage, time horizon and data requirements. Table 3.3 shows each of the classification in more details.

Table 3.3. *Classification of Energy Model*
Adapted from Van Beeck (1999)

General Classification	Specific Type
Model purpose	General: forecasting, exploring, backcasting Specific: energy demand, energy supply, impacts, appraisal, integrated approach, modular build-up
Model Structure	Degree of endogenization, description of non-energy sectors, description end-uses, description supply technologies.
Analytical approach	Top-Down, Bottom-Up, Hybrid
Underlying method	Econometric, Macro-Economic, Economic Equilibrium, Optimization, Simulation, Spreadsheet/Toolbox, Backcasting, Multi-Criteria.
Mathematical approach	Linear programming, mixed-integer programming, dynamic programming
Sectoral coverage	Energy sectors or overall economy
Geographical coverage	Global, Regional, National, Local, or Project
Time horizon	Short, Medium, Long Term
Data requirements	Qualitative, quantitative, monetary, aggregated, disaggregated.

Each model has a different purpose. It either has a general or specific purpose to address certain problems at hand. Incorrect model application may result in misinterpretation of the outcome and questionable policy recommendations. In terms of the general type of the model, the purpose can be forecasting, exploring or backcasting. Forecasting is prediction of future value based on historical trends. Many of energy problems require forecast of some value, for example, in the investment planning problems, estimates of the future energy demand or future energy prices is required. Exploring or scenario analysis, offers a range of possible scenarios and compared it to ‘business as usual’ reference scenario. The scenarios rely on range of assumptions that could change ‘the course’ of the future. Scenario analysis might be useful to explore how specific policy would impact the system. Backcasting, unlike exploration of the future, look from the future to present state. It involves the description of intended state of the future and explore how the path can be achieved from the present.

In terms of specific purpose of the model, although models that focus on only one aspect exist, generally, recent models serve as a combination of several purposes. Very common examples are demand-supply matching models and impact-appraisal models. In addition, IAMs integrate several modules that together able to assess energy, economic and earth system and how they interact with each other.

The structure of the model describes what kind of assumptions the model was built upon. Several parameters most of the time are described as exogenous, i.e., defined/assumed by the modeler based on previous studies or by expert knowledge, as oppose to endogenous, i.e., as variables, the levels of which are determined within the model. Some of these typical external assumptions or exogenous parameters are for example (Van Beeck, 1999): population growth, economic growth, energy demand, price and income elasticities of energy demand and tax system.

Concerning the underlying method used, there are several commonly used methodologies in the literature. They are: econometric, macroeconomic, economic equilibrium, optimization, simulation, spreadsheet, backcasting and multicriteria methodologies. Most common methodologies applied in the literature are explained further as follows.

Econometric Models: Econometric analyses combine economic theory, mathematical tools and statistical methods (Tintner, 1953) to deal “..with problems of an economic nature”(Kleinpeter, 1995). Past market behaviors were extrapolated into the future by applying statistical methods. Thus, econometrics rely on aggregated past data to predict the future value in terms of defined inputs. Traditionally, econometric methods are used frequently in order to understand the relations between energy and economic systems. Over the course of time more complex econometrics models came into play, which are generally characterized as open-ended, growth-driven macro econometric models with no assumption of equilibrium (Herbst, Toro, Reitze, & Jochem, 2012). The disadvantages of this methodology are lack of a representative set of technology options (Van Beeck, 1999) and the high data requirements for credible results generated from past data (Herbst et al., 2012).

Macroeconomic Models: The methodology considers the interaction between the sectors in the economy that makes up the economic system. It is often based on a neo-Keynesian perspective (i.e., output is demand driven) and used for energy demand analysis. The transactions between sectors are described in Input-Output (IO) tables. This table is the backbone of the analysis of energy-economy links. However, one must notice that the IO approach holds the assumptions of constant returns to scale and the possibility of perfect aggregation. In macroeconomic models, energy system is treated as the energy sector which is a part of the whole economy. The macroeconomic methodology is lacking in technical representation of energy system, thus could not capture the technological details (Herbst et al., 2012).

Economic Equilibrium Models: Generally speaking, an economic equilibrium model is a kind of macroeconomic model that relies on neo-classical assumptions: rationality, perfect knowledge, diminishing returns and perfect market equilibrium (Van Beeck, 1999). Equilibrium can be partial or general. In terms of partial equilibrium, the equilibrium state only considers one specific market (e.g. equilibrium of supply and demand in energy sectors). In contrast, general equilibrium considers economic equilibrium for all markets in the economy, therefore, the feedback effect between sectors are accounted (Fathurrahman, Kat, & Soytaș, 2017). The disadvantage of these models is that the transition costs are understated due to uncertainty on the time path towards the new equilibrium (Van Beeck, 1999).

Optimization Models: The main aim of the method is to find optimal solution for given objectives through a set of constraints which draw the boundaries of the problem, represent the actual system and model assumptions. Most applications in energy models use optimization for deciding on investment in energy sectors. The disadvantage is that optimization models usually involve highly complicated systems and if some criteria are missing, they may lead to misrepresentation of the real problem (Chvatal, 1983). In addition, as it relies highly on quantitative data, the qualitative aspects of decision making might not be captured in the model.

Energy models can also be distinguished based on their spatial (sectoral and geographical coverage), temporal (time horizon) and data requirements. However, despite of many ways to categorize energy models, analysts tend to classify them mostly in terms of the analytical approach they follow. The model may be classified as a bottom-up or a top-down or the most recent one, a hybrid type. Taking into consideration the relevancy of these classifications in this study, the following subchapter discusses the bottom-up and top-down models in more detail.

3.4. Bottom-Up vs Top-Down Models

The top-down approach termed also as the ‘economic approach’ uses the influence of prices and markets in defining the energy system. The economic model is the backbone of this type of model. The first class of this economy-wide models started when Leontief introduced IO computational system, which led to its extended applications in energy systems, for example by Bullard & Herendeen (1975), Hoch, Carson Jr., Katz, & McDonald (1984) and Hudson & Jorgenson (1974). The IO macroeconomic model has advantages in its ability to describe the structure of the economy. It lays out the flow of goods and services into different economic sectors and agents in terms of specific IO coefficients and value added. Application of IO framework in terms of energy study is for example to determine ‘the energy cost of goods and services’, that is how much energy is required to produce goods and service as outlined by Bullard & Herendeen (1975). The IO model is also used for energy demand projections by examining the structural relationship between energy sector and the rest of the economy embedded in the IO model (Hoch et al., 1984; Hudson, 2014).

In the following years, the top-down model has evolved taking advantage of advances in computational power and theoretical and applied economics (Feddersen, Habermacher, Imhof, & van der Ploeg, 2015). The IO model is extended to Social Accounting Matrix (SAM), providing social dimension (i.e., differentiation of household income) which became the basic database for CGE modeling (Fathurrahman et al., 2017). The further development of Hudson-Jorgensen model (Hudson & Jorgenson, 1974) led to the development of Computable General Equilibrium (CGE) modeling.

Herbst, Toro, Reitze, & Jochem (2012) noted that conventional top-down energy models in the past examined technological developments mostly based on regulatory (such as: bans, technical standards and technological targets) and price policies (such as: Subsidies, taxes and surcharges). In addition, the most important advantage of a top-down model is its ability to assess economic and societal effects, which are important in determining the energy policy impact on the socio-economic dimension. However, several disadvantages of the models also persist (Herbst et al., 2012):

- Lack of technological detail and rather generalized information.
- Undermining of the complexity of non-monetary issues such as lack of knowledge, inadequate decision routines, or group-specific interests of technology producers or of whole sales.
- Favoring only monetary based policy, e.g. price-based policies (taxes, subsidies, etc.), since the focus of the models are on monetary forms.

The second branch of energy models are bottom-up models. It is usually termed as ‘engineering approach’ and it emphasizes the technical characteristics of the energy sector (Bhattacharyya & Timilsina, 2009). The models apply simulation and optimization methods in the engineering sciences with technology-rich representations of a partial equilibrium (equilibrium only in energy sector). The bottom-up energy models are typically used to find optimal solution for the expansion of the energy system under a pre-determined criterion or multiple criteria. Such as, minimizing cost or emissions subject to several defined constrains or coupling the objectives of minimizing cost and emissions in a multi-objective setting.

The bottom up energy modeling has advantages in its ability to incorporate a high degree of technological detail and ability to give detailed evaluations of technology- or sector-specific policies (Herbst et al., 2012). However, it neglects the interaction between the energy sector and overall economic activity, changes in economic structures, prices and employment. It requires disaggregated data that means heavily dependent on high resolution and credible data (Böhringer & Rutherford, 2008).

In more recent applications, both approaches have been used for analyzing costs of mitigating global warming (Feddersen et al., 2015). The different characteristics of both models have been explored in Van Beeck (1999) can be seen in Table 3.4.

Table 3.4. *Characteristics of Top-down and Bottom-up Energy Models Adapted from Van Beeck (1999)*

Top-Down Models	**Bottom-Up Models**
Cannot explicitly represent technologies	Allow for detailed description of technologies
Reflect available technologies adopted by the market	Reflect technical potential
The “most efficient” technologies are given by the production frontier (which is set by market behavior)	Efficient technologies can lie beyond the economic production frontier suggested by market behavior
Use aggregated data for predicting purposes	Use disaggregated data for exploring purposes
Based on observed market behavior	Independent of observed market behavior
Disregard the technically most efficient technologies available, thus underestimate potential for efficiency improvements	Disregard market thresholds (hidden costs and other constraints), thus overestimate the potential for efficiency improvements
Determine energy demand through aggregate economic indices (GNP, price elasticities), but vary in addressing energy supply	Represent supply technologies in detail using disaggregated data, but vary in addressing energy consumption
Endogenize behavioral relationships	Assess costs of technological options directly
Assumes there are no discontinuities in historical trends	Assumes interactions between energy sector and other sectors is negligible

The difference of two approaches may generate two divergent results, as for example, in the case of the economic impact of climate policy and emission reduction potentials (Cline et al., 1996; Wilson & Swisher, 1993). Both model capabilities can be represented in a three-dimensional structure, which Hourcade, Jaccard, Bataille, & Ghersi (2006) noted as the three-dimensional assessment of energy models (see Figure 3.2).

Figure 3.2 is useful in contrasting both approaches in energy modeling. The bottom-up model has more details in technological explicitness however lacking in macroeconomic completeness and microeconomic realism. Since it is lacking the macro and micro economic realism, the models tend to under estimate the costs of switching from one technology to another. On the other hand, the top-down model can represent macroeconomic aspects better but lacks technological details. This implies that changing form of energy technology for political or environmental objectives would be costly, as the substitution of technologies is somehow restricted due to historically-based elasticities.

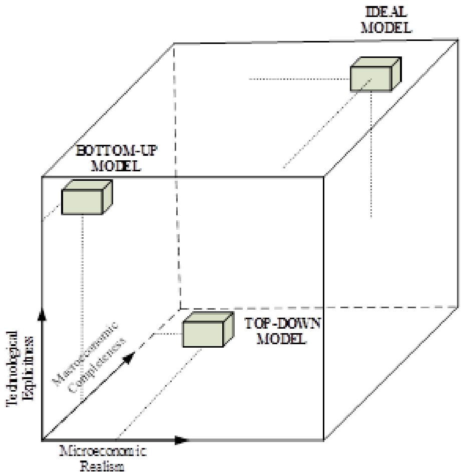


Figure 3.2. Three-dimensional Assessment of Energy Models
Adapted from Hourcade et al. (2006)

It also displays the 'ideal model' which is able to tackle deficiencies of both approaches. This kind of approach is known as the hybrid model. The hybrid model may complement both models' weaknesses by possessing high energy sector detail as well as complete macro- and micro-economic representation. Thus, the link between energy sector and general economy can be analyzed.

3.5. Hybrid Models

The relationship between energy and economy can be quite complicated as it happens that feedback loop between two is happening. On one hand, the growth in the economy will require additional energy input, on the other hand, the energy sector will also provide feedback to the overall economy through its increasing supply requirement, price changes and additional investments. A simple representation of such interactions can be seen in Figure 3.3.

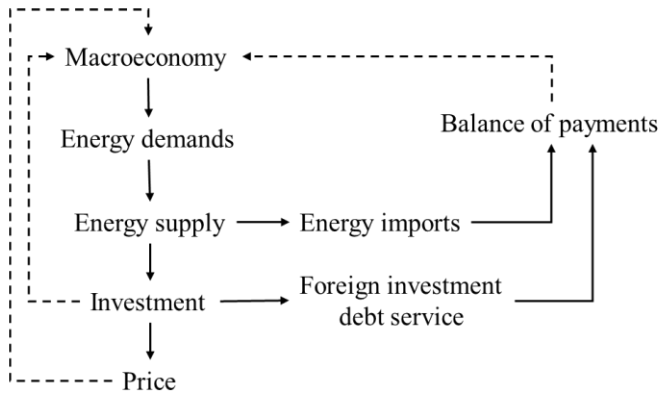


Figure 3.3. The Linkages between Economy and Energy
Adapted from Munasinghe & Meier (1993)

The solid line depicts the impact from macroeconomic changes to the energy sector, which Munasinghe & Meier (1993) termed as forward linkages. For example, the growth in overall GDP, the demand for energy will generally increase which should be compensated by the sufficient energy supply. The additional supply will require new investment or imports, which ultimately will create new energy price and balance of payments.

In contrast, the dashed lines depict the impact of changes in energy sector to the whole economy, termed as backward linkages. From our previous example, the balance of payments, investment, and price, will ultimately impact the whole economy. Both economy and energy sector will then provide feedback loop until convergence or economic equilibrium is reached .

The formal link between the macroeconomy and the energy sector is represented in many hybrid type energy-economic models. The hybrid models, by definition, is a variation of different model types. The linking between sub-models is possible through either a hard- or a soft-link.

In the case of a soft-linking, two or more different models are used and run independently from each other. The link between the models is established through specially defined interfaces until the results of both models converge. Thus, soft-linking practically involves two main nodes of information processing: by using formal models and by using linking procedures, which relies highly on judgement of the modeler (Wene, 1996). Deciding on convergence requires choice of common measuring points (CMPs), which act as the points where linking is established. In order to decide the CMP, the comparison of both models is useful in order to analyze the input-output processing in the model (Wene, 1996). The CMP for example, can be in terms of prices and quantities (Kumbaroğlu & Madlener, 2003).

The recent example of soft-linking application is demonstrated by (Krook-Riekkola, Berg, Ahlgren, & Söderholm, 2017). The authors used soft-linking approach to integrate EMEC, a CGE model and TIMES-Sweden, a bottom up energy model of Sweden. The linking of models was realized through prior comparison and decision on CMP. The outcome pointing out the significance of soft-linking in assessing national energy and climate policy.

In contrast to soft-linking, in the hard-link approach, different type of models is firmly linked to each other. The models are fully integrated and calculations take place simultaneously (Wene, 1996). The approach often leads towards simplified description of one of the models (Remme & Blesl, 2006), for example, a simplified introduction of energy system in CGE model (Böhringer & Rutherford, 2008).

The hard-linking approach is useful for addressing the global picture when the regional details are inferior, while soft-linking approach is usually more useful in national scale, where more detailed models can be kept together (Bauer, Edenhofer, & Kypreos, 2008; Böhringer & Rutherford, 2009). In summary, soft-link approach can simply be represented as *practicality*, *transparency* and *learning*, while hard-linking can be summarized as *productivity*, *uniqueness* and *control* (Wene, 1996).

In energy policy evaluation, Bohringer & Rutherford (2008) present an overview of hybrid modeling exercises. Several early efforts of hybrid energy models can also be seen in 'energy-economic models' rows in Table 3.2. The 'integrated models' rows depict the hard-link based models, while 'model sets' are models with soft-linking approach. Other examples of more recent important contributions are MARKAL-MACRO model (A. S. Manne & Wene, 1992), MERGE model (A. Manne, Mendelsohn, & Richels, 1995), MESSAGE-MACRO (Messner & Schrattenholzer, 2000) and WITCH model (Bosetti, Carraro, Galeotti, Massetti, & Tavoni, 2006).

3.6. Recent Energy Modeling Challenges

In the previous sub-chapters, we have discussed the early applications of energy models, the typical categorization of models, and finally the emerging 'hybrid' type of modeling approach. While oil crisis set the momentum for development of energy models and change general policy perspectives to more long-term thinking, climate change problems have influenced modelers to view energy system modeling through multidimensional perspective, merging the economic, social and environmental aspects all together.

It is quite understandable that the expanding applications and extensions of energy models arise in order to answer the current energy problems. Climate change has become the main global challenge in the 21st century due to its possible multidimensional impacts. In Paris, world leaders agreed to extend efforts to limit GHGs to prevent global average temperature from increasing more than 2^{o}C. The transitions to sustainable energy system (i.e., integrating renewable energy and improving energy-use efficiency) is believed to be the answer to this problem. To be exact, policy makers need to know impact of their policies on costs and characteristics of low GHG technologies, the ability of consumers and businesses to adopt new technologies, and influence of energy transition on the general economy (such as employment, competitiveness and economic structure) (Hourcade, Jaccard, Bataille, & Ghersi, 2006). The current energy modeling challenges can thus be viewed as derivatives of energy system transition issues.

From the supply-side perspective, the transition to sustainable energy system will require significant deployment of renewable-based energy technologies. However, transformation to renewable energy system poses great challenges. The viability of such system is still widely debated. While there exist studies that put forth a feasible cost of supplying power demand via 100% (or close to 100%) renewables (Budischak et al., 2013), other studies suggest that such a system will be costly due to intermittent nature of renewable power generation which needs expensive storage infrastructure (Gross et al., 2006). Such issue can only be dealt by delivering relevant spatial and temporal resolution into energy models (Pfenninger, Hawkes, & Keirstead, 2014).

Current challenges in energy modeling from supply perspectives include several aspects such as variability, decentralization, the need for flexibility and realistic behavior of the market. One of the approaches is by using regulatory-based market model (Bogdanov & Breyer, 2016). For example, (Karavas, Kyriakarakos, Arvanitis, & Papadakis, 2015) simulate a decentralized power market by using agent-based systems approach. The authors conclude the feasibility and favorability of decentralization energy management system. In addition, many recent studies try to model energy system with high penetration of renewable energy and show that how such a system may be possible by tackling variability and assuring flexibility (e.g. Bogdanov & Breyer, 2016; Frew, Becker, Dvorak, Andresen, & Jacobson, 2016; Mileva, Johnston, Nelson, & Kammen, 2016; Quiggin & Buswell, 2016).

The challenge in the demand side involves all effort to pursue more efficiency in energy use. While the expectation of the improved efficiency can be estimated through empirical studies, the recent challenge in this aspect consists of the social acceptance of the new improved system and technologies (Hourcade et al., 2006). There is a need to integrate behavioral aspects and acceptance of the consumer aspects to a new energy system (Keles, Jochem, McKenna, Ruppert, & Fichtner, 2017). This is important since it appears that efforts to improve efficiency might not always result in a lower energy demand, due to a phenomena called the rebound effect (Smeets et al., 2014). The energy model should be behaviorally realistic. It should take into consideration how energy efficiency policies would be accepted by the society (Gargiulo & Gallachóir, 2013).

These challenges have triggered the proliferation of studies in those directions. In addition, other modelers try to combine several models, and link them together either through soft-linking or hard-linking (Gargiulo & Gallachóir, 2013). In this study, our approach will be by integrating multiple models, via soft-linking procedures to assess sustainable development pathways for Turkey.

CHAPTER 4

MODELING TURKISH SUSTAINABLE ENERGY SYSTEM

4.1. Introduction

Turkey is one of the most populous countries in the world (19th as of 2018) with more than 80 million people. It is located between South-eastern Europe and South-western Asia. Total land area of Turkey is 785,347 sq. km with a density in 2018 of 103.5 person per sq. km (Yapp & Dewdney, 2019).

In terms of the economy, during the past few decades Turkey had a thriving economy partly due to its strategic location. The location makes it a convenient pathway in connecting markets in Asia, Middle East and Africa, Russia and Europe. The general economic, social and energy figures of Turkey is presented in Table 4.1. Turkey's economy grew on average by 7.4 percent during 2010-2015 period. However, in the following years, the economy is experiencing difficult periods, with market volatility and rising external stress (OECD, 2018). The GDP growth rate in 2018 is recorded at 2.6% (with a 3% contraction observed in the last quarter) and unemployment rate increased to 11%. In order to sustain the previous economic achievements, the government is currently restoring the stability and accelerating the structural reforms through various fiscal and non-fiscal policies (European Commission, 2019).

As the economy grew, considerable improvements in living standards have also been achieved. By doing so, steady increase in energy demand has been recorded as a direct consequence for the aforementioned growth rate. Between 2010 and 2015, the average growth rate of final energy demand was 4.3%. In addition, in 2017, the final energy demand has reached 104.04 million tonnes of oil equivalent (Mtoe), increased 6.9% from the previous year.

Table 4.1. *General Economic, Social and Energy Figures*

Indicator	Year			
	2010-2015 Average	**2016**	**2017**	**2018**
Socio-Economic Indicators				
Population (Million person)[1]	76.20	79.81	80.81	82.00
Annual change (%)	1.3%	1.4%	1.3%	1.5%
GDP (constant 2010 billion US$)[2]	936.13	1,122.51	1,206.04	1,236.99
Real GDP growth (%)	7.4%	3.2%	7.4%	2.6%
GDP per-capita (constant 2010 US$)[2]	12,393.81	14,062.73	14,870.68	15,026.71
Unemployment Rate (%) Total[3]	9.6%	10.9%	10.9%	11.0%
Consumer Price Index (annual change) (%)[3]	..	7.8%	11.1%	16.3%
Current Account Balance (% of GDP)[3]	..	-3.8%	-5.6%	-3.6%
Energy indicators				
Final Energy Demand* (Mtoe)[4]	82.97	97.34	104.04	..
Annual change (%)	4.3%	4.3%	6.9%	..
Gross Electricity Generation (TWh)[5]	239.00	274.41	297.28	..
Annual change (%)	5.1%	4.8%	8.3%	..
Electricity Installed Capacity (GW)[5]	61.03	78.5	85.20	..
Annual change (%)	8.1%	7.3%	8.5%	..

* Not included non-energy use

[1] TurkStat (2019b) [2] World Bank (2019) [3] European Commission (2019) [4] GDEA (2019) [5] TEIAS (2019a)

The growth in demand is also accompanied by increase in electricity supply. In 2017, the gross electricity generation was accounted as 297.28 terawatt-hours (TWh), provided by total installed power capacity of 85 gigawatt (GW). The steady increase in demand in the following years will require more energy resources. Thus, securing adequate energy resources becomes increasingly challenging since at the same time there is an urgent need to reduce emissions and promote more environmentally friendly policies.

This chapter will discuss about the methodological approach to model the sustainable Turkish energy system. First, the sustainability challenges of Turkish energy system are discussed. These challenges become the background in the considerations for the development of scenarios in the model. Second, the developed scenarios are explained along with various assumptions linked to these scenarios. Lastly, the modeling methodology and the software used will be discussed together with presenting the main data sources of the model.

4.2. Turkish Energy Challenges

In order to assess the current challenges in Turkish energy system, the overall view of the balance between energy supply and demand of the country has to be investigated. One way to look at the current energy dynamics is through the energy balance. It is the static representation of energy system in a time period. Every year, the government through General Directorate of Energy Affairs disseminates the energy balance table that can be accessed through their web page (GDEA, 2019).

While the original energy balance table has more detail, the simple representation of the energy balance for Turkey in 2017 is graphically presented in Figure 4.1. During the period, the total primary energy consumption in Turkey is 144.98 Mtoe. The primary energy sources are coal (39.45 Mtoe), oil (43.98 Mtoe), natural gas (44.26 Mtoe), geothermal (7.13 Mtoe), hydro (5.01 Mtoe) and other renewable energy (5.18 Mtoe). Fossil fuel comprises most of the primary energy supply accounted for 88% of the total. In the consumers' side, the consuming sectors are disaggregated to industry, service, residential, transport, agriculture, non-energy use and electricity and heat sectors which comprises of 24.97, 7.15, 18.18, 28.33, 3.65, 7.37, and 55.36 Mtoe respectively. Electricity and heat sector are the highest consuming sector with the total share of 38.2%.

Apart from the relative and absolute quantity of the primary energy sources and sectoral use, Figure 4.1 can also tell the relative distribution of consumptions for each energy sources. For instance, out of 39.45 Mtoe of coal, 24% goes to industry, 6.8% to services, 8.6% to residential, and 59.8% to electricity and heat. From this, we can see that more than 80% of coal is consumed by only electricity heat and industrial sector. In other words, the coal industry is highly dependent on those sectors. This kind of analysis can be carried out as well for other energy sources.

In addition, analysis of the sectoral primary energy consumption can also be assessed. Transportation sector for example, is highly dependent on oil product as 98% of the energy consumption is fulfilled by this resource. The remaining energy demand is fulfilled by natural gas and biofuel. The lack of diversification can be a problem, since, during an oil supply disruption, the transportation sector may become very vulnerable. The same analysis can be done to other economic sectors as well.

Aside from the analysis of its own energy system, the benchmarking of energy system can also be done to see the current challenges of Turkish energy system. There are various indexes that has been developed to measure and evaluate the sustainability of energy system. Some of the examples of such measurement are Energy Architecture Performance Index (EAPI) (World Economic Forum, 2017), Energy Sustainability Index (ESI) (World Energy Council, 2018) and Sustainable Energy System Index (SESI) (Fathurrahman, 2016). For Turkey, none of the above-mentioned indexes favors a very strong sustainability in Turkish energy system. Out of 127 countries being assessed in EAPI, Turkey lies in 41th position. The lowest score was recorded at economic growth and development dimension, which include the indicator of energy import (World Economic Forum, 2017). For ESI, Turkey holds the 44th

position out of 125 countries. Similar to EAPI, the least score for Turkey is in terms of energy security, which include energy import dependency indicator (World Energy Council, 2018). Furthermore, SESI marks environmental sustainability as lowest score for the sustainability of Turkish energy system (Fathurrahman, 2016).

4.2.1. High Dependency on Fossil Fuels

From the snapshot of the energy system, one can notice the challenge that it is facing. First, high dependency on fossil fuels and lack of utilization of renewable energy. 88% of total primary energy consumption in Turkey is from fossil fuels (oil, coal and natural gas), while the remaining 12% is met with the renewables. Fossil-fuel based energy system was concluded to be unsustainable practice that might harm future well-being of the country due to its environmental impact and depletion of resources (Fathurrahman, 2016). In addition, Turkey is a country with a poor fossil-fuel energy resources, consequently, dependency on foreign energy resources will increase if the current practice prevails.

Renewable energy was limited due to high cost, technical challenges and comparative instability (Nalan, Murat, & Nuri, 2009). However, the cost of renewable energy is declining as well as the technological know-how has improved, accordingly, the utilization of renewable energy is increasing and expected to increase in the near future. Turkish government also made a plan to increase the utilization of renewable energy through 'Renewable Energy Action Plan' (MENR, 2014). One limitation of such policy is that it does not cover a long-term period. This study also sought to address the pertaining gap.

Heavy reliance on fossil-based energy has resulted in GHG emissions. Figure 4.2 presents the development of Turkey's GHG emissions by sectors from 1990-2017. GHG Emissions increased from 427.6 MtCO2e in 2011 to 526.3 MtCO2e in 2017. It

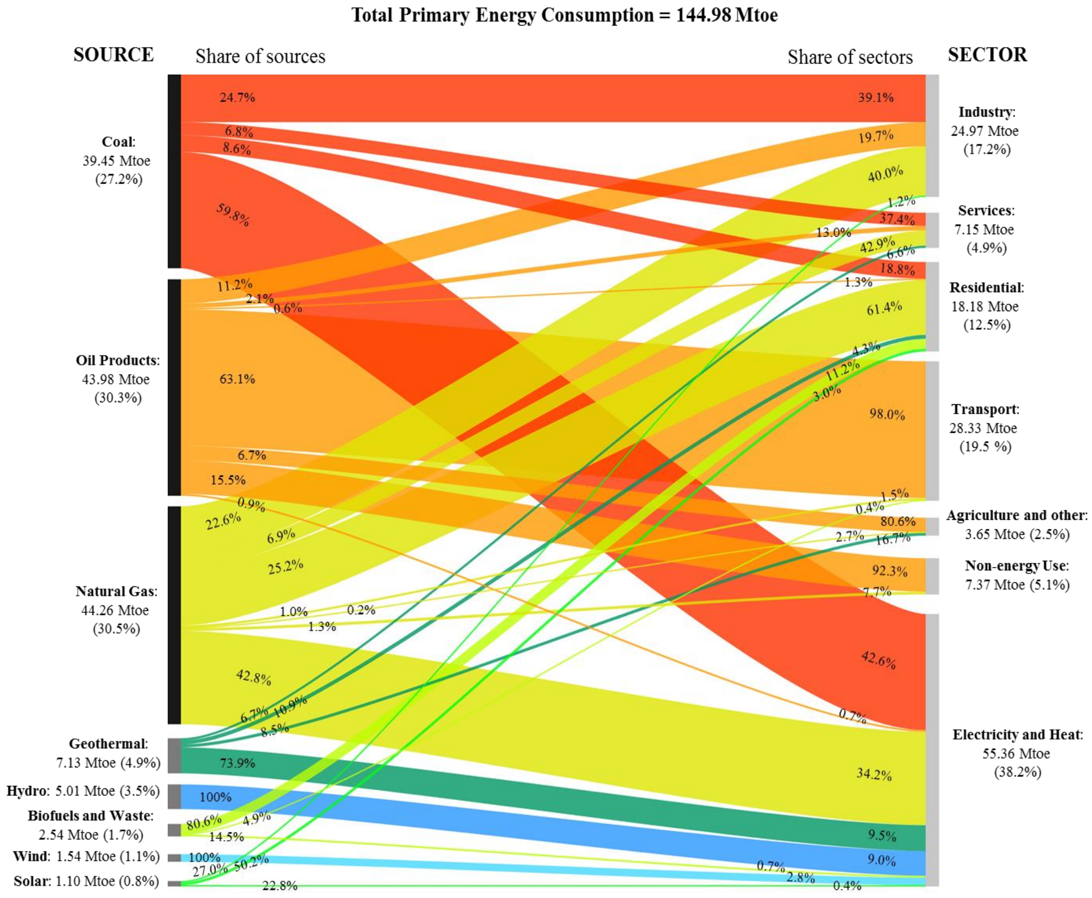


Figure 4.1. Total Primary Energy Consumption in Turkey, 2017
Source: Own calculation based on Turkish Energy Balance 2017 (GDEA, 2019)

corresponds to CAGR[4] of 4%, one of the several positive rates and the highest among OECD countries. That means, if the current rate persists, the GHG emissions would be doubled within less than 20 years. The energy sector contributes the most to the total GHG emissions. In 2017, 72.2% of total emissions is coming from energy sector. During 2011-2017, the CAGR of emissions from the use of energy is recorded at 3%.

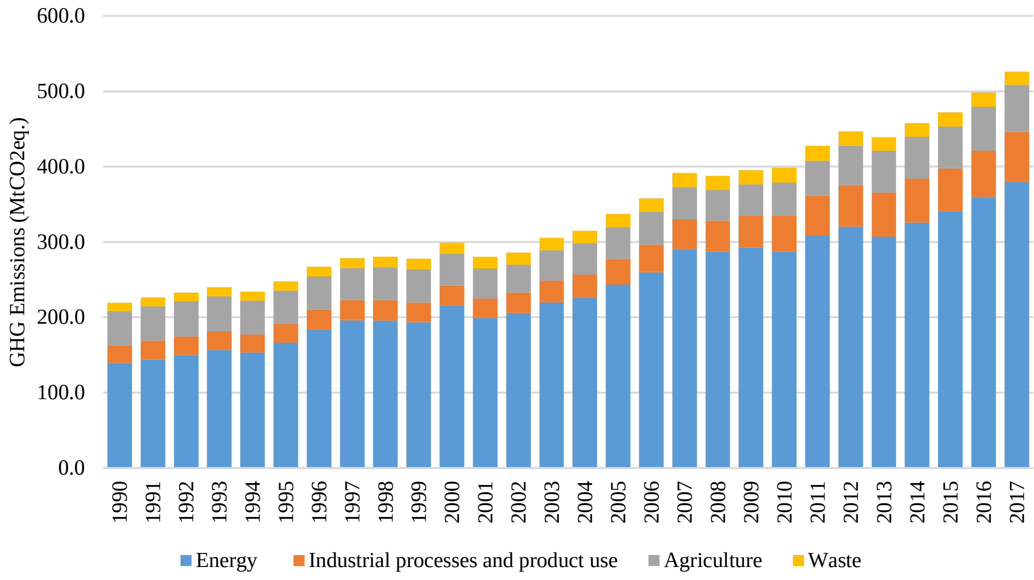


Figure 4.2. Greenhouse Gas Emissions by Sectors (MtCO2e), 1990 – 2017
Source: Based on data from TurkStat (2019a)

In Turkey, climate change would possibly decrease water resource, increase aridity and drought and increasing heat waves, which ultimately allow adverse impact to well-being of the society (Şen, 2013; Huhne & Slingo, 2011; MEU, 2018).

4.2.2. Lack of Domestic Energy Resources

Another challenge of Turkish energy system is its lack of domestic energy resources. Limited amount of domestic fossil-fuel resources has made Turkey very dependent on imported resources. Figure 4.3 presents the development of Turkish energy imports during the period 1990 to 2017. Net imports of energy resources have risen from 54%

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[4] CAGR stands for Compound Annual Growth Rate. It is a measure of annual growth within certain period. CAGR is calculated as: $CAGR = \left(\frac{end\ value}{start\ value}\right)^{\frac{1}{no.of\ years}} - 1$

in 1990 to 77% in 2017. In 2011, energy imports were 113.4 Mtoe and has increased to 145.3 Mtoe in 2017, a CAGR of 4%. With the current rate, the amount of energy imports will be doubled in 18 years. In fact, it is estimated that the dependency on energy imports would reach 82% in 2020 (Sözen, 2009).

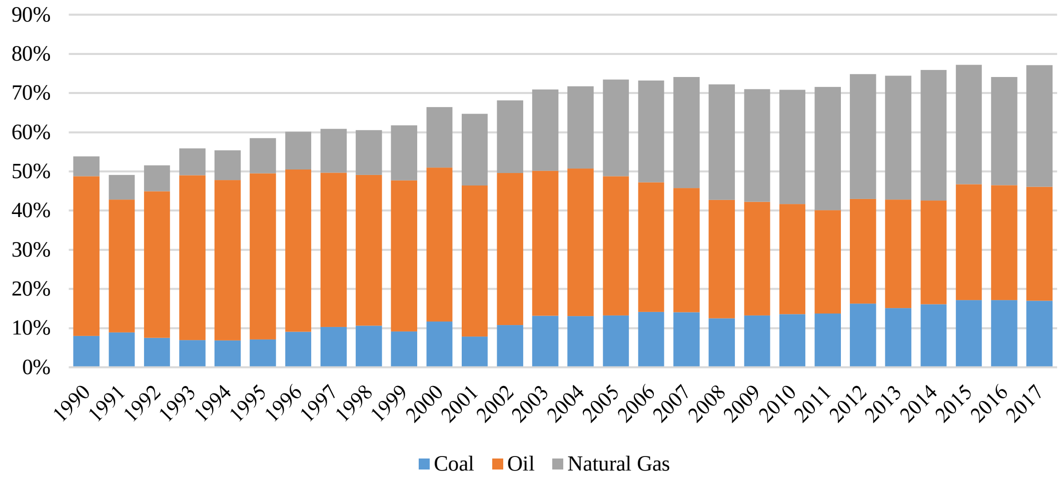

Figure 4.3. Net Primary Energy Import (% of Total Primary Energy Supply)
Source: Based on data from GDEA (2019)

With increasing dependency on foreign supply, Turkey is highly exposed to external shocks and fluctuations of the price in the global energy market. Furthermore, worsening global political dynamics might also play role in threatening the energy security of the country. Geopolitical dynamics and fluctuation of energy prices are common risks that accompanied the country which depends too much on foreign energy resources. If a stable and peaceful future were expected, then high dependency would not be a problem. However, looking at current circumstances, the region is subject to unstable geopolitical situation.

4.3. Energy Policy and the Need for a Long-term View

In July 2019, the 11th Development plan was approved by the Turkish parliament, introduced and publicized. The development plan covers the period between 2019-2023 and serve as a roadmap to improve the country's position in the international arena and enhance its welfare (Anadolu Agency, 2019). In addition, the 11th development plan also serves as a guiding policy document in order to meet the Turkish ambitious 2023 Vision[6]. Based on the document, The main objective of the plan on Turkish energy system is "..to ensure the continuous, quality, sustainable, secure and affordable supply of energy." (TC Cumhurbaşkanliği, 2019). It is described into several targets to be fulfilled in 2023 which include (MENR, 2014; MENR, 2012; TC Cumhurbaşkanliği, 2019; Bloomberg New Energy Finance, 2014):

- Increasing installed power to 109 GW
- Advancing the share of renewables in electricity generation to 38 percent
- Maximizing the use of hydropower
- Increase the electricity per capita to 4,324 kWh/person
- Wind power installed capacity to be 20 GW, Geothermal 1 GW, Solar 5 GW and Biomass 1 GW
- Transmission lines extension to 60,717 km
- Power distribution unit capacity improvement to 158,460 MVA
- Smart grids system application
- Improving the storage capacity of natural gas to 5 billion m3
- Energy stock exchange establishment
- Nuclear power plants commissioning (2 operational nuclear power plants, with a 3rd under construction by 2023)
- Build additional coal power plant with a total capacity of 18,500 MW
- Energy efficiency reduction of 20% compared to 2011

As can be seen, the planning documents cover only medium-term targets (i.e., to the year 2023) and insignificant attention is given to long-term energy planning. In terms of energy planning, the long-term views and expectations cannot be neglected. This is due to the nature of energy sector which characterized as high upfront capital and long lifetime (20-60 yr.) instalments. Hence, investment to be planned and realized now,

[6] The year 2023 will mark the 100th anniversary of Turkish Republic. The government sets up various goal in several main themes such as: economy, energy, foreign policy, health care, transportation, tourism and education.

will affect the long-term overall energy system of the country. Sudden dramatic changes in the system will pose a higher economic, social, and environmental risks. That is the reason why a long-term vision of energy system is necessary. It should answer the future uncertainty questions such as: How will the energy system look like in the long-term? What will be the primary sources? How much is the cost? What will be the social, economic and environmental consequences?

The existent of long-term vision would allow a smoother transition to new energy future for the energy system. In the present study we formulated the long-term pathways (up to 2050) for smooth shift to a sustainable energy system with a particular emphasis on the electricity sector.

4.4. Electricity Sector Highlights

Electrical energy plays a very significant role in the current energy system as the highest consuming sector of primary energy. Furthermore, the role of electricity in final energy demand is expected to rise as the energy systems are in a resilient transition from fossil-fuel to electricity-based technology.

The installed capacity of power production system by various primary energy sources during the period 2011-2017 is given in Table 4.2. In addition, the annual gross electricity generation[7] from each energy sources are presented in Table 4.3. With the increasing needs of power, Turkey's gross electricity generation has increased from 229.4 TWh in 2011 to 297.28 TWh in 2017 or equivalent to an annual average growth rate of 4.4%. To produce this amount of electricity, the power capacity increased from 52.91 GW to 85.2 GW; which corresponds to an annual average capacity growth of 8.3%. In terms of the sources of energy, fossil fuels dominated both the installed capacity and the generation capacity for all years and reached 54.3% and 70.4% of the total power system in 2017. Due to heavy reliance on fossil fuels, the GHG emissions factors in Turkey is comparatively high.

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[7] Gross electricity generation is the total amount of electricity generated by a power plant over a specific period of time. This does not account the consumption of electricity for own-use.

Table 4.2. *Installed Power Capacity 2011-2017*

Energy Resources	**Installed Capacity (GW)**							**CAGR**
	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2011-2017***
Coal	12.55	12.58	12.61	14.81	15.52	17.36	18.71	6.9%
Natural Gas	13.14	14.12	17.17	18.72	18.53	19.56	22.00	9.0%
Oil	8.11	8.17	8.64	7.96	7.48	7.00	5.58	-6.1%
Hydro	17.14	19.61	22.29	23.64	25.87	26.68	27.27	8.1%
Wind	1.73	2.26	2.76	3.63	4.50	5.75	6.52	24.8%
Solar	**…**	…	…	0.04	0.25	0.83	3.42	822.5%
Biomass	0.13	0.17	0.24	0.30	0.37	0.50	0.64	31.2%
Geothermal	0.11	0.16	0.31	0.40	0.62	0.82	1.06	45.1%
Total	52.91	57.06	64.01	69.52	73.15	78.50	85.20	8.3%

* For Solar CAGR 2014-2017

Source: TEIAS (2019)

Table 4.3. *Power Generation 2011-2017*

Energy Resources	**Electricity Generation (TWh)**							**CAGR**
	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2011-2017***
Coal	66.22	68.01	63.79	76.26	76.17	92.27	97.48	6.7%
Natural Gas	104.05	104.50	105.12	120.58	99.22	89.23	110.49	1.0%
Oil	0.90	1.64	1.74	2.15	2.22	1.93	1.20	4.8%
Hydro	52.34	57.87	59.42	40.64	67.15	67.23	58.22	1.8%
Wind	4.72	5.86	7.56	8.52	11.65	15.52	17.90	24.9%
Solar	**…**	…	…	0.02	0.19	1.04	2.89	1188.6%
Biomass	0.47	0.72	1.17	1.43	1.76	2.37	2.97	36.0%
Geothermal	0.69	0.90	1.36	2.36	3.42	4.82	6.13	43.8%
Total	229.40	239.50	240.15	251.96	261.78	274.41	297.28	4.4%

* For Solar CAGR 2014-2017

Source: TEIAS (2019)

However, it can be seen that there is a significant diffusion of renewable energy to the system. In terms of additional capacity, solar was the fastest growing energy source with 822% annual growth during 2014-2017. Other renewable energy sources grew fast as well. During 2011-2017 period, Geothermal annual average growth rate was 45%, Biomass 31.2%, Wind 24.8% and Hydro 8.1%. Overall, Renewable Energy capacity increased from 19.11 GW in 2011 to 38.92 GW in 2017, equivalent to annual growth of 12.6%. These additions of Renewable energy have also increased the share of renewables in total gross electricity generation. In 2011, 58.23 TWh (25.4% of total gross electricity generation) electricity was generated from all renewables, while in 2017 it rose to 88.11 TWh (29.6% of total total gross electricity generation).

The balance of electricity supply-demand of the country for the year 2017 is presented in Figure 4.4. Total gross generation of electricity in the year 2017 is 297.3 TWh, while the final electricity consumption is 247.2 TWh. The difference between gross electricity generation and final (net) demand[9] is 50.1 TWh or 16.9% of the gross generation. These comprise of power plant own consumptions, network (transmission and distribution) losses and net foreign electricity trade.

Most of the electricity is generated through fossil-based electricity generation plants. Coal generated 32.8% while natural gas and oil generated 37.2% and 0.4% of the electricity respectively. 29.6% of electricity comes from renewables. Among them the highest contributor is hydro, which generated around 19.6% of gross electricity. Wind, solar and other renewable-based power plants are accounted for 6.0%, 1.0% and 3.1% of the gross electricity generation respectively. In terms of the consumers, industry holds the biggest share, accounted for 46.4% of total electricity consumption. In other sectors, residential accounts for 22.3%, service 27.8%, agriculture 3.0% and transportation 0.5% of total electricity consumption.

[9] Final electricity demand or net electricity demand is the total amount of electricity consumed by users over a period of time. This include the lost of electricity due to power plant’s own-use, transmission and distribution losses and net foreign electricity trade.

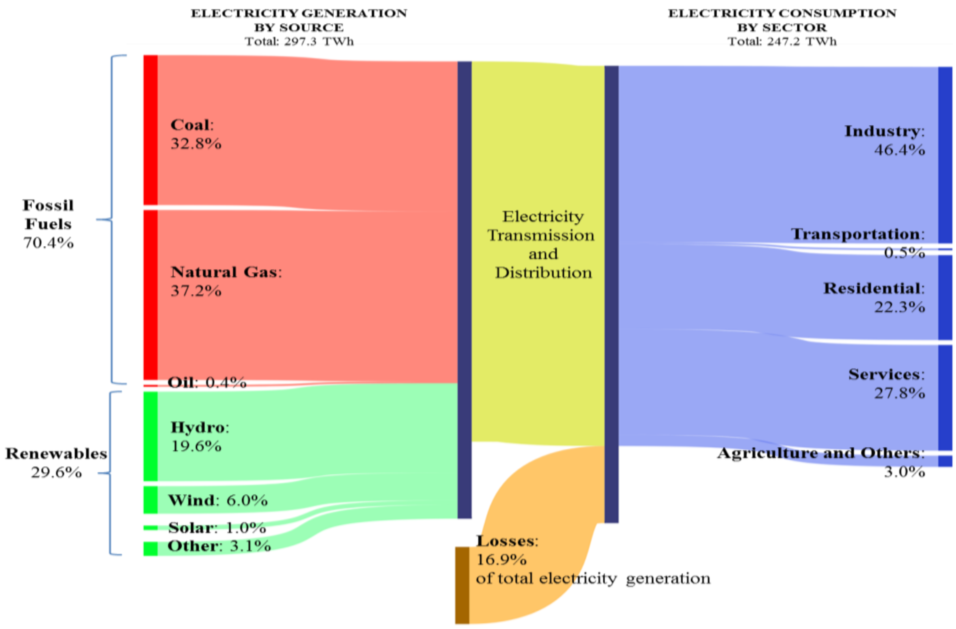

Figure 4.4. Gross Electricity Generation and Net Consumption in Turkey, 2017
Source: Own calculation based on GDEA (2019) and TEIAS (2019)

4.5. Resource Potential

While the majority of Turkish energy needs is fulfilled through foreign resources, there are still a considerable amount of untapped domestic resources to be utilized. The advantages of having the domestic resources is to be more independent and less vulnerable to external shocks. Domestic resources utilization would also lessen the burden of Turkish energy import bills. According to Turkish Statistical Institute's (TurkStat) data, Turkey's energy import bill was 37.2 billion US$ in 2017, and was increased to 42.9 billion US$ in 2018. This correspond to 19.2% of Turkey's total import bill (Hurriyet Daily News, 2019).

4.5.1. Coal

In terms of fossil fuel resources, Turkey does not have remarkable reserve of oil and natural gas. However, considerable amount of lignite and hard coal reserves are available. Out of 2,454 Mtoe fossil energy sources of Turkey, 63% belongs to lignite and 28% comes from hard coal, making a total of 91% domestic fossil fuels comes from coal (M. Ozturk & Yuksel, 2016). Coal also plays a significant role in overall structure of electricity generation of the country. In 2017, coal accounts for 32.8% of total gross electricity generation. However, the share of domestic coal in the total primary energy supply is less than the imported coal. While the total gross electricity generation from coal was 97.5 TWh, domestic coal was accounted for 46.36 TWh of them or 47.6% of the total coal-based electricity generation.

In light of utilizing more domestic resources the efforts to find more reserves has been speeding up. As a result, the lignite reserves which were 8.3 billion tonnes (Bt) has increased to 17.9 Bt by the end of 2015 (MENR, n.d.-b). In terms of electrical capacity, the potential capacity of the domestic coal could be as high as 23.5 GW (Ö. Önenli, 2019).

4.5.2. Hydro

When we look at the Renewable energy resources, up to now, hydropower is the most important renewable energy resource that gives a substantial amount to Turkey's electricity demand. The gross annual hydroelectric potential in Turkey is estimated to be around 433,000 GWh, almost half of which is technically exploitable and 28.0% of it is economically viable (Melikoglu, 2013; DSI, 2017). Looking at its huge potential to exploit, the government aims a target to increase the installed capacity of hydroelectric to 36 GW by 2023 (MENR, 2014).

The responsible body for the hydroelectric energy is The General Directorate of State Hydraulic Works (DSI). The plans and potential capacity to exploit the resource is summarized in its strategic plan. In the strategic plan (DSI, 2017), it is estimated that the total hydroelectric potential capacity is 46 GW, with the breakdown: 26,161 MW in operation, 5,927 MW under construction and 13,984 MW to be constructed.

4.5.3. Wind

The wind energy potential of Turkey is substantial with elevation averaged at 1,132 m and the total coastal length of 7,200 km (Kucukali & Dinçkal, 2014). Wind energy is still relatively untapped despite of its huge resource potential. The theoretical total wind potential capacity is estimated at 88 GW, however the technically available capacity might reach to the level of 48 GW (Melikoglu, 2016). While in 2017 the total installed wind energy capacity was 6.5 GW, within the renewable energy action plan, the government planned to increase it to 20 GW by 2023 (MENR, 2014).

4.5.4. Solar

Solar energy is yet to have a significant contribution in Turkish electricity generation. In 2017, its share of generating electricity was less than 1% of total gross electricity generation. Although its utilization to generate electricity is still limited, the use of solar panel for domestic hot water production is common especially in sunny region in Turkey (Yousefi-Sahzabi et al., 2017).

Due to its geographical position, the total yearly radiation in Turkey is around 1,527 kWh/m2-year (MENR, 2019). It is estimated by the General Directorate of Electric Power Resources Survey and Development Administration, EIEI, (predecessor of General Directorate of Renewable Energy) that the theoretical solar potential in Turkey reach 376 TWh (Onenli, Akinoglu, & Ercan, 2019; Prăvălie, Patriche, & Bandoc, 2019) or equivalent to a total potential capacity of around 200 GW (Önenli, 2019). Looking at its potential, the government set a target in 2023, to increase total capacity of solar power to 5 GW (MENR, 2014).

4.5.5. Biomass

In Turkey, Biomass energy which consists of wastes from animal, residues of agriculture, charcoal, fuel wood, and other biological-source fuels, has the estimated annual gross theoretical potential of about 135–150 Mtoe. From that amount, the theoretical net potential is 90 Mtoe/year, the economic potential is 25 Mtoe/year, and the total recoverable potential is about 17 Mtoe/year (Yousefi-Sahzabi et al., 2017). In addition, in terms of potential electric capacity, it is estimated that biomass resources may have the potential of 6.2 GW (Balat, 2010). In the power supply mix, the government set the target in 2023 to rise Biomass energy-base power plant to reach 1 GW (MENR, 2014).

4.5.6. Geothermal

Turkey is located on the seismically active Mediterranean earthquake belt which also holds some geothermal energy potential especially in West Anatolian Provinces (Yousefi-Sahzabi et al., 2017). The types of geothermal resources have direct contribution on how the resources being utilized. In Turkey, direct-use of heat is more preferable since the resource they have is in the low to medium temperature range (Kose, 2007).

It is estimated that Turkey holds the seventh place in the world for its geothermal potential. The total potential is 60 GW, however, only 4.5 GW has proven potential for generating electricity (M. Ozturk & Yuksel, 2016). The geothermal resource for generating electricity is relatively untapped with current installed capacity of around 1 GW.

4.5.7. Summary of Domestic Resource Potential

In summary, the total potential domestic resources electric capacity is 328.2 GW. This value corresponds to almost 4 times as much electric installed capacity of 2017. Table 4.4 summarize the domestic resources potential capacity of each resources. These values are the values used in the model to limit the maximum utilization of the domestic resources.

Table 4.4. *Domestic Resources Potential*

Domestic Resources	Potential Capacity (GW)
Hydro	46
Wind	48
Solar	200
Other Renewables	10.7
Geothermal	4.5
Biomass and waste	6.2
Domestic Coal	23.5

4.6. Scenario Descriptions

The scenarios developed in the study are pathways for sustainable energy system transition. It meant to answer the sustainability challenges of Turkish energy system that has been discussed in Chapter 4.2. The scenarios used in the study are as follow:

Reference scenario: Base case (BaseCase)

The BaseCase scenario is the reference pathway which assume the development of energy system to follow the same pattern as in the base period.

Sustainable Energy Pathways:

- Maximizing Local Resources (MaxLocal)

  The MaxLocal is the scenario where the domestic resources will be prioritized to utilize more than the imported ones. The domestic resources are renewable energy (solar, wind, hydro, geothermal, biomass and waste) and domestic coal. Within this pathway, the imported energy resources for electricity generation will decrease significantly at the end of the planning horizon.

- Minimizing GHG Emissions (MinGHG)

  The MinGHG is the scenario with the objective to minimize total GHG emission within the planning horizon (2017-2050). Within the scenario, the Renewable energy will take over the fossil fuel-based electricity generation, thus, having GHG emissions at minimal level.

- Full Renewable Energy Utilization (FullRE)

  The FullRE aims to maximized the utilization of the Renewable energy to reach its full potential at the end of planning horizon.

Furthermore, in all scenarios, three different levels of economic growth projection (i.e. low, mid and high) are introduced. In order to run the model, there are some basic assumptions which are used to model the electricity supply outputs. The general assumptions for all the scenarios are as follows:

- In all scenarios the electricity supply is supposed to satisfy the underlying energy demand projections with the minimum idle capacity as possible.
- After 2020, the nuclear capacity is fixed at 4.8 GW. This is coming from the on-going Akkuyu Nuclear Power Plant (NPP) project which is expected to operate its first unit in 2023 and subsequently operating in full capacity (4.8 GW) in 2025.
- The additional and or declining of the renewable-based electricity generation is at most 20% of its previous year. That means, it is not possible to have a significant jump in the increase or decrease of electricity generation in each technology. For example, if a renewable technology generates 100 GWh of electricity in its first year, the following year it could only increase to a maximum of 120 GWh or decrease down to at most 80 GWh. This formulation allows a smoother transition for each technology to decrease and increase its capacity. Furthermore, the rate for non-renewable energy is set as 5%. The value is conservative assumption based on historical annual growth (CAGR) of electricity generation as can be seen in Table 4.3.

4.7. Modeling Approach

The subchapter presents the methodological framework of hybrid energy modeling through soft linking approach. Linking top down and bottom up energy model is meant to improve the decision making of energy policy at the national level, particularly in terms of implementing a sustainable energy system. It also aims to contribute to recent application of formulating a hybrid energy model either theoretically and methodologically. The hybrid model is expected to supplement each of the model's weaknesses and provide robust results. In this work, 3 separate models, namely a CGE model based on GTAP database (GTAP-CGE), Power Sector Linear Program (Power-LP) and Long-range Energy Alternatives Planning System (LEAP) model are used to simulate the pathways to sustainable electricity system in Turkey.

The simple representation of the modeling approach can be seen in Figure 4.5. First, GTAP-CGE economic model is used for the demand projection. The output of the model is then used as exogenous input parameter for GAMS Power-LP model. The Power-LP model is needed to model the supply side of the electricity system. Finally, both the outputs of GTAP-CGE and Power-LP are summarized in LEAP which has better capability of reporting and presenting the results of the overall system.

4.7.1. GTAP-CGE Model

CGE model is economic model with the main aim to find an equilibrium in the whole economic structure. The CGE model in the study is built on GTAP 9 database (Aguiar, Narayanan, & McDougall, 2016). Furthermore, the main architecture of the model is based on TR-EDGE model developed by (Kat, Paltsev, & Yuan, 2018).

As has been discussed in chapter 2 and also provided in many empirical literatures (such as. Sari & Soytas, 2009; Soytas & Sari, 2009; Soytas & Sari, 2006), there exist a strong relationship between energy consumption and the economy. Hence, our main aim of using this economic model is to get projection of the electricity demand while keeping the links and interactions in the overall economy. The CGE model has been used by many scholars in dealing with the energy-economic analysis (for example Kat et al., 2018; Yeldan, Voyvoda, Berke, Şahin, & Gacal, 2015; Acar & Yeldan, 2016; Kolsuz & Yeldan, 2017).

The model is a recursive-dynamic model where the benchmark year is 2011 and solved from 2017 and 2020 to 2050 with interval over 5 year. While the main database is GTAP 9, supplemental data from Turkish Statistical Institute (TUIK), World Bank and Ministry of Energy and Natural Resources were utilized in order to calibrate the model to recent energy and economic trends.

GTAP 9 includes 140 regions, 57 sectors and 8 factors of productions with reference years 2004, 2007, and 2011 (Aguiar et al., 2016). To achieve the goal of the study, this level of disaggregation is not necessary, therefore the data is aggregated into: 2 regions (i.e. Turkey and ROW), 9 production sectors (Industry, Agriculture, Service,

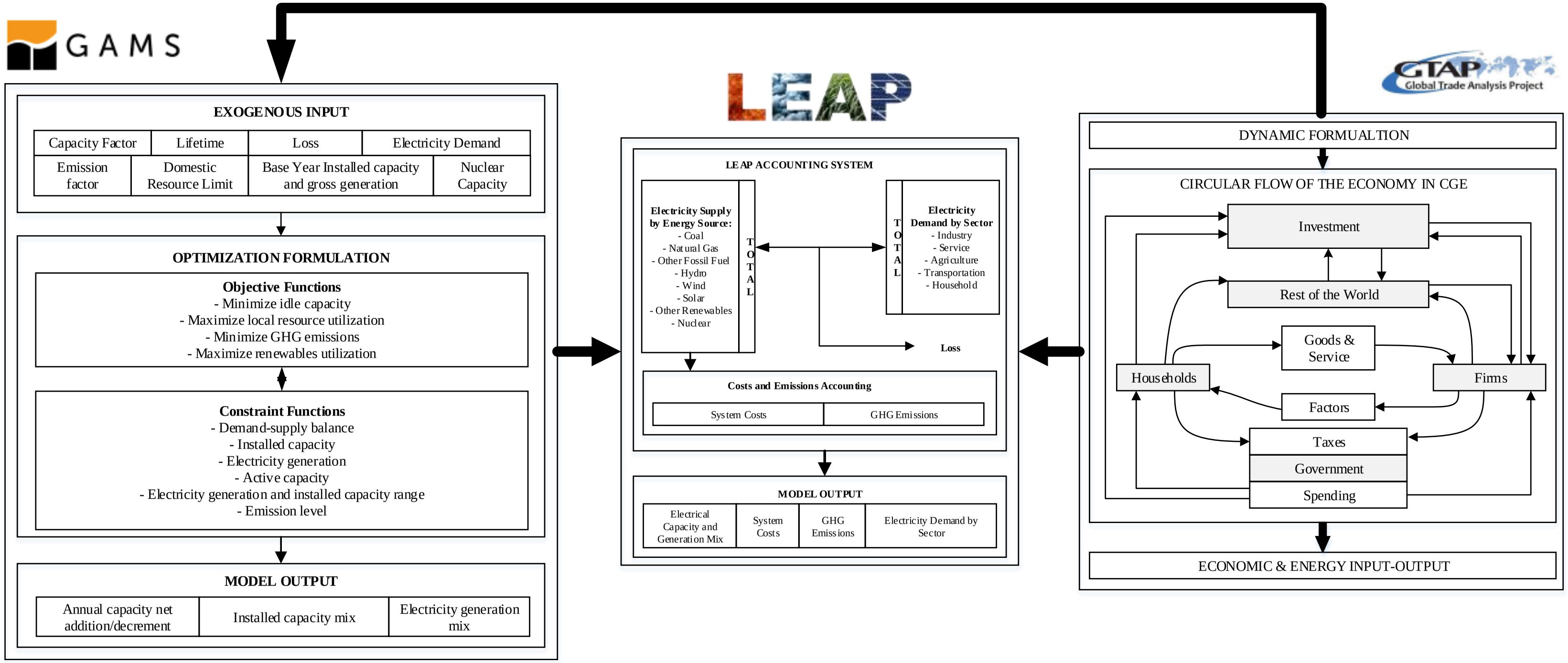

Figure 4.5. Diagram of the Modeling Approach

Transportation, Oil, Oil Refinery, Gas, Coal, Electricity), 3 final consumption sectors (Household, Government, Investment) and 4 factors of production (capital, land, natural resources and labour). Furthermore, the latest available year (i.e., 2011) is used as a benchmark.

The model is written in Mathematical Programming System for General Equilibrium (MPS/GE) language (Rutherford, 1999) which solved as the mixed complementary problem (MCP) in GAMS 23 (GAMS Development Corporation, 2010). Within this formulation, both equalities and inequalities include in the model (Mathiesen, 2008; Rutherford, 2002).

In CGE model, in order to reach equilibrium, three types of conditions should be satisfied by every agent in the economy: zero profit, market clearance, and income balance (Paltsev, 2004).

- *Zero-profit condition*: This condition means that any activity with positive output must earn zero profit. Or, if no production activity takes place, the profit must be negative. In MCP formulation, the following condition has to be satisfied by all sectors:

$$-profit \geq 0; output \geq 0; output^T.(-profit) = 0 \tag{5.1}$$

- *Market-clearing conditions*: Market clears when the supply equal to demand for each commodity with a positive price. In MCP formulation, the condition must be met for every good and factor of production in the economy:

$$supply - demand \geq 0; price \geq 0; price^T.(supply - demand) = 0 \tag{5.2}$$

- *Income-balance conditions*: For each agent in the economy (including government), the income must be equal to the value of factor endowments and tax revenue:

$$income = endowment + tax\ revenue \tag{5.3}$$

The applied recursive structure implies that current period prices determined production, consumption, savings and investment (Kat et al., 2018). Savings which determined by household's utility function is equal to aggregate investment. In addition, the capital in a period is determined by previous period's investment and depreciation of previous period's capital. Mathematically it can be described as follows:

$$K_{r,t} = Inv_{r,t-1} + (1 - \delta_r).K_{r,t-1} \tag{5.4}$$

Where:

$K_{r,t}$ = Capital in region r in period t;

$Inv_{r,t-1}$ = Investment in region r in period t-1

δ_r = Depreciation rate of capital in region r from t-1 to t

The growth of labor endowment is exogenously determined through population growth information published by TUIK and UN. Similarly, the growth of government expenditures and current account balance are assumed based on historical data from TUIK.

In addition, we also assumed productivity growth for both capital and labor as 0.91% for Turkey. Furthermore, to account for low and high growth scenarios, the productivity parameter is taken as 0.64% for low growth scenario and 1.18% for high growth scenario. All other growth parameters used in the model are following Kat et al. (2018):

- *Land use*: 1% annual growth, to account for improvement in land use productivity for both Turkey and ROW
- *Natural resources depletion*: Annual depletion of 2% in Turkey and 0.1% for ROW

The sectoral aggregation and nesting structures of the sectors used in the model are provided in the Appendix E.

4.7.2. Power Sector Linear Program (Power-LP) Model

The Power-LP model is utilized in order to get the projection of the electricity supply sectors. The main framework of the model is shown in Figure 4.5. The power model in this study is the modified and extended version of the model used in Önenli (2019). The additional modifications and extensions in the model are as follow:

- *Customization of fuel groupings*: These changes implicate on updating other parameters, such as: capacity factor, base year electricity demand, base year electricity generation and capacity, and additional limit for 'Other Renewables' technology.
- *Different assumptions employed in each scenario*: Assumptions of scenario is updated depending on the needs of each scenario.
- *Additional objective equation to model FullRE scenario*: The maximization of electricity generation from renewables will serve as objective function.
- *Electricity Loss is introduced*: Loss is the difference between gross electricity generations and final demand which may occur due to transmission and distribution losses and net foreign electricity trade.

The model has 3 main parts: Exogenous inputs, optimization formulation and model output. In general, the main aim of the LP model is to get the projection of: annual power capacity net addition/decrement, installed capacity mix and electricity generation mix.

To run the model, sets, exogenous parameters and decision variables are defined. Sets of the model can be seen in Table 4.5. There are 9 types of exogenous variable in the model. Those variables together with its descriptions and data sources are presented in Table 4.6. Furthermore, the decision variables defined in the model are shown in Table 4.7.

Table 4.5. *Sets in Power-LP Model*

Sets	Descriptions	Value
t	Years	2017, 2020-2050 (5 years interval)
tt(t)	Years subset of t	2020-2050 (5 years interval)
i	Power technologies	Hydro, Wind, Solar, OthRen, NaturalGas, ImpCoal, DomCoal, OthFos, Nuclear
nuc(i)	Nuclear, subset of i	Nuclear
rnw(i)	Renewables, subset of i	Hydro, Wind, Solar, OthRen
local(i)	Domestic technologies, subset of i	Hydro, Wind, Solar, OthRen, DomCoal

Table 4.6. *Exogenous Parameters in the Power-LP Model*

Parameters	Descriptions	Data source
Capacity Factor	Share of maximum available hours the technology could operate at its full rated capacity	Own calculation based on TEIAS (2019b). See Appendix F.
Installed Capacity	Base year installed capacity of each technology	see Table 4.2
Actual Generation	Base year gross electricity generation for each technology	see Table 4.3
Electricity Demand	Projection of the total electricity demand for the whole planning horizon (2017-2050)	CGE Model Output
Emission Factor	Emission factor for each fossil-based technology	Based on Kat et al. (2018)
Life Time	The life time of each technology	IPCC (2015). See Appendix F.
Domestic Resource Limit	Upper limit for domestic resource-based technology	See Table 4.4
Loss	Difference between gross generation and final electricity demand fixed at 16.9%	Calculated based on base year value. See Chapter 4.4
Nuclear Capacity	Nuclear capacity is fixed at 4.8 GW and active after 2025	Model assumption based on planned operational of Akkuyu NPP

Table 4.7. *Decision Variables*

Variables	Descriptions
vEmis(i,t)	Emission due to generation of technology i in year t (Mton)
vAnnEmis(t)	Total emissions in year t (Mton)
vTotEmis	Total emissions throughout 2020-2050 (Mton)
vInsCap(i,t)	Installed capacity of technology i in year t (GW)
vInsCapAct(i,t)	Actively used Installed capacity of technology i in year t (GW)
vAnnInsCap(t)	Total installed capacity in year t (GW)
vNewInsCap(i,t)	Newly installed capacity in year t (GW)
vEleGen(i,t)	Generation by technology i in year t (TWh)
vTotEleGen(t)	Total generation in year t (TWh)
vIdleCap(tt)	Idle Capcity (GW)

The model is run and solved as a Linear Program (LP) in GAMS 23 (GAMS Development Corporation, 2010). In the LP optimization, the model is solved by maximizing or minimizing the objective functions within several sets of constraint equations. Each scenario has a different objective function but similar constraints. The objective functions of the scenarios are as follow:

- *BaseCase*: The main objective in the BaseCase scenario is to minimize idle capacity. Mathematically it is described as follow (eq. 5.5):

$$obj(BaseCase) = Min \left\{ \sum_{\forall i,tt} [vInsCap(i,tt) - vInsCapAct(i,tt)] \right\} \tag{5.5}$$

  This objective function is also added as a secondary objective in the following scenarios. In other words, among the solutions which are determined based on the main criteria of each scenario, the model gives priority to the one with minimum idle capacity. Note that the coefficients *M* are assigned in a way that the scenario's main concern, e.g., maximizing local resources, is still the primary objective.
- *MaxLocal*: The objective of the MaxLocal is to maximize the electricity generation coming from local resources. In addition, it also tries to keep the idle capacity at minimum. It can be described as follow (eq. 5.6):

$$obj(MaxLocal) = Max\left\{\sum_{\forall i,tt|local(i)} vEleGen(i,tt) - \alpha * \sum_{\forall i,tt}[vInsCap(i,tt) - vInsCapAct(i,tt)]\right\} \tag{5.6}$$

- *MinGHG*: The scenario has dual objective: Minimizing emissions and minimizing idle capacity. The following equation (eq. 5.7) described this objective specification:

$$obj(MinGHG) = Min\left\{\sum_{\forall i,tt}[EmisFac(i) * vEleGen(i,tt)] + \alpha * \sum_{\forall i,tt}[vInsCap(i,tt) - vInsCapAct(i,tt)]\right\} \tag{5.7}$$

- *FullRE*: The FullRE has similar objective as MaxLocal. However, instead of domestic resources, the maximization of renewables in the electricity generation is taken as the objective. Mathematically it can be described as follow (eq. 5.8):

$$obj(FullRE) = Max\left\{\sum_{\forall i,tt|rnw(i)} vEleGen(i,tt) - \alpha * \sum_{\forall i,tt}[vInsCap(i,tt) - vInsCapAct(i,tt)]\right\} \tag{5.8}$$

Where:

$obj(SCENARIO)$ = Specific objective based on scenario (SCENARIO: BaseCase, MaxLocal, MinGHG, FullRE)

α = Scale factor

Furthermore, the model is having various constraints. Such as:

- *Demand-Supply Balance* (eq. 5.9): the total electricity generated by all technologies in a period, vTotEleGen(tt), is equal to the electricity demand, EleDem(tt), divided by one minus loss, Loss(tt). The loss value is fixed at base year value. It is calculated as the difference between base year electricity consumption and gross electricity generation.

$$vTotEleGen(tt) = \frac{EleDem(tt)}{1 - Loss(tt)} \tag{5.9}$$

- *Installed capacity* (eq. 5.10; eq. 5.11): The installed capacity of technology i in year tt, vAnnInsCap(tt), is equal to the installed capacity of that technology in the previous period (tt-1) plus the newly installed capacity of that technology in year tt, vNewInsCap(i,tt), minus the depreciated capacity of the base year, DepRate(i,tt) (eq. 5.10). In addition, total annual installed capacity, vAnnInsCap(tt), is the sum of installed capacity of each technology in year tt (eq. 5.11).

$$vInsCap(i,tt) = vInsCap(i,tt-1) - DepRate(i,tt) * vInsCap(i,t_0) + vNewInsCap(i,tt) \tag{5.10}$$

$$vAnnInsCap(tt) = \sum_{\forall i} vInsCap(i,tt) \tag{5.11}$$

- *Electricity Generation* (eq. 5.12; eq. 5.13): The electricity generation of technology I in year tt, vEleGen(i,tt), is the product of number of hours in a year (8760) multiply by its capacity factor, CapFac(i), and its installed capacity (eq. 5.12). Furthermore, the total annual electricity generation vTotEleGen(t) is the sum of electricity generations of each technology year in year t (eq. 5.13).

$$vEleGen(i,tt) = 8760 * CapFac(i) * vInsCapAct(i,tt)/1000 \tag{5.12}$$

$$vTotEleGen(t) = \sum_{\forall i} vEleGen(i,t) \tag{5.13}$$

- *Active capacity* (eq. 5.14): The active capacity (or the utilized capacity) of a technology in a year, vInsCapAct(i,tt), should be lower than the installed capacity for the corresponding technology.

$$vInsCapAct(i,tt) \leq vInsCap(i,tt) \tag{5.14}$$

- *Electricity generation and Installed capacity range* (eq. 5.5; eq. 5.5): ensures that the electricity generation of technology i in a year may have some lower (LB(i,tt)) and upper bounds (UB(i,tt)) set as a ratio of total electricity generation in the given year (eq. 5.15). On the other hand the second equation sets lower (LB2(i,t)) and upper bounds (UB2(i,t)) as a ratio of the capacity in the previous period (eq. 5.16). This equation provides a permissible limit for additional or decreament of electricity generation in the following year.

$$LB(i,tt) * vTotEleGen(tt) \leq vEleGen(i,tt) \leq UB(i,tt) * vTotEleGen(tt) \tag{5.15}$$

$$(1 - LB2(i,t)) * vEleGen(i,t-1) \leq vEleGen(i,tt) \leq (1 + UB2(i,t)) * vEleGen(i,t-1) \tag{5.16}$$

- *Emissions Equations* (eq. 5.17; eq. 5.18; eq. 5.19): are the equations related to emissions. Emissions of technology i in year t (vEmis(i,t)) is calculated by multiplying Emission factor of the technology (EmisFac(i)) and the electricity generation of that technology (eq. 5.17). Furthermore, two other equations represent the annual emissions (vAnnEmis(t)) (eq. 5.18) and cumulative emissions (vTotEmis) (eq. 5.19) throughout the model horizon, respectively.

$$vEmis(i,t) = EmisFac(i) * vEleGen(i,t) \tag{5.17}$$

$$vAnnEmis(t) = \sum_{\forall i} vEmis(i,t) \tag{5.18}$$

$$vTotEmis = \sum_{\forall tt} vAnnEmis(tt) \tag{5.19}$$

The GAMS code of the model can be seen in Appendix F.

4.7.3. LEAP Model

Long-range Energy Alternatives Planning (LEAP) (Heaps, 2016) is a windows-based tool for energy planning and GHG mitigation assessment developed by the Stockholm Environment Institute (SEI) that has been applied in over 190 countries. LEAP is an energy accounting framework, rather than a model that simulates the behavior of a system in which outcomes are unknown, instead it asks users to explicitly specify outcomes (Stockholm Environment Institute, 2005). Main function of these tools is to manage data and results. In addition, it has a flexible approach to modeling which based on non-controversial physical accounting in its calculation algorithm (Stockholm Environment Institute, 2005).

LEAP is typically used to examine GHG and local air pollutant emissions, economic costs, energy security, resource requirements and technology and activity trends (Emodi, Emodi, Murthy, & Emodi, 2017). The model is closely following IPCC GHG Inventory Guidelines which includes Tier 1 default emissions factors and standard Global Warming Potential (GWP) values (Stockholm Environment Institute, 2006).

The schematic diagram of the modeling with LEAP in this study is presented in Figure 4.5. The results of CGE and LP model are presented in LEAP which has the main advantages of its reporting capabilities. The CGE sets the electricity demand projection while the LP model gives information about the supply sector. LEAP, in turn, collected that information and summarizes necessary output for the whole system analysis. Apart from typical energy supply-demand balance, additional information on technological costs and emissions are also calculated in LEAP. Thus, the comparison of cost and GHG emissions of each scenario can be presented. The algorithm of the model can be seen in detail in Appendix G.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1. Electricity Demand

In the study, the electricity demand projection is the output of the CGE model. The projection results are shown in Table 5.1. Our middle growth estimate shows that Turkish economy will grow annually around 3.3%. Furthermore, the low growth rate is expected to be 2.5% while the high growth rate value is 4.0%. It also can be seen in Table 5.1 that for the low growth case, the annual growth was declining from 1.9%-3.2% during period 2020-2025 to less than 3% annual growth in 2045-2050. For the mid growth scenario, the maximum annual growth is 3.9% during 2020-2025 period, and it declines to 2.7% at the end of the period. For the high growth case, 4.7% annual growth rate is achieved as the highest and it declines to a lowest at 3.3%. Our GDP growth estimations are within the range of the OECD's estimation for Turkey, which shows the estimated annual growth rate of 3.6% for 2017-2050 (OECD, 2019).

Based on the projection results, Turkish gross electricity demand in 2050 will be somewhere between 675.0 TWh and 1,085.0 TWh, with the mid estimate as 860.4 TWh. It corresponds to an annual growth rate of between 2.5% - 4.0% in the 2017-2050 period. In terms of net electricity demand, it is estimated that in 2050, it will be somewhere between 556.6 TWh and 882.2 TWh. However, it is also worth noting that the real electricity demand might be higher due to penetration of electric vehicles (Moon, Park, Jeong, & Lee, 2018), more service-based economy and energy substitution in industrial sector (Liu & Liu, 2015). Those future uncertainties are not covered within the scope of the demand projections.

Table 5.1. *Projection Results of Electricity Demand and GDP*

Parameter		2017	2020	2025	2030	2035	2040	2045	2050	CAGR 2017-2050
Gross Electricity Demand (TWh)	**Low**	296.7	314.9	368.9	426.0	485.4	546.8	610.1	675.0	2.5%
	Mid	296.7	328.1	399.5	478.3	563.9	656.2	755.0	860.4	3.3%
	High	296.7	341.7	432.1	535.7	652.4	782.7	926.8	1085.0	4.0%
Net Electricity Demand (TWh)	**Low**	247.2	262.7	307.1	353.9	402.5	452.5	503.9	556.6	2.5%
	Mid	247.2	273.3	331.7	395.9	465.4	540.0	619.6	704.2	3.2%
	High	247.2	284.1	357.8	441.8	536.1	640.9	756.2	882.2	3.9%
Net Electricity Demand Per Capita (TWh/Person)	**Low**	3,059.1	3,131.3	3,457.0	3,792.2	4,141.8	4,510.4	4,900.1	5,313.5	1.7%
	Mid	3,059.1	3,257.2	3,733.5	4,241.9	4,789.0	5,382.0	6,025.0	6,723.0	2.4%
	High	3,059.1	3,386.6	4,027.1	4,733.9	5,517.1	6,387.6	7,353.1	8,422.4	3.1%
Annual GDP Growth (%)	**Low**	5.9%	1.9%	3.2%	2.9%	2.6%	2.4%	2.2%	2.1%	2.5%
	Mid	5.9%	3.3%	3.9%	3.6%	3.3%	3.1%	2.9%	2.7%	3.3%
	High	5.9%	4.6%	4.7%	4.3%	4.0%	3.8%	3.5%	3.3%	4.0%

Furthermore, the electricity demand per capita estimation can also be obtained. Energy consumption is correlated with human development and well-being[10] (Ediger & Tatlıdil, 2006; Ouedraogo, 2013; Pasternak & Livermore, 2000), with a very high level of development[11] starts on average at 4,000 KWh/person (Pasternak & Livermore, 2000). Based on this definition, Turkey could reach a very high human development levels as soon as 2025 with estimated electricity per capita at 4027.14 KWh/person. This also means that the government target to have electricity consumption of 4,324 kWh/person in 2023 (TC Cumhurbaşkanliği, 2019) will not be met. In addition, the living standard of EU-28 in 2016, with electricity consumption of 6,000 KWh/person (IEA, 2019) could only be reached between 2035-2040.

[10] Here, human development and well-being are based on Human Development Index (HDI). HDI is a composite indicator developed by United Nations Development Programme (UNDP) which tries to measure the human well-being.

[11] A very high human development means that the lifespan, education and decent standard of living are very high. Based on UNDP's HDI, this is equivalent to HDI greater than 0.9.

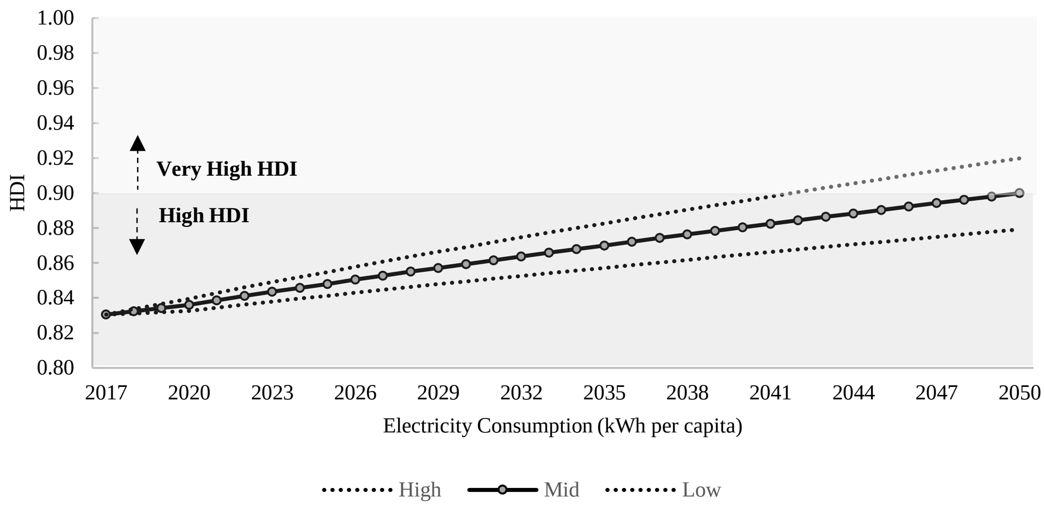

Figure 5.1. HDI Estimates for Turkey 2017-2050

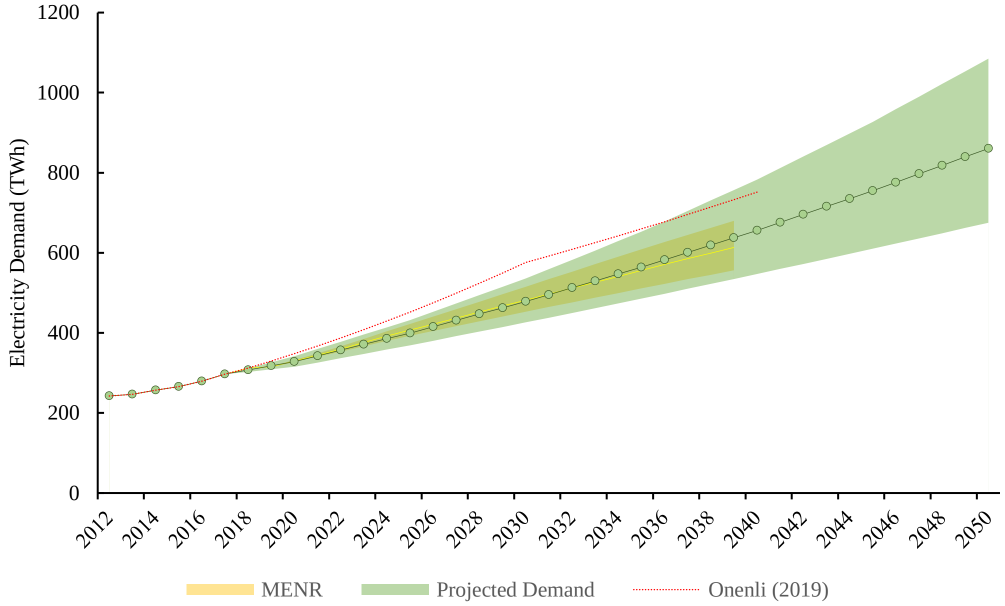

Figure 5.2. Comparison of Gross Electricity Demand with Other Studies

We can also estimate the level of well-being through the estimation of HDI. Supplemented by the point estimate in Pasternak & Livermore (2000), the development of HDI in Turkey based on low, mid and high economic growth scenario can be seen in Figure 5.1. The very high human development threshold in HDI is 0.9. Thus, Turkey could attain a very high development in 2040 the earliest.

The projection results are comparable with other studies. Figure 5.2 presents our gross electricity demand projections compared to MENR (n.d.-a) and Önenli (2019). It shows that, between 2018 and 2035, our estimations are lower than Önenli (2019) but within the range of MENR's estimates. Furthermore, after 2035, Önenli (2019) estimation is within the range of ours. Our estimations are also not far from the study in Yumurtaci & Asmaz (2004).

Apart from the aggregated gross and net electricity consumption, estimation of sectoral-based net electricity demand is also obtained. Here, the electricity consumer is decomposed into 5 sectors, namely: industry, agriculture, service, transportation and household. The detailed aggregation of the sectors can be seen in Table E.27 in Appendix E. In 2050, the highest consumer of electricity is industry with electricity consumption between 259.61 to 419.35 TWh. The electricity consumptions of other sectors are, 135.85 – 237.45 TWh for household, 140.13 – 189.07 TWh for service, 18.20 – 31.83 TWh agriculture and 2.79 – 4.56 TWh for transportation.

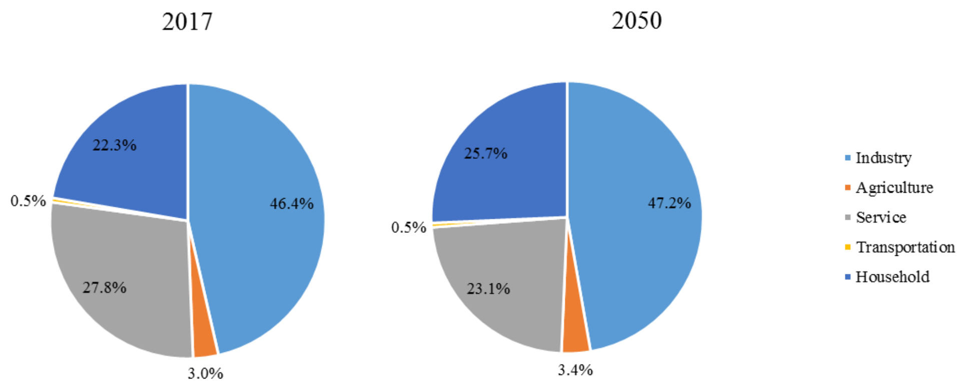

Figure 5.3. Sectoral Share of Electricity Demand in 2017 and 2050 (Mid growth)

In terms of the share of each sector, both industry, household and transport increase their share in total electricity consumption by 2050. As shown in Figure 5.3, industry share of consumption increases from 46.4% in 2017 to 47.2%. For the same period, household has the highest rise from 22.3% to 25.7%. In comparison, the service sector shows declining electricity share, it declines from 27.8% to 23.1%. This trend of electricity consumption shares are in accordance with the estimated energy consumptions by sector for a developing country in Riahi et al. (2012).

In conclusion, our electricity demand results are comparable with other studies. The detailed results of electricity demand projection can be seen in Appendix A.

5.2. Power Generation and Associated GHG Emissions

The demand for electricity must be balanced with steady and continuous supply. The gross power generation will increase more than doubled, up from its level 297.28 TWh in 2017, to between 662.48 – 1,050.16 TWh in 2050. This is equivalent to an annual electricity generation growth rate between 2.5% - 3.9%.

In reference scenario, the power generation mix is not very much different with the base year. Fossil fuels still dominating most of the power needs. In sustainable energy pathways (scenario MaxLocal, MinGHG and FullRE) however, there is a significant increase in renewable power generation, and the fossil fuel use is diminishing gradually. The development of power generation based on its primary energy sources can be seen in Figure 5.4.

The sustainable energy pathways provide changes in the power generation structure compared to the BaseCase reference. In general, it can be observed that renewable-based power is increasing in all scenarios after 2025. However, the degree and type of renewables vary across the scenarios. For MaxLocal scenario, the main focus is to allow all domestic-based resources to take over imported ones. Thus, apart from renewable energy, the domestic coal still exists in the generation mix. In terms of MinGHG, instead of coal, the need of electricity that cannot be satisfied by renewables

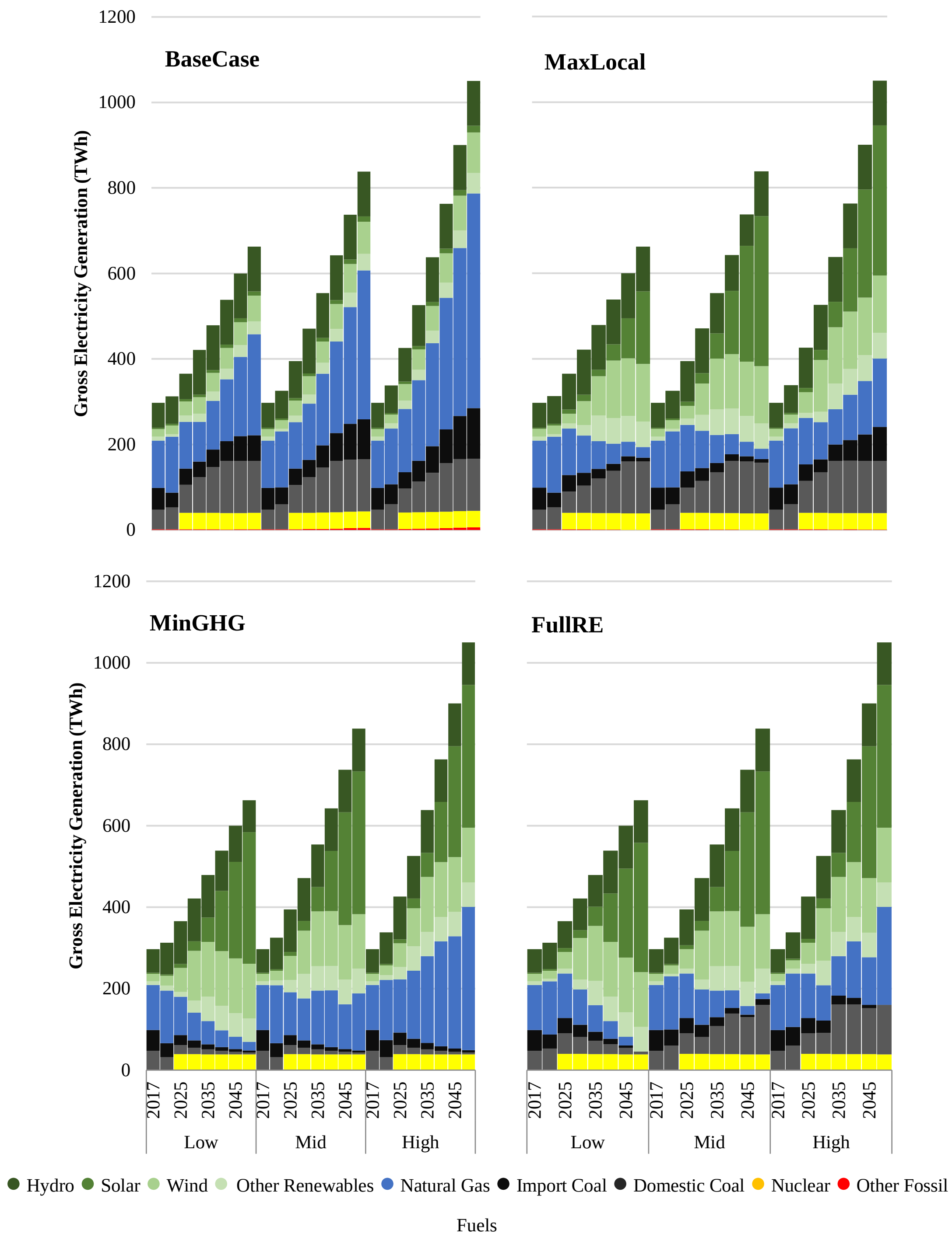

Figure 5.4. Gross Electricity Generation Development for All Scenarios

is supplied through natural gas. For FullRE, both natural gas and coal play important role in balancing the power that could not be satisfied through renewables.

The changing of electricity generation mix between 2017 and 2050 can be seen more clearly in Figure 5.5. In 2050, for the reference scenario, the share of renewables will be between 25% to 31%, compared to the base year value of 30%. This figure changes dramatically within the sustainable pathways. The share of renewables in total electricity generation improve at different rates. In MaxLocal, the share of renewables in the last planning period will be between 62%-77%, for MinGHG between 62%-89% and for FullRE it will be somewhere around 62%-93%. The highest share of renewables can be achieved within FullRE scenario, provided the economy grow within low growth trajectory. In MaxLocal scenario, we can observe that there is still significant coal share in the generation mix between 15%-20%, due to the focus of the scenario, which is to provide electricity from domestic based resources. The coal in the mix is mostly coming from domestic coal.

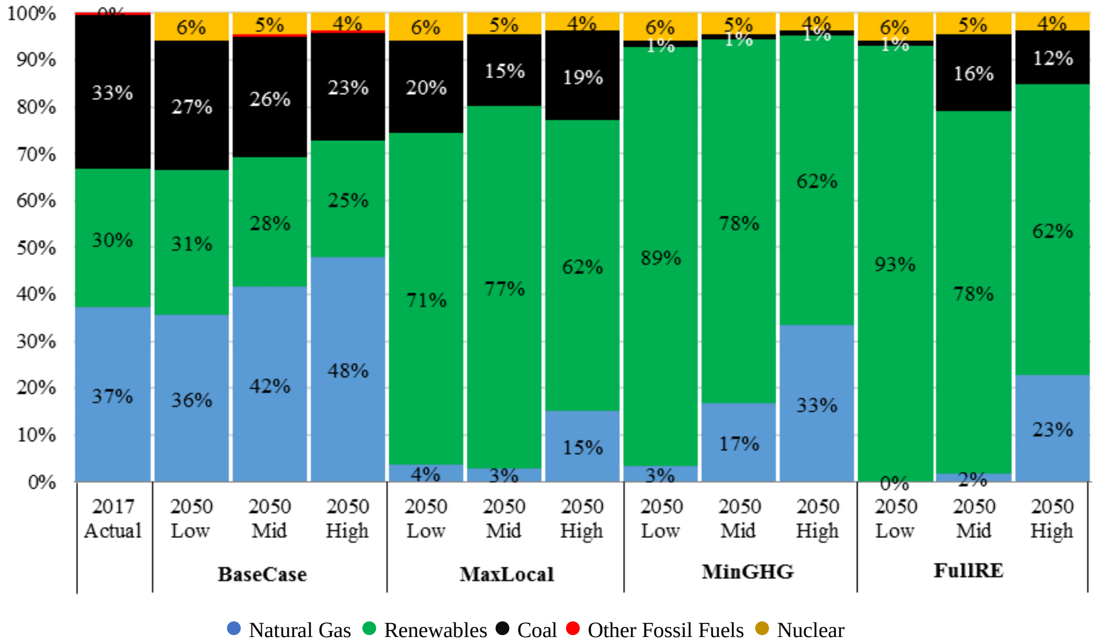

Figure 5.5. Electricity Generation Mix in 2017 and 2050 for All Scenarios

It is also observed that, except for MaxLocal scenario, highest share of renewables can be attained within the low economic growth trajectory. This is because, the low economic growth corresponds to lower energy demand which makes the higher penetration of renewables possible. Hence, it is very important to keep energy demand in check to ease the burden of the electricity system.

The modeling exercise has shown that high deployment of renewable energy in electricity sector is possible to attain. However, it is also worth noting that since the model runs in annual basis, the issue of intermittency of renewables is not explicitly assessed. The intermittency is the problem of short-term electricity supply that needs more temporal details (i.e. hourly basis) in the model (Rowe, Sayeef, & Platt, 2016). Furthermore, the results show that it is not possible to reach the 100% renewables generation due to the potential limit and low capacity factor of renewable resources. Even if all renewables are working at full capacities, there is still a need for other power plants to meet the demand.

The electricity generation mix gives direct consequences to the GHG emissions it produces. Without any significant change in overall mix (BaseCase reference), the GHG emission from power sector will increase over 2 times its base year value to the level between 301.55 – 489.27 MtCO2e in 2050. This is equivalent to annual growth of emissions of 2.0% - 3.5%.

Under the sustainable pathways, the degree of GHG decrease variously among scenarios. For, MaxLocal, in 2050 the emissions will decrease to between 146.21 – 287.45 MtCO2e. Most of the remaining emissions are from the coal-based power generation. In MinGHG scenario, the emissions could decrease to as low as 19.85 MtCO2e., while the upper bound could be 170.01 MtCO2e. The remaining fossil-based generation is still needed to balance the power coming from renewables. Lastly, in the FullRE scenario, the emissions in the end of the planning horizon would be around 7.67 – 238.04 MtCO2e. The remaining fossil-based generation is to compensate an unmet demand that could be satisfied with full deployment of renewable energy. The comparison of emission pathways for all scenarios can be seen in Figure 5.6.

The dashed lines in the Figure 5.6 are the upper and lower bound value to account the different growth pathways. While the solid lines are the mid estimates. We can see from the graph that both MaxLocal and FullRE show the same emission pathways like the BaseCase until 2025. However, after 2025 they diverge significantly. From 2025-2030, MaxLocal and FullRE still have the same emissions pathways, however, after 2030 it diverges significantly. This is due to increase in renewable utilization in FullRE while in MaxLocal some of the electricity needs are still met by domestic coal. In terms of MinGHG, after 2020, the GHG emissions diverge from all other scenarios. This is due to the results of minimization of GHG emissions which give earlier renewable energy deployment into the overall electricity generation.

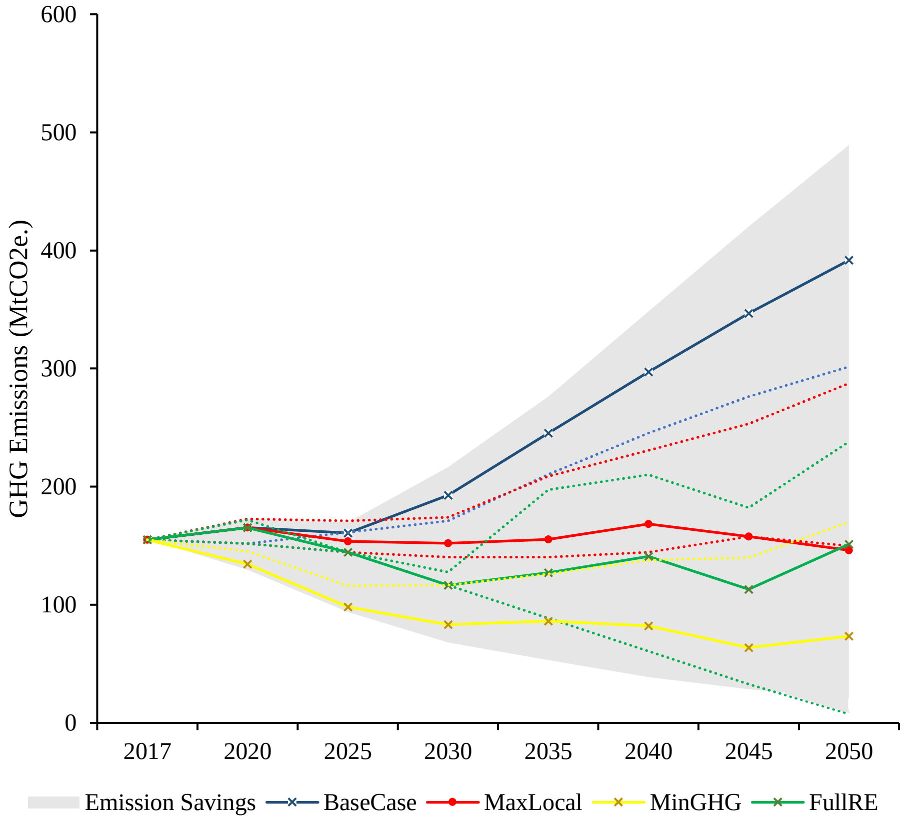

Figure 5.6. GHG Emissions in Power Sector for All Scenarios

Turkish government pledged to 21% of total GHG emissions reduction from its base case growth in 2030 (Republic of Turkey, 2015). Based on our mid growth pathways and with our BaseCase as a reference, in 2030, GHG emissions from electricity generation sectors will decrease 21.1% in MaxLocal, 56.8% in MinGHG and 39.5% in FullRE scenario.

Detailed numerical results of electricity generations and GHG emissions for all scenarios can be seen in Appendix C and Appendix D respectively.

5.3. Required Power Investment and Cost Comparison

While the electricity generation information is needed to see how the electricity demand can be met as well as the development of the GHG emissions, the power capacity information is useful to see the degree of investments required in the power system. The development of installed capacity of each technology for the BaseCase scenario can be seen in Table 5.2.

Table 5.2. *BaseCase Installed Capacity 2017-2050, in GW*

	2017	2035		2050		CAGR 2017-2035		CAGR 2035-2050		CAGR 2017-2050	
	Actual	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Renewables	**38.9**	**70.8**	**77.3**	**78.2**	**97.1**	3.4%	3.9%	2.0%	4.7%	2.1%	2.8%
Hydro	27.3	46.0	46.0	46.0	46.0	2.9%	2.9%	0.0%	0.0%	1.6%	1.6%
Wind	6.5	15.4	20.6	21.3	33.8	4.9%	6.6%	6.7%	10.4%	3.7%	5.1%
Solar	3.4	5.5	5.5	5.5	8.7	2.7%	2.7%	0.0%	9.6%	1.5%	2.9%
Other Renewables	1.7	3.9	5.2	5.4	8.6	4.7%	6.4%	6.7%	10.6%	3.5%	5.0%
Natural Gas	26.3	22.8	48.3	47.3	100.5	-0.8%	3.4%	15.7%	15.8%	1.8%	4.1%
Coal	**20.0**	**28.7**	**29.8**	**35.1**	**46.5**	2.0%	2.2%	4.1%	9.3%	1.7%	2.6%
Domestic Coal	9.9	20.7	17.8	23.5	23.5	4.2%	3.3%	2.6%	5.7%	2.7%	2.7%
Import Coal	9.3	8.0	12.0	11.6	23.0	-0.8%	1.4%	7.7%	13.9%	0.7%	2.8%
Other Fossil Fuels	0.8	0.5	1.0	0.4	2.0	-2.2%	1.6%	-4.4%	14.9%	-1.9%	3.0%
Nuclear	0.0	4.8	4.8	4.8	4.8	…	…	…	…	…	…
Total	**85.2**	**127.6**	**161.2**	**165.8**	**250.9**						

In the BaseCase scenario, the power capacity in 2050 need to increase at least 2 times of its level in 2017 to reach a level between 165.8 – 250.9 GW. In terms of the technology, wind and other renewables show the strongest annual growth accounted between 3.7 – 5.1% and 3.5 – 5. 0% for wind and other renewables respectively. Furthermore, the overall renewable-based power plant grows annually at a rate between 2.1 - 2.8%.

Under sustainable energy pathways (scenario MaxLocal, MinGHG and FullRE), there is a significant increase for the power capacity (Figure 5.7). The capacity needed is 236.4 – 380.8 GW for MaxLocal, 288.4 – 382.4 GW for MinGHG and 292.1 – 381.1 GW for FullRE. The rises of power capacity in all scenarios (compared to the BaseCase) are due to the additional balancing and power reserve capacities needed for the renewable-based power plant which increase in all scenarios.

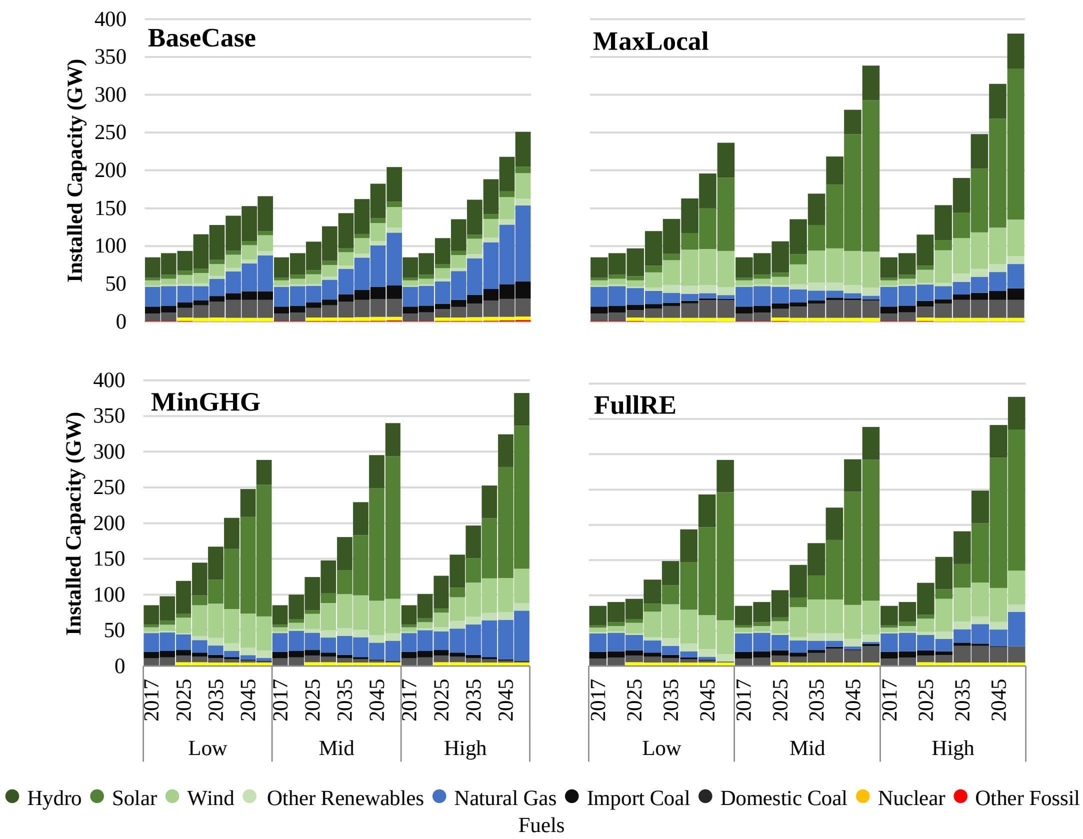

Figure 5.7. Installed Capacity Development for All Scenarios

The sustainable energy pathways provide changes in the power generation structure compared to BaseCase reference scenario. In general, it can be observed that substantial renewable energy capacity is increasing in all scenarios after 2025. However, the degree and type of renewables varies between the scenarios.

The difference of additional capacity between BaseCase reference and sustainable pathways can be seen in Figure 5.8. It tells us about the substitution of required capacity between the BaseCase and the sustainable pathways. The fossil-based power plants (i.e., Natural gas, coal and other fossil fuels) are substituted by renewables in various degree. However, from this graph, we could not really tell the difference between each sustainable pathway.

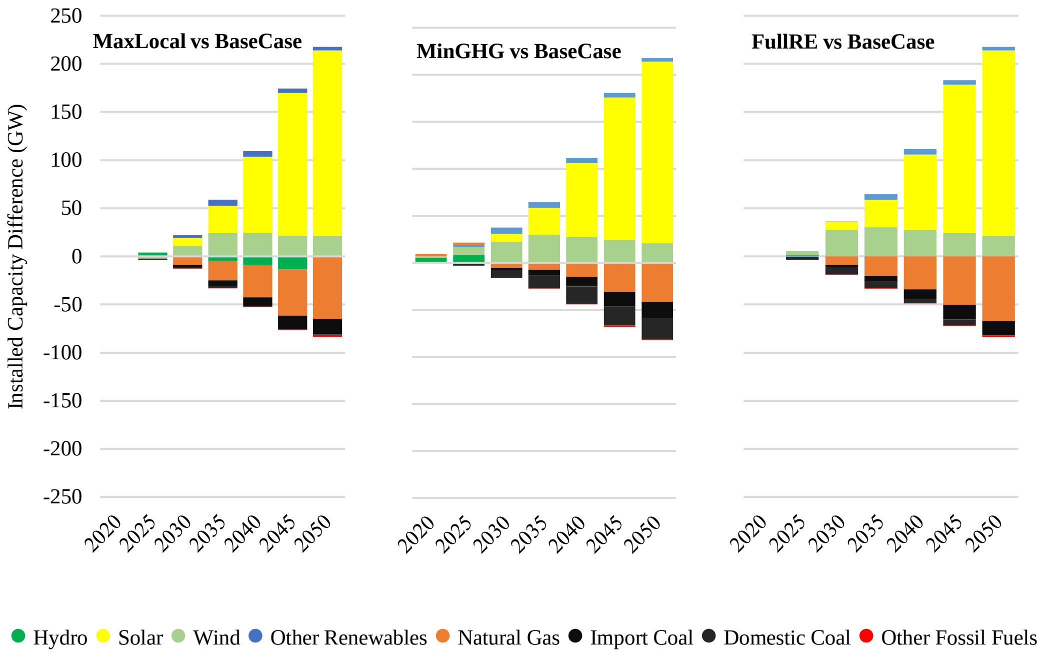

Figure 5.8. Installed Capacity Difference between BaseCase and Sustainable Energy Pathways (Mid Growth)

In order to look at different degrees and types of additional capacity within and between the sustainable energy pathways, Figure 5.9 is presented. It is now clearer that the difference between MaxLocal, MinGHG and FullRE is in terms of the use of fossil fuels to complement renewables in order to fulfill the demand. MaxLocal still utilized significant domestic coal for power generation, while in MinGHG and

FullRE, it is substituted by natural gas and renewables such as solar and wind. For MinGHG and FullRE, the difference is observed in terms of the use of fossil fuels to balance the renewables. MinGHG used more natural gas while FullRE utilized more coal. Detailed numerical results of power capacity for all scenarios can be seen in Appendix B.

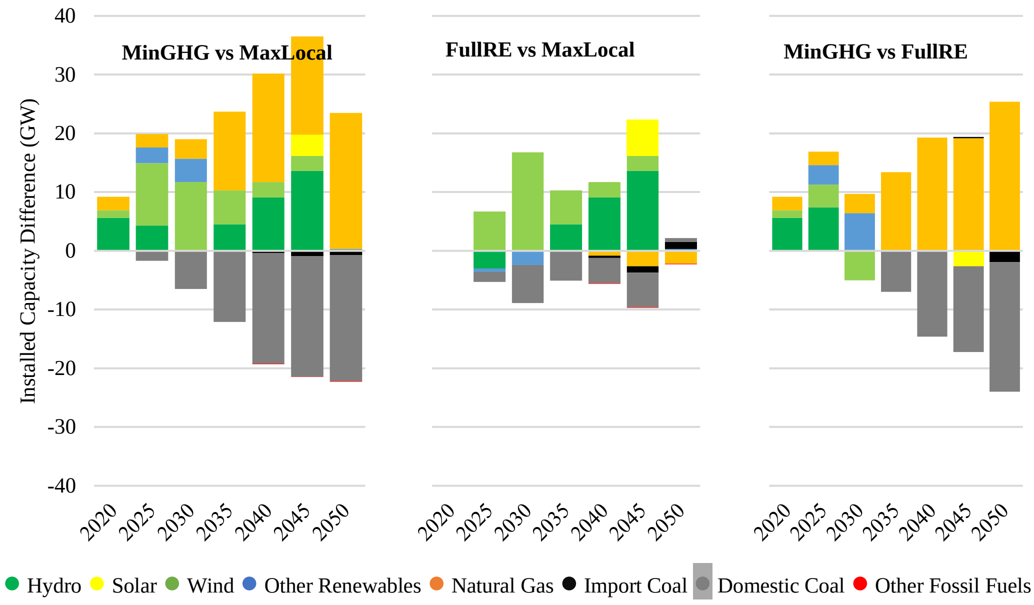

Figure 5.9. Installed Capacity Difference between Sustainable Energy Pathways (Mid Growth)

The associated increase in power capacity will need substantial costs. The sum of total discounted (at 5% discount rate), undiscounted (real) total costs and cumulative GHG emissions for the whole planning horizon (i.e., 2017-2050) is shown in Table 5.3.

The Net Present Value (NPV) of total power productions in 2017-2050 are between 150.6 to 342.4 billion US$. The cost includes three cost variables: capital, fixed and variable costs. They do not include environmental or social costs. Furthermore, the cumulative emissions from all possible scenarios are in the range of 2,292.36 to 9,624.21 MtCO2e.

In terms of each scenario, the BaseCase reference scenario has NPV of between 150.6 – 191.1 billion US$, MaxLocal 210.7 – 325.4 billion US$, MinGHG 299.5 – 332.8 billion US$ and FullRE 259.7 – 342.4 billion US$. The lowest cumulative emissions could be achieved through MinGHG under low growth scenario with 2,498.85 MtCO2e. This pathway of electricity system will need the most expensive investment of all scenarios in low growth case amounted to 299.5 bill US$.

The economic cost of pursuing sustainable energy pathways in real (undiscounted) term is in the range of 607.9 – 1,031.9 billion US$. In other words, on average, it would cost between 18.42 and 31.27 billion US$ per year by 2050. These values are equivalent to just between 2.2% and 3.7% of Turkey's GDP in 2018. Considering the benefits of such structural shift that could reduce dependence on imported energy resources and provide a transition from fossil fuels to renewable energy, this cost can be regarded as fairly reasonable.

Table 5.3. *Total Costs and Cumulative GHG Emissions*

Scenario		**Discounted Total Cost (billion US$)**	**Undiscounted Total Cost (billion US$)**	**Cumulative Overall Emission (MtCO2e)**
BaseCase	Low	150.6	387.7	7,144.57
	Mid	171.7	449.7	8,360.58
	High	191.1	516.7	9,624.21
MaxLocal	Low	210.7	607.9	5,014.55
	Mid	301.7	921.0	5,366.97
	High	325.4	978.4	7,068.54
MinGHG	Low	299.5	875.0	2,292.36
	Mid	321.9	946.2	3,156.51
	High	332.8	982.7	4,603.34
FullRE	Low	259.7	788.8	3,177.95
	Mid	311.3	944.8	4,655.10
	High	342.4	1,031.9	6,043.29

The difference in cumulative emissions between the sustainable pathways (MaxLocal, MinGHG, FullRE) and the BaseCase tell us about the possible overall emissions reduction. For MaxLocal this value is between 2,130.0 – 2,993.6 MtCO2e., for MinGHG 4,852.2 to 5,204.1 MtCO2e and for FullRE it is between 3,580.9 and 3,966.6 MtCO2e. Comparing between the sustainable pathways with the BaseCase, we get the discounted average cost of avoiding GHG emissions. In the case of MaxLocal, the value is equivalent to between 28.2 and 52.5 US$ per tonne of CO2e. While for MinGHG and FullRE the costs of avoiding GHG emissions is in the range of 28.2 – 30.7 US$/tCO2e and 27.5 – 42.3 US$/tCO2e. The abatement costs to pursue the sustainable energy pathways are reasonable and would not burden the overall economy too much. As has been pointed out in many other studies (such as, Kat et al., 2018; Yeldan et al., 2015; Gambhir, Napp, Emmott, & Anandarajah, 2014; Yang, Yeh, Zakerinia, Ramea, & McCollum, 2015), even with higher abatement costs than ours, the impact on the GDP is reasonable. Table 5.4 presents the GHG reductions, cost difference and cost of avoiding GHG emissions for all scenarios.

Table 5.4. *Cost of Avoiding GHG Emissions*

	MaxLocal			**MinGHG**			**FullRE**		
	Low	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
GHG Reduction (MtCO2e)	2,130.0	2,993.6	2,555.7	4,852.2	5,204.1	5,020.9	3,966.6	3,705.5	3,580.9
Difference in NPV (billion US$)	60.1	130.0	134.3	148.9	150.2	141.7	109.1	139.6	151.3
Discounted Cost of Avoiding GHG emissions (US$/tCO2e)	28.2	43.4	52.5	30.7	28.9	28.2	27.5	37.7	42.3

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1. Summary

In the study we developed a hybrid energy-economic model to assess the sustainable energy pathways in Turkish electricity system. Three different models, namely: GTAP-CGE, Power-LP and LEAP are soft-linked and the integrated framework is used to model the Turkish electricity system as the case study. The GTAP-CGE model is an economic equilibrium model which serve as the model of Turkish economy. The main output of the model is the sectoral (as well as aggregate) electricity demand. The electricity demand become the main linking of the CGE-GTAP model with the Power-LP model. Power-LP model is a simple power supply optimization model which aim to find the power supply mix that satisfies the specific model objectives and thereby generates scenarios. Both CGE-GTAP and Power-LP model output are inputted into LEAP which summarizes the whole electricity system. Furthermore, the cost and calculations and comparison of each model is also performed in LEAP.

There are four main scenarios being simulated each with 3 different economic growth expectation (low, mid, high):

- *BaseCase*: Reference scenario, follow the current distribution of electricity system
- *MaxLocal*: Maximization of local based-resources (i.e., renewables and domestic coal)
- *MinGHG*: Minimization of GHG emissions throughout the planning horizon
- *FullRE*: Maximization of renewables in electricity generation share and attempt to achieve full renewables capacity in the end of planning horizon.

The BaseCase is also called reference scenario. While other 3 scenarios are what we named sustainable energy pathways. The simulations show varying results as shown in Table 6.1.

First, in terms of net electricity demand, during 2017-2050 it will grow at an annual rate between 2.5% to 3.9% or equivalent to a level of 556.6 to 882.2 TWh at the end of planning horizon (2050).

Second, depending on the scenarios, the projected electricity demand will need various additional power capacity. For the reference BaseCase, between 165.8-250.9 GW of power capacity will be needed in 2050. In comparison, the sustainable pathways will need higher power capacity, due to high penetration of renewables. For the MaxLocal, in the last planning years, 236.4 – 380.8 GW will be required. In MinGHG, the corresponding level of power capacity is between 288.4 - 382.4 GW. Finally, the FullRE will need a rise in power capacity to between 292.1 and 381.1 GW.

Third, we managed to obtain the power generation that satisfy the electricity demand. In the BaseCase, the electricity generation mix is not too different than the base year 2017 value. However, the sustainable energy pathways show significant penetration of renewable energy shares in the electricity generation mix. In 2050, for MaxLocal the share of renewables could be between 62%-77%, compare to the share in MinGHG that could amount to between 62%-89% and FullRE share of around 62% - 93%.

Fourth, the additional power capacity will need extra investment which ranges from 150.6 to 342.4 billion US$ for all scenarios. The least cost power capacity expansion, as expected, is coming from BaseCase scenario which amounts between 150.6 - 191.1 billion US$. In terms of sustainable pathways, the cheapest one is coming from MaxLocal which costs between 210.7 - 325.4 billion US$ and the most expensive one is MinGHG (between 299.5 - 332.8 Billion US$).

Table 6.1. *Summary of Modeling Results*

Scenario	2017	2020			2030			2040			2050			CAGR 2017-2050		
	Actual	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
Net Electricity Demand (TWh)	247.2	262.7	273.3	284.1	353.9	395.9	441.8	452.5	540.0	640.9	556.6	704.2	882.2	2.5%	3.2%	3.9%
Installed Capacity (GW)																
BaseCase	85.2	90.6	90.6	90.7	115.7	126.2	135.6	139.9	162.0	188.3	165.8	204.6	250.9	2.0%	2.7%	3.3%
MaxLocal		90.6	90.6	90.7	119.9	135.4	153.9	163.0	218.2	248.2	236.4	338.7	380.8	3.1%	4.3%	4.6%
MinGHG		97.5	99.8	100.8	144.9	147.9	155.9	207.3	229.2	252.8	288.4	339.9	382.4	3.8%	4.3%	4.7%
FullRE		90.6	90.6	90.8	122.2	143.2	154.6	193.5	224.5	248.4	292.1	338.6	381.1	3.8%	4.3%	4.6%
Share of Renewables in Electricity Generation (%)																
BaseCase	30%	30%	29%	30%	40%	37%	33%	35%	31%	29%	31%	28%	25%	0.1%	-0.2%	-0.5%
MaxLocal		30%	29%	30%	48%	51%	52%	63%	65%	59%	71%	77%	62%	2.7%	2.9%	2.3%
MinGHG		37%	36%	35%	67%	63%	54%	82%	70%	59%	89%	78%	62%	3.4%	3.0%	2.3%
FullRE		30%	29%	30%	53%	58%	60%	78%	70%	59%	93%	78%	62%	3.5%	3.0%	2.3%
NPV of electricity production (Bill US$)																
BaseCase							between 150.6 - 191.1							…		…
MaxLocal							between 210.7 - 325.4							…		…
MinGHG							between 299.5 - 332.8							…		…
FullRE							between 259.7 - 342.4							…		…
Cumulative GHG Emissions (MtCO2e.)																
BaseCase							between 7,144.57 - 9,624.21							…		…
MaxLocal							between 5,014.55 - 7,068.54							…		…
MinGHG							between 2,292.36 - 4,603.34							…		…
FullRE							between 3,177.95 - 6,043.29							…		…

Lastly, the GHG emissions of each scenario is able to be compared as well. The BaseCase reference scenario will result total cumulative (2017-2050) GHG emissions of between 7,144.57 and 9,624.21 MtCO2e. Within the sustainable energy pathways, the substantial decrease of GHG emission can be achieved. MinGHG scenario provide the strongest decrease in emissions amounted to cumulative emissions between 2,292.36 - 4,603.34 MtCO2e. In comparison, MaxLocal provides cumulative emissions of between 5,014.55 - 7,068.54 MtCO2e and FullRE between 3,177.95 - 6,043.29 MtCO2e.

6.2. Conclusions

There is a common understanding that energy system of the future should be sustainable. On one hand it should allow a secure and uninterrupted energy supply, on the other hand it should be able to meet the goal of the society without putting pressure on environmental sustainability. But then, the remaining question is ‘how can these be achieved?’ In the past decades we experienced a radical transformation of the energy system. Assuring the sustainability of the future energy system requires the next transition to be completed over the next few decades to come.

From our previous discussion regarding sustainability and energy transition, the sustainability of energy system can be achieved mainly via two fundamental ways: renewable energy-based technology application in the supply side and improvement of energy efficiency in the consumer side. Fossil-fuel based energy services can no longer be the main option as it has persistent impact on the local, regional and most importantly global environment. The shift to renewable energy is indisputably favorable as the resources are limitless. However, there are various challenges in terms of technical, economic, social and political aspects. Technically, the problem of intermittency is a longstanding constrain on the integration of the renewable energy to current conventional system. In addition, the potency of renewable energy resources is dependent on its geographical situation.

The first step to safeguard a smooth transition to energy system is through long-term energy planning. This is because, energy system has a characteristic of high capital and long lifetime which makes long-term planning become very crucial. There has been great interest in developing a robust model that could provide meaningful insights for policy makers. The recent applications of hybrid-type of energy models can narrow the gap between the energy-economy and environment which are crucial elements in sustainable energy system. In the study we developed a hybrid-type model to close those gaps and provide meaningful feedback for policy makers. More specifically, to give insight how transition to sustainable energy system can be achieved, with Turkey as a case study.

Energy system in Turkey is regarded as unsustainable due to two main challenges: high import dependency and high fossil fuel utilization. Based on 3 different economic expectations (low, mid, high), we model 3 pathways for sustainable energy system: Maximizing Local Resources, Minimizing GHG emissions and Maximizing Renewable energy. The model suggests the transition to renewable-based electricity with its share in 2050 ranging between 62% and 93%. The share of electricity generation from non-renewables will peak in 2030 for all sustainable pathways. After 2030, the share of renewables in electricity generation mix is increasing to more than 50%. In terms of the renewable energy technology, in 2050, our mid growth estimate show that for MaxLocal, 41.8% of electricity is generated through solar, 12.5% hydro, 16.1% wind and 7.0% other renewables which equivalent to 77.3% of renewables in electricity generation. For MinGHG and FullRE, solar supplied 41.8%, wind 16.1%, hydro 12.5% and other renewables 7.2% which make up 77.5% of renewable electricity.

The cumulative emissions reduction achieved in sustainable pathways is between 2,130.0 (MaxLocal-Low) and 5,204.1 (MinGHG-Mid) MtCO2e. This is equivalent to a GHG reduction cost of a tonne of CO2e between 28.2 and 52.5 US$. Out of all sustainable pathways, MinGHG provide the most expensive costs with NPV between 299.5 - 332.8 billion US$. The cheapest transitions could be achieved at between 210.7

- 325.4 billion US$ by following the MaxLocal scenario. However, there is a trade-off between costs and emissions reductions as higher emissions reduction tend to require more costs.

6.2.1. Policy Implications

Currently, Turkish government only has a mid-term energy targets. The results of this analysis can help policy makers in formulizing the long-term energy planning to allow smooth transition to sustainable energy system. Based on all sustainable energy pathways in this study, robust and gradual improvement in renewable-based power generation need to be done as early as 2025.

Energy demand projection show different trajectories depending on achieved economic growth. The study observed that higher penetration of renewables can be attained in lower electricity demand trajectory. Demand-based management could be important to keep the electricity consumption in check. Hence, various policy targeting to more efficient use of energy in all sectors should be pursued.

Furthermore, current energy targets should be updated to reflect more on current situation. Setting a long-term target is necessary in order to ensure the smooth transitions. Several long-term target that can be drawn based on this study are:

- Fossil-based electricity generation must peak at least in 2030. That means the share of fossil fuels in electricity generation should not be more than 50% after 2030.
- Government can set the target to achieve 60% renewables in electricity generation by 2050.
- Setting GHG emissions limit for electricity generation in 2050. Our results show that sustainable pathways can be achieved with emissions level between 7.7 and 287.4 $MtCO_2e$ in 2050.
- In terms of the technology, full integration of renewables should be started as early as the year 2025. By doing so, full deployment of hydro (46 GW) could

be realized by 2025, other renewables (10.7 GW) by 2030, wind (48 GW) by 2035 and solar (190 GW) by 2050.

- Constant monitoring of the policy should be done to ensure the compliance of the government target. Furthermore, some threshold level (e.g., based on share of renewable energy or renewables installed capacity) can be set to see the progress of the transitions and allow reassessment of the policy if the threshold value is not satisfied.

Finally, despite the intention of the government to build more nuclear power plant, our assessments show that with only one NPP (4.8 GW Akkuyu NPP), it is possible to have a more sustainable electricity generation.

6.2.2. Caveats and Further Studies

Like any other models, the modelling exercise presented in this study has several caveats that need to be understood. These are:

- The model does not explicitly account for energy efficiency improvement.
- The problems of intermittency in renewable energy is not explicitly assessed in the model. Besides, the technical constraints in expansion of transmission capacity and the potential role of storage technologies are not considered. The models can be elaborated with the evidences introduced in two recent studies by SHURA Energy Transition Center[14] , i.e., Godron, Cebeci, Tör, & Saygın (2018) on the options for transmission expansion in Turkey's power system and Saygın, Cebeci, Tör, & Godron (2019) that takes energy storage with batteries and pumped-hydro storage options into account.
- All scenarios are related to renewable energy penetration which based on current available technology. Other options such as carbon capture and storage (CCS) or high nuclear penetration are not assessed.

[14] SHURA Energy Transition Center was founded by the European Climate Foundation (ECF), Agora Energiewende and Istanbul Policy Center (IPC) at Sabancı University. It serves as a platform for discussions on policy, technological, and economic aspects of the Turkey's energy sector.

- No interaction or feedback effects from energy to the economy accounted in the model.
- The intergenerational equity of energy use is not assessed in the study.
- The penetration of renewables are examined by considering the technical potential only, i.e., without consideration of social and political aspects.
- Electricity sector discussed in the study is only a piece of bigger puzzle in the whole energy system.

This study is very important for policymakers to assess various technology and policy options to have a future sustainable Turkish energy system. Accordingly, this type of system analysis needs to continue and improved in order to provide more robust tool for policy analysis and energy planning. The future works include:

- Accounting of feedback from energy system to the economy to account for energy system impact to the economy and society.
- Electricity supply model with more detail temporal scale (i.e., a resolution of hourly basis) to address intermittency problems in renewable energy penetrations.
- We assume the nuclear with constant capacity, however, the government is seeking to have nuclear-based electricity system, this problem regarding nuclear has to be investigated more thoroughly, not only from techno-economic perspective but also from social aspect.
- Water use impacts of future electricity and fuels should also be assessed.
- Considerations of social aspect in the model (such as social acceptance) might be useful to get insight from the social point of view. The majority of the model only accounted for economic, technical and environmental part, and left the social part unassessed. Furthermore, consideration of intergenerational equity of energy use should also be incorporated in the study.
- Complete energy system modeling can be useful to get bigger picture of the complex energy system.

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APPENDICES

A. NUMERICAL RESULTS: NET ELECTRICITY DEMAND PROJECTION

The net electricity demand projections for all economic growth expectations are shown in Table A.1. The value in parentheses is the share of total electricity demand of each sector over each period.

Table A.1. *Net Electricity Demand Projection for All Growth Level, in TWh*

Year	Growth Level	Sectors					
		Industry	**Agriculture**	**Service**	**Transportation**	**Household**	**Total**
2017	Actual	114.77	7.33	68.68	1.25	55.17	247.21
		(0.46)	(0.03)	(0.28)	(0.01)	(0.22)	(1)
2020	Low	121.37	7.74	74.00	1.30	58.30	262.72
		(0.46)	(0.03)	(0.28)	(0)	(0.22)	(1)
	Mid	126.96	8.15	75.59	1.37	61.22	273.28
		(0.46)	(0.03)	(0.28)	(0)	(0.22)	(1)
	High	132.69	8.57	77.19	1.43	64.24	284.13
		(0.47)	(0.03)	(0.27)	(0.01)	(0.23)	(1)
2025	Low	142.44	9.24	84.65	1.52	69.29	307.14
		(0.46)	(0.03)	(0.28)	(0)	(0.23)	(1)
	Mid	155.12	10.17	88.74	1.66	76.02	331.70
		(0.47)	(0.03)	(0.27)	(0.01)	(0.23)	(1)
	High	168.55	11.17	93.01	1.81	83.26	357.79
		(0.47)	(0.03)	(0.26)	(0.01)	(0.23)	(1)
2030	Low	164.58	10.85	95.62	1.76	81.13	353.92
		(0.47)	(0.03)	(0.27)	(0)	(0.23)	(1)
	Mid	185.99	12.45	102.67	1.99	92.80	395.89
		(0.47)	(0.03)	(0.26)	(0.01)	(0.23)	(1)
	High	209.32	14.23	110.21	2.24	105.81	441.81
		(0.47)	(0.03)	(0.25)	(0.01)	(0.24)	(1)
2035	Low	187.47	12.55	106.72	2.00	93.74	402.49
		(0.47)	(0.03)	(0.27)	(0)	(0.23)	(1)
	Mid	219.29	14.99	117.17	2.34	111.60	465.38
		(0.47)	(0.03)	(0.25)	(0.01)	(0.24)	(1)
	High	254.84	17.80	128.57	2.73	132.19	536.14
		(0.48)	(0.03)	(0.24)	(0.01)	(0.25)	(1)

Table A.1 (continued)

2040	Low	210.98	14.35	117.88	2.25	107.07	452.54
		(0.47)	(0.03)	(0.26)	(0)	(0.24)	(1)
	Mid	254.87	17.80	132.12	2.73	132.47	539.99
		(0.47)	(0.03)	(0.24)	(0.01)	(0.25)	(1)
	High	305.05	21.90	147.94	3.28	162.70	640.87
		(0.48)	(0.03)	(0.23)	(0.01)	(0.25)	(1)
2045	Low	235.04	16.24	129.04	2.52	121.11	503.94
		(0.47)	(0.03)	(0.26)	(0)	(0.24)	(1)
	Mid	292.68	20.89	147.43	3.14	155.49	619.63
		(0.47)	(0.03)	(0.24)	(0.01)	(0.25)	(1)
	High	359.92	26.57	168.16	3.89	197.68	756.22
		(0.48)	(0.04)	(0.22)	(0.01)	(0.26)	(1)
2050	Low	259.61	18.20	140.13	2.79	135.85	556.59
		(0.47)	(0.03)	(0.25)	(0.01)	(0.24)	(1)
	Mid	332.64	24.25	163.00	3.59	180.76	704.23
		(0.47)	(0.03)	(0.23)	(0.01)	(0.26)	(1)
	High	419.35	31.83	189.07	4.56	237.45	882.25
		(0.48)	(0.04)	(0.21)	(0.01)	(0.27)	(1)

B. NUMERICAL RESULTS: POWER CAPACITY

Table B.2 to B.13 shows the power capacity of each scenario. The value in parentheses is the share of total capacity of each energy resource over each period.

Table B.2. *Power Capacity for BaseCase-Low Scenario, in GW*

	2017	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydro	27.27	28.4	26.03	46	46	46	46	46
	32.00%	*31.36%*	*27.93%*	*39.80%*	*36.06%*	*32.87%*	*30.11%*	*27.72%*
Wind	6.52	7.2	11.78	13.58	15.44	17.36	19.33	21.35
	7.65%	*7.95%*	*12.64%*	*11.75%*	*12.10%*	*12.41%*	*12.65%*	*12.86%*
Solar	3.42	5.5	5.5	5.5	5.5	5.5	5.5	5.51
	4.01%	*6.07%*	*5.90%*	*4.76%*	*4.31%*	*3.93%*	*3.60%*	*3.32%*
Other Renewables	1.71	2.4	2.7	3.45	3.92	4.41	4.91	5.43
	2.01%	*2.65%*	*2.90%*	*2.98%*	*3.07%*	*3.15%*	*3.21%*	*3.27%*
Natural Gas	26.32	26.2	21.81	18.65	22.83	29.03	37.05	47.28
	30.89%	*28.93%*	*23.40%*	*16.13%*	*17.89%*	*20.74%*	*24.25%*	*28.49%*
Import Coal	9.31	8.9	7.35	7.01	7.97	8.96	11.25	11.63
	10.93%	*9.83%*	*7.89%*	*6.06%*	*6.25%*	*6.40%*	*7.36%*	*7.01%*
Domestic Coal	9.91	11.3	12.68	16.18	20.65	23.54	23.54	23.54
	11.63%	*12.48%*	*13.61%*	*14.00%*	*16.19%*	*16.82%*	*15.41%*	*14.18%*
Other Fossil Fuels	0.75	0.67	0.55	0.42	0.47	0.34	0.38	0.42
	0.88%	*0.74%*	*0.59%*	*0.36%*	*0.37%*	*0.24%*	*0.25%*	*0.25%*
Nuclear	0	0	4.8	4.8	4.8	4.8	4.8	4.8
	0.00%	*0.00%*	*5.15%*	*4.15%*	*3.76%*	*3.43%*	*3.14%*	*2.89%*
Total	85.21	90.57	93.2	115.59	127.58	139.94	152.76	165.96
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table B.3. *Power Capacity for BaseCase-Mid Scenario, in GW*

	2017	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydro	27.27	28.4	37.75	46	46	46	46	46
	32.00%	*31.36%*	*35.69%*	*36.46%*	*32.08%*	*28.40%*	*25.20%*	*22.48%*
Wind	6.52	7.2	12.73	15.19	17.85	20.72	23.77	27.02
	7.65%	*7.95%*	*12.04%*	*12.04%*	*12.45%*	*12.79%*	*13.02%*	*13.20%*
Solar	3.42	5.5	5.5	5.5	5.5	5.5	6.14	6.98
	4.01%	*6.07%*	*5.20%*	*4.36%*	*3.84%*	*3.40%*	*3.36%*	*3.41%*
Other Renewables	1.71	2.4	2.7	3.86	4.54	5.26	6.04	6.87
	2.01%	*2.65%*	*2.55%*	*3.06%*	*3.17%*	*3.25%*	*3.31%*	*3.36%*
Natural Gas	26.32	26.2	21.81	26.3	33.57	42.85	54.68	69.79
	30.89%	*28.93%*	*20.62%*	*20.85%*	*23.41%*	*26.45%*	*29.96%*	*34.10%*
Import Coal	9.31	8.9	7.35	7.84	10.01	12.77	16.3	18.04
	10.93%	*9.83%*	*6.95%*	*6.21%*	*6.98%*	*7.88%*	*8.93%*	*8.82%*
Domestic Coal	9.91	11.3	12.58	16.06	20.36	23.1	23.54	23.54
	11.63%	*12.48%*	*11.89%*	*12.73%*	*14.20%*	*14.26%*	*12.90%*	*11.50%*
Other Fossil Fuels	0.75	0.67	0.55	0.61	0.77	0.99	1.26	1.61
	0.88%	*0.74%*	*0.52%*	*0.48%*	*0.54%*	*0.61%*	*0.69%*	*0.79%*
Nuclear	0	0	4.8	4.8	4.8	4.8	4.8	4.8
	0.00%	*0.00%*	*4.54%*	*3.80%*	*3.35%*	*2.96%*	*2.63%*	*2.35%*
Total	85.21	90.57	105.77	126.16	143.4	161.99	182.53	204.65
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table B.4. *Power Capacity for BaseCase-High Scenario, in GW*

	2017	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydro	27.27	28.4	34.4	42.01	46	46	46	46
	32.01%	*31.35%*	*34.40%*	*35.51%*	*35.01%*	*31.57%*	*28.64%*	*25.97%*
Wind	6.52	7.2	13.73	16.95	20.57	24.59	29.01	33.85
	7.65%	*7.95%*	*13.73%*	*14.33%*	*15.65%*	*16.88%*	*18.06%*	*19.11%*
Solar	3.42	5.5	5.5	5.5	5.5	6.35	7.49	8.74
	4.01%	*6.07%*	*5.50%*	*4.65%*	*4.19%*	*4.36%*	*4.66%*	*4.94%*
Other Renewables	1.71	2.4	3.49	4.31	5.23	6.25	7.37	8.6
	2.01%	*2.65%*	*3.49%*	*3.64%*	*3.98%*	*4.29%*	*4.59%*	*4.86%*
Natural Gas	26.32	26.2	29.68	37.87	48.34	61.69	78.74	100.49
	30.89%	*28.92%*	*29.68%*	*32.01%*	*36.79%*	*42.34%*	*49.03%*	*56.74%*
Import Coal	9.31	8.9	7.35	9.38	11.97	15.28	19.5	22.95
	10.93%	*9.82%*	*7.35%*	*7.93%*	*9.11%*	*10.49%*	*12.14%*	*12.96%*
Domestic Coal	9.91	11.42	10.93	13.94	17.8	21.9	23.54	23.54
	11.63%	*12.60%*	*10.93%*	*11.78%*	*13.55%*	*15.03%*	*14.66%*	*13.29%*
Other Fossil Fuels	0.75	0.67	0.65	0.82	1.05	1.34	1.71	2.02
	0.88%	*0.74%*	*0.65%*	*0.69%*	*0.80%*	*0.92%*	*1.06%*	*1.14%*
Nuclear	0	0	4.8	4.8	4.8	4.8	4.8	4.8
	0.00%	*0.00%*	*4.80%*	*4.06%*	*3.65%*	*3.29%*	*2.99%*	*2.71%*
Total	85.2	90.6	100	118.3	131.4	145.7	160.6	177.1
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table B.5. *Power Capacity for MaxLocal-Low Scenario, in GW*

	2017	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydro	27.27	28.4	37.01	46	46	46	46	46
	32.00%	*31.36%*	*38.19%*	*38.35%*	*33.81%*	*28.22%*	*23.47%*	*19.45%*
Wind	6.52	7.2	8.12	20.2	32.55	48	48	48
	7.65%	*7.95%*	*8.38%*	*16.84%*	*23.93%*	*29.44%*	*24.49%*	*20.30%*
Solar	3.42	5.5	5.5	8.68	8.68	21.6	53.74	96.78
	4.01%	*6.07%*	*5.68%*	*7.24%*	*6.38%*	*13.25%*	*27.42%*	*40.92%*
Other Renewables	1.71	2.4	2.12	4.3	10.7	10.7	10.7	10.7
	2.01%	*2.65%*	*2.19%*	*3.59%*	*7.86%*	*6.56%*	*5.46%*	*4.52%*
Natural Gas	26.32	26.2	21.81	17.43	13.04	9.44	6.83	4.94
	30.89%	*28.93%*	*22.51%*	*14.53%*	*9.58%*	*5.79%*	*3.48%*	*2.09%*
Import Coal	9.31	8.9	7.35	5.8	4.25	3.07	2.22	1.61
	10.93%	*9.83%*	*7.58%*	*4.84%*	*3.12%*	*1.88%*	*1.13%*	*0.68%*
Domestic Coal	9.91	11.3	9.65	12.31	15.72	19.19	23.54	23.54
	11.63%	*12.48%*	*9.96%*	*10.26%*	*11.55%*	*11.77%*	*12.01%*	*9.95%*
Other Fossil Fuels	0.75	0.67	0.55	0.42	0.31	0.22	0.16	0.12
	0.88%	*0.74%*	*0.57%*	*0.35%*	*0.23%*	*0.13%*	*0.08%*	*0.05%*
Nuclear	0	0	4.8	4.8	4.8	4.8	4.8	4.8
	0.00%	*0.00%*	*4.95%*	*4.00%*	*3.53%*	*2.94%*	*2.45%*	*2.03%*
Total	85.21	90.57	96.91	119.94	136.05	163.02	195.99	236.49
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table B.6. *Power Capacity for MaxLocal-Mid Scenario, in GW*

	2017	2020	2025	2030	2035	2040	2045	2050
Hydro	27.27	28.4	41.65	46	41.45	36.91	32.36	46
	32.00%	*31.36%*	*39.22%*	*33.98%*	*24.52%*	*16.91%*	*11.55%*	*13.58%*
Wind	6.52	7.2	10.51	26.16	42.21	45.41	45.41	48
	7.65%	*7.95%*	*9.90%*	*19.32%*	*24.97%*	*20.81%*	*16.20%*	*14.17%*
Solar	3.42	5.5	5.5	13.59	33.82	84.15	154.23	200
	4.01%	*6.07%*	*5.18%*	*10.04%*	*20.01%*	*38.56%*	*55.03%*	*59.04%*
Other Renewables	1.71	2.4	2.7	6.72	10.7	10.7	10.7	10.42
	2.01%	*2.65%*	*2.54%*	*4.96%*	*6.33%*	*4.90%*	*3.82%*	*3.08%*
Natural Gas	26.32	26.2	21.81	17.43	13.04	9.44	6.83	4.94
	30.89%	*28.93%*	*20.54%*	*12.88%*	*7.71%*	*4.33%*	*2.44%*	*1.46%*
Import Coal	9.31	8.9	7.35	5.8	4.25	3.07	2.22	1.61
	10.93%	*9.83%*	*6.92%*	*4.28%*	*2.51%*	*1.41%*	*0.79%*	*0.48%*
Domestic Coal	9.91	11.3	11.32	14.45	18.45	23.54	23.54	22.87
	11.63%	*12.48%*	*10.66%*	*10.67%*	*10.92%*	*10.79%*	*8.40%*	*6.75%*
Other Fossil Fuels	0.75	0.67	0.55	0.42	0.31	0.22	0.16	0.12
	0.88%	*0.74%*	*0.52%*	*0.31%*	*0.18%*	*0.10%*	*0.06%*	*0.04%*
Nuclear	0	0	4.8	4.8	4.8	4.8	4.8	4.8
	0.00%	*0.00%*	*4.52%*	*3.55%*	*2.84%*	*2.20%*	*1.71%*	*1.42%*
Total	85.21	90.57	106.19	135.37	169.03	218.24	280.25	338.76
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table B.7. *Power Capacity for MaxLocal-High Scenario, in GW*

	2017	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydro	27.27	28.4	41.23	46	46	46	46	46
	32.01%	*31.35%*	*41.23%*	*38.88%*	*35.01%*	*31.57%*	*28.64%*	*25.97%*
Wind	6.52	7.2	17.34	43.14	47.01	48	48	48
	7.65%	*7.95%*	*17.34%*	*36.47%*	*35.78%*	*32.94%*	*29.89%*	*27.10%*
Solar	3.42	5.5	5.5	13.59	33.82	84.15	144.05	200
	4.01%	*6.07%*	*5.50%*	*11.49%*	*25.74%*	*57.76%*	*89.69%*	*112.93%*
Other Renewables	1.71	2.4	2.12	4.3	10.7	10.7	10.7	10.7
	2.01%	*2.65%*	*2.12%*	*3.63%*	*8.14%*	*7.34%*	*6.66%*	*6.04%*
Natural Gas	26.32	26.2	21.81	17.43	16.6	21.19	25.04	31.96
	30.89%	*28.92%*	*21.81%*	*14.73%*	*12.63%*	*14.54%*	*15.59%*	*18.05%*
Import Coal	9.31	8.9	7.35	5.8	7.4	9.44	12.05	15.38
	10.93%	*9.82%*	*7.35%*	*4.90%*	*5.63%*	*6.48%*	*7.50%*	*8.68%*
Domestic Coal	9.91	11.42	14.45	18.45	23.54	23.54	23.54	23.54
	11.63%	*12.60%*	*14.45%*	*15.60%*	*17.91%*	*16.16%*	*14.66%*	*13.29%*
Other Fossil Fuels	0.75	0.67	0.55	0.42	0.31	0.39	0.28	0.36
	0.88%	*0.74%*	*0.55%*	*0.36%*	*0.24%*	*0.27%*	*0.17%*	*0.20%*
Nuclear	0	0	4.8	4.8	4.8	4.8	4.8	4.8
	0.00%	*0.00%*	*4.80%*	*4.06%*	*3.65%*	*3.29%*	*2.99%*	*2.71%*
Total	85.2	90.6	100	118.3	131.4	145.7	160.6	177.1
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table B.8. *Power Capacity for MinGHG-Low Scenario, in GW*

	2017	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydro	27.27	34.02	46	46	46	43.38	38.83	34.29
	32.00%	*34.90%*	*38.68%*	*31.75%*	*27.50%*	*20.93%*	*15.68%*	*11.88%*
Wind	6.52	8.5	21.15	43.58	48	48	48	48
	7.65%	*8.72%*	*17.78%*	*30.08%*	*28.70%*	*23.16%*	*19.38%*	*16.64%*
Solar	3.42	5.5	5.5	13.59	33.82	84.15	135.25	184.61
	4.01%	*5.64%*	*4.62%*	*9.38%*	*20.22%*	*40.61%*	*54.61%*	*63.98%*
Other Renewables	1.71	2.4	2.12	5.26	10.7	10.7	10.42	10.13
	2.01%	*2.46%*	*1.78%*	*3.63%*	*6.40%*	*5.16%*	*4.21%*	*3.51%*
Natural Gas	26.32	26.2	21.81	17.43	13.04	8.65	5.97	4.32
	30.89%	*26.87%*	*18.34%*	*12.03%*	*7.80%*	*4.17%*	*2.41%*	*1.50%*
Import Coal	9.31	8.9	7.35	5.8	4.25	2.7	1.31	0.95
	10.93%	*9.13%*	*6.18%*	*4.00%*	*2.54%*	*1.30%*	*0.53%*	*0.33%*
Domestic Coal	9.91	11.3	9.65	8	6.34	4.69	3.04	1.39
	11.63%	*11.59%*	*8.11%*	*5.52%*	*3.79%*	*2.26%*	*1.23%*	*0.48%*
Other Fossil Fuels	0.75	0.67	0.55	0.42	0.3	0.17	0.05	0.04
	0.88%	*0.69%*	*0.46%*	*0.29%*	*0.18%*	*0.08%*	*0.02%*	*0.01%*
Nuclear	0	0	4.8	4.8	4.8	4.8	4.8	4.8
	0.00%	*0.00%*	*4.04%*	*3.31%*	*2.87%*	*2.32%*	*1.94%*	*1.66%*
Total	85.21	97.49	118.93	144.88	167.25	207.24	247.67	288.53
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table B.9. *Power Capacity for MinGHG-Mid Scenario, in GW*

	2017	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydro	27.27	34.02	46	46	46	46	46	46
	32.00%	*34.11%*	*36.97%*	*31.10%*	*25.47%*	*20.08%*	*15.58%*	*13.53%*
Wind	6.52	8.5	21.15	37.9	48	48	48	48
	7.65%	*8.52%*	*17.00%*	*25.63%*	*26.58%*	*20.95%*	*16.26%*	*14.12%*
Solar	3.42	5.5	5.5	13.59	33.82	84.15	157.81	200
	4.01%	*5.51%*	*4.42%*	*9.19%*	*18.73%*	*36.73%*	*53.46%*	*58.82%*
Other Renewables	1.71	2.4	5.38	10.7	10.7	10.7	10.7	10.7
	2.01%	*2.41%*	*4.32%*	*7.24%*	*5.92%*	*4.67%*	*3.62%*	*3.15%*
Natural Gas	26.32	28.45	24.06	20.68	26.39	27.9	23.51	28.14
	30.89%	*28.52%*	*19.33%*	*13.98%*	*14.61%*	*12.18%*	*7.96%*	*8.28%*
Import Coal	9.31	8.9	7.35	5.8	4.25	2.7	1.31	0.95
	10.93%	*8.92%*	*5.91%*	*3.92%*	*2.35%*	*1.18%*	*0.44%*	*0.28%*
Domestic Coal	9.91	11.3	9.65	8	6.34	4.69	3.04	1.39
	11.63%	*11.33%*	*7.75%*	*5.41%*	*3.51%*	*2.05%*	*1.03%*	*0.41%*
Other Fossil Fuels	0.75	0.67	0.55	0.42	0.3	0.17	0.05	0.04
	0.88%	*0.67%*	*0.44%*	*0.28%*	*0.17%*	*0.07%*	*0.02%*	*0.01%*
Nuclear	0	0	4.8	4.8	4.8	4.8	4.8	4.8
	0.00%	*0.00%*	*3.86%*	*3.25%*	*2.66%*	*2.10%*	*1.63%*	*1.41%*
Total	85.21	99.74	124.44	147.89	180.6	229.11	295.22	340.02
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table B.10. *Power Capacity for MinGHG-High Scenario, in GW*

	2017	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydro	27.27	34.02	46	46	46	46	46	46
	32.01%	*37.55%*	*46.00%*	*38.88%*	*35.01%*	*31.57%*	*28.64%*	*25.97%*
Wind	6.52	8.5	20.88	33.22	48	48	48	48
	7.65%	*9.38%*	*20.88%*	*28.08%*	*36.53%*	*32.94%*	*29.89%*	*27.10%*
Solar	3.42	5.5	5.5	13.59	33.82	84.15	155.45	200
	4.01%	*6.07%*	*5.50%*	*11.49%*	*25.74%*	*57.76%*	*96.79%*	*112.93%*
Other Renewables	1.71	2.4	5.38	10.7	10.7	10.7	10.7	10.7
	2.01%	*2.65%*	*5.38%*	*9.04%*	*8.14%*	*7.34%*	*6.66%*	*6.04%*
Natural Gas	26.32	29.45	26.19	33.42	42.66	51.52	55.12	70.35
	30.89%	*32.51%*	*26.19%*	*28.25%*	*32.47%*	*35.36%*	*34.32%*	*39.72%*
Import Coal	9.31	8.9	7.35	5.8	4.25	2.7	1.62	1.17
	10.93%	*9.82%*	*7.35%*	*4.90%*	*3.23%*	*1.85%*	*1.01%*	*0.66%*
Domestic Coal	9.91	11.3	9.65	8	6.34	4.69	3.04	1.39
	11.63%	*12.47%*	*9.65%*	*6.76%*	*4.82%*	*3.22%*	*1.89%*	*0.78%*
Other Fossil Fuels	0.75	0.67	0.55	0.42	0.3	0.17	0.05	0.04
	0.88%	*0.74%*	*0.55%*	*0.36%*	*0.23%*	*0.12%*	*0.03%*	*0.02%*
Nuclear	0	0	4.8	4.8	4.8	4.8	4.8	4.8
	0.00%	*0.00%*	*4.80%*	*4.06%*	*3.65%*	*3.29%*	*2.99%*	*2.71%*
Total	85.2	90.6	100	118.3	131.4	145.7	160.6	177.1
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table B.11. *Power Capacity for FullRE-Low Scenario, in GW*

	2017	2020	2025	2030	2035	2040	2045	2050
Hydro	27.27	28.4	28.94	33.98	33.98	46	46	46
	32.00%	*31.36%*	*30.34%*	*27.81%*	*22.86%*	*23.77%*	*18.94%*	*15.75%*
Wind	6.52	7.2	14.67	36.5	48	48	48	48
	7.65%	*7.95%*	*15.38%*	*29.87%*	*32.29%*	*24.80%*	*19.76%*	*16.43%*
Solar	3.42	5.5	5.5	10.95	27.25	67.81	124.91	181.19
	4.01%	*6.07%*	*5.77%*	*8.96%*	*18.33%*	*35.04%*	*51.42%*	*62.03%*
Other Renewables	1.71	2.4	2.12	4.3	10.7	10.7	10.7	10.7
	2.01%	*2.65%*	*2.22%*	*3.52%*	*7.20%*	*5.53%*	*4.40%*	*3.66%*
Natural Gas	26.32	26.2	21.81	17.43	13.04	8.65	4.27	0
	30.89%	*28.93%*	*22.86%*	*14.27%*	*8.77%*	*4.47%*	*1.76%*	*0.00%*
Import Coal	9.31	8.9	7.35	5.8	4.25	2.7	1.15	0
	10.93%	*9.83%*	*7.71%*	*4.75%*	*2.86%*	*1.40%*	*0.47%*	*0.00%*
Domestic Coal	9.91	11.3	9.65	8	6.34	4.69	3.04	1.39
	11.63%	*12.48%*	*10.12%*	*6.55%*	*4.26%*	*2.42%*	*1.25%*	*0.48%*
Other Fossil Fuels	0.75	0.67	0.55	0.42	0.3	0.17	0.05	0
	0.88%	*0.74%*	*0.58%*	*0.34%*	*0.20%*	*0.09%*	*0.02%*	*0.00%*
Nuclear	0	0	4.8	4.8	4.8	4.8	4.8	4.8
	0.00%	*0.00%*	*5.03%*	*3.93%*	*3.23%*	*2.48%*	*1.98%*	*1.64%*
Total	85.21	90.57	95.39	122.18	148.66	193.52	242.92	292.08
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table B.12. *Power Capacity for FullRE-Mid Scenario, in GW*

	2017	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydro	27.27	28.4	38.61	46	46	46	46	46
	32.00%	*31.36%*	*35.87%*	*32.11%*	*26.40%*	*20.49%*	*15.70%*	*13.58%*
Wind	6.52	7.2	17.24	42.91	48	48	48	48
	7.65%	*7.95%*	*16.02%*	*29.95%*	*27.55%*	*21.38%*	*16.38%*	*14.18%*
Solar	3.42	5.5	5.5	13.59	33.82	84.15	160.45	200
	4.01%	*6.07%*	*5.11%*	*9.49%*	*19.41%*	*37.49%*	*54.75%*	*59.07%*
Other Renewables	1.71	2.4	2.12	4.3	10.7	10.7	10.7	10.7
	2.01%	*2.65%*	*1.97%*	*3.00%*	*6.14%*	*4.77%*	*3.65%*	*3.16%*
Natural Gas	26.32	26.2	21.81	17.43	13.04	8.65	4.27	2.72
	30.89%	*28.93%*	*20.26%*	*12.17%*	*7.48%*	*3.85%*	*1.46%*	*0.80%*
Import Coal	9.31	8.9	7.35	5.8	4.25	2.7	1.15	2.85
	10.93%	*9.83%*	*6.83%*	*4.05%*	*2.44%*	*1.20%*	*0.39%*	*0.84%*
Domestic Coal	9.91	11.3	9.65	8	13.31	19.29	17.64	23.54
	11.63%	*12.48%*	*8.97%*	*5.58%*	*7.64%*	*8.59%*	*6.02%*	*6.95%*
Other Fossil Fuels	0.75	0.67	0.55	0.42	0.3	0.17	0.05	0
	0.88%	*0.74%*	*0.51%*	*0.29%*	*0.17%*	*0.08%*	*0.02%*	*0.00%*
Nuclear	0	0	4.8	4.8	4.8	4.8	4.8	4.8
	0.00%	*0.00%*	*4.46%*	*3.35%*	*2.76%*	*2.14%*	*1.64%*	*1.42%*
Total	85.21	90.57	107.63	143.25	174.22	224.46	293.06	338.61
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table B.13. *Power Capacity for FullRE-High Scenario, in GW*

	2017	2020	2025	2030	2035	2040	2045	2050
Hydro	27.27	28.4	45.38	46	46	46	46	46
	32.01%	*31.35%*	*45.38%*	*38.88%*	*35.01%*	*31.57%*	*28.64%*	*25.97%*
Wind	6.52	7.42	18.46	45.92	48	48	48	48
	7.65%	*8.19%*	*18.46%*	*38.82%*	*36.53%*	*32.94%*	*29.89%*	*27.10%*
Solar	3.42	5.5	5.5	13.59	33.82	84.15	184.7	200
	4.01%	*6.07%*	*5.50%*	*11.49%*	*25.74%*	*57.76%*	*115.01%*	*112.93%*
Other Renewables	1.71	2.4	4.3	10.7	10.7	10.7	10.7	10.7
	2.01%	*2.65%*	*4.30%*	*9.04%*	*8.14%*	*7.34%*	*6.66%*	*6.04%*
Natural Gas	26.32	26.2	21.81	17.43	19.31	27.84	23.45	48.11
	30.89%	*28.92%*	*21.81%*	*14.73%*	*14.70%*	*19.11%*	*14.60%*	*27.17%*
Import Coal	9.31	8.9	7.35	5.8	4.25	3.1	1.55	0
	10.93%	*9.82%*	*7.35%*	*4.90%*	*3.23%*	*2.13%*	*0.97%*	*0.00%*
Domestic Coal	9.91	11.3	9.65	10	23.54	23.54	21.89	23.54
	11.63%	*12.47%*	*9.65%*	*8.45%*	*17.91%*	*16.16%*	*13.63%*	*13.29%*
Other Fossil Fuels	0.75	0.67	0.55	0.42	0.3	0.25	0.12	0
	0.88%	*0.74%*	*0.55%*	*0.36%*	*0.23%*	*0.17%*	*0.07%*	*0.00%*
Nuclear	0	0	4.8	4.8	4.8	4.8	4.8	4.8
	0.00%	*0.00%*	*4.80%*	*4.06%*	*3.65%*	*3.29%*	*2.99%*	*2.71%*
Total	85.2	90.6	100	118.3	131.4	145.7	160.6	177.1
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

C. NUMERICAL RESULTS: POWER GENERATION

Table C.14 to C.25 shows the power generation of each scenario. The value in parentheses is the share of total generation of each energy resource over each period.

Table C.14. *Power Generation for BaseCase-Low Scenario, in TWh*

	2017	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydro	58.20	64.70	59.30	104.80	104.80	104.80	104.80	104.80
	19.58%	*20.69%*	*16.22%*	*24.88%*	*21.87%*	*19.45%*	*17.47%*	*15.81%*
Wind	17.90	20.20	33.00	38.10	43.30	48.70	54.20	59.90
	6.02%	*6.46%*	*9.03%*	*9.05%*	*9.04%*	*9.04%*	*9.03%*	*9.04%*
Solar	2.90	3.80	5.30	6.10	7.00	7.90	8.70	9.70
	0.98%	*1.22%*	*1.45%*	*1.45%*	*1.46%*	*1.47%*	*1.45%*	*1.46%*
Other Renewables	9.10	6.10	15.10	19.30	22.00	24.70	27.50	30.40
	3.06%	*1.95%*	*4.13%*	*4.58%*	*4.59%*	*4.58%*	*4.58%*	*4.59%*
Natural Gas	110.50	130.80	108.90	93.10	114.00	144.90	185.00	236.10
	37.17%	*41.83%*	*29.79%*	*22.10%*	*23.79%*	*26.89%*	*30.84%*	*35.63%*
Import Coal	51.10	34.20	38.00	36.20	41.20	46.30	58.10	60.10
	17.19%	*10.94%*	*10.40%*	*8.59%*	*8.60%*	*8.59%*	*9.68%*	*9.07%*
Domestic Coal	46.40	51.30	65.50	83.60	106.70	121.70	121.70	121.70
	15.61%	*16.41%*	*17.92%*	*19.85%*	*22.27%*	*22.59%*	*20.29%*	*18.36%*
Other Fossil Fuels	1.20	1.60	1.70	1.30	1.50	1.10	1.20	1.30
	0.40%	*0.51%*	*0.47%*	*0.31%*	*0.31%*	*0.20%*	*0.20%*	*0.20%*
Nuclear	0.00	0.00	38.70	38.70	38.70	38.70	38.70	38.70
	0.00%	*0.00%*	*10.59%*	*9.19%*	*8.08%*	*7.18%*	*6.45%*	*5.84%*
Total	297.30	312.70	365.50	421.20	479.20	538.80	599.90	662.70
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table C.15. *Power Generation for BaseCase-Mid Scenario, in TWh*

	2017	2020	2025	2030	2035	2040	2045	2050
Hydro	58.20	64.70	86.00	104.80	104.80	104.80	104.80	104.80
	19.58%	*19.89%*	*21.78%*	*22.24%*	*18.92%*	*16.30%*	*14.21%*	*12.50%*
Wind	17.90	20.20	35.70	42.60	50.10	58.10	66.60	75.70
	6.02%	*6.21%*	*9.04%*	*9.04%*	*9.04%*	*9.04%*	*9.03%*	*9.03%*
Solar	2.90	3.80	5.80	6.90	8.10	9.40	10.80	12.20
	0.98%	*1.17%*	*1.47%*	*1.46%*	*1.46%*	*1.46%*	*1.46%*	*1.46%*
Other Renewables	9.10	6.10	15.10	21.60	25.40	29.50	33.90	38.50
	3.06%	*1.88%*	*3.82%*	*4.58%*	*4.58%*	*4.59%*	*4.60%*	*4.59%*
Natural Gas	110.50	130.80	108.90	131.30	167.60	213.90	273.00	348.50
	37.17%	*40.21%*	*27.58%*	*27.86%*	*30.25%*	*33.27%*	*37.01%*	*41.57%*
Import Coal	51.10	39.70	38.00	40.50	51.70	66.00	84.20	93.20
	17.19%	*12.20%*	*9.62%*	*8.59%*	*9.33%*	*10.27%*	*11.41%*	*11.12%*
Domestic Coal	46.40	58.40	65.00	83.00	105.20	119.40	121.70	121.70
	15.61%	*17.95%*	*16.46%*	*17.61%*	*18.99%*	*18.57%*	*16.50%*	*14.52%*
Other Fossil Fuels	1.20	1.60	1.70	1.90	2.40	3.10	4.00	5.10
	0.40%	*0.49%*	*0.43%*	*0.40%*	*0.43%*	*0.48%*	*0.54%*	*0.61%*
Nuclear	0.00	0.00	38.70	38.70	38.70	38.70	38.70	38.70
	0.00%	*0.00%*	*9.80%*	*8.21%*	*6.99%*	*6.02%*	*5.25%*	*4.62%*
Total	297.30	325.30	394.90	471.30	554.00	642.90	737.70	838.40
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table C.16. *Power Generation for BaseCase-High Scenario, in TWh*

	2017	2020	2025	2030	2035	2040	2045	2050
Hydro	58.20	64.70	78.30	95.70	104.80	104.80	104.80	104.80
	19.58%	*19.13%*	*18.38%*	*18.19%*	*16.42%*	*13.74%*	*11.64%*	*9.98%*
Wind	17.90	20.20	38.50	47.50	57.70	68.90	81.30	94.90
	6.02%	*5.97%*	*9.04%*	*9.03%*	*9.04%*	*9.03%*	*9.03%*	*9.03%*
Solar	2.90	3.80	6.20	7.70	9.30	11.10	13.10	15.30
	0.98%	*1.12%*	*1.46%*	*1.46%*	*1.46%*	*1.45%*	*1.46%*	*1.46%*
Other Renewables	9.10	12.10	19.60	24.20	29.30	35.00	41.30	48.20
	3.06%	*3.58%*	*4.60%*	*4.60%*	*4.59%*	*4.59%*	*4.59%*	*4.59%*
Natural Gas	110.50	130.80	148.20	189.10	241.40	308.00	393.10	501.80
	37.17%	*38.68%*	*34.79%*	*35.94%*	*37.81%*	*40.37%*	*43.67%*	*47.77%*
Import Coal	51.10	46.00	38.00	48.50	61.90	79.00	100.80	118.60
	17.19%	*13.60%*	*8.92%*	*9.22%*	*9.70%*	*10.36%*	*11.20%*	*11.29%*
Domestic Coal	46.40	59.00	56.50	72.10	92.00	113.20	121.70	121.70
	15.61%	*17.45%*	*13.26%*	*13.70%*	*14.41%*	*14.84%*	*13.52%*	*11.59%*
Other Fossil Fuels	1.20	1.60	2.00	2.60	3.30	4.20	5.40	6.40
	0.40%	*0.47%*	*0.47%*	*0.49%*	*0.52%*	*0.55%*	*0.60%*	*0.61%*
Nuclear	0.00	0.00	38.70	38.70	38.70	38.70	38.70	38.70
	0.00%	*0.00%*	*9.08%*	*7.36%*	*6.06%*	*5.07%*	*4.30%*	*3.68%*
Total	297.30	338.20	426.00	526.10	638.40	762.90	900.20	1050.40
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table C.17. *Power Generation for MaxLocal-Low Scenario, in TWh*

	2017	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydro	58.20	64.70	84.30	104.80	104.80	104.80	104.80	104.80
	19.58%	*20.69%*	*23.05%*	*24.88%*	*21.87%*	*19.45%*	*17.46%*	*15.81%*
Wind	17.90	20.20	22.80	56.60	91.30	134.60	134.60	134.60
	6.02%	*6.46%*	*6.23%*	*13.43%*	*19.05%*	*24.98%*	*22.43%*	*20.31%*
Solar	2.90	3.80	9.60	15.20	15.20	37.80	94.20	169.60
	0.98%	*1.22%*	*2.62%*	*3.61%*	*3.17%*	*7.02%*	*15.70%*	*25.59%*
Other Renewables	9.10	6.10	11.90	24.10	60.00	60.00	60.00	60.00
	3.06%	*1.95%*	*3.25%*	*5.72%*	*12.52%*	*11.14%*	*10.00%*	*9.05%*
Natural Gas	110.50	130.80	108.90	87.00	65.10	47.10	34.10	24.70
	37.17%	*41.83%*	*29.77%*	*20.65%*	*13.58%*	*8.74%*	*5.68%*	*3.73%*
Import Coal	51.10	34.20	38.00	30.00	22.00	15.90	11.50	8.30
	17.19%	*10.94%*	*10.39%*	*7.12%*	*4.59%*	*2.95%*	*1.92%*	*1.25%*
Domestic Coal	46.40	51.30	49.90	63.60	81.20	99.20	121.70	121.70
	15.61%	*16.41%*	*13.64%*	*15.10%*	*16.94%*	*18.41%*	*20.28%*	*18.36%*
Other Fossil Fuels	1.20	1.60	1.70	1.30	1.00	0.70	0.50	0.40
	0.40%	*0.51%*	*0.46%*	*0.31%*	*0.21%*	*0.13%*	*0.08%*	*0.06%*
Nuclear	0.00	0.00	38.70	38.70	38.70	38.70	38.70	38.70
	0.00%	*0.00%*	*10.58%*	*9.19%*	*8.07%*	*7.18%*	*6.45%*	*5.84%*
Total	297.30	312.70	365.80	421.30	479.30	538.80	600.10	662.80
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table C.18. *Power Generation for MaxLocal-Mid Scenario, in TWh*

	2017	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydro	58.20	64.70	94.90	104.80	94.40	84.10	73.70	104.80
	19.58%	*19.89%*	*24.03%*	*22.24%*	*17.04%*	*13.08%*	*9.99%*	*12.50%*
Wind	17.90	20.20	29.50	73.30	118.30	127.30	127.30	134.60
	6.02%	*6.21%*	*7.47%*	*15.55%*	*21.35%*	*19.80%*	*17.26%*	*16.05%*
Solar	2.90	3.80	9.60	23.80	59.30	147.40	270.20	350.40
	0.98%	*1.17%*	*2.43%*	*5.05%*	*10.70%*	*22.93%*	*36.63%*	*41.79%*
Other Renewables	9.10	6.10	15.10	37.70	60.00	60.00	60.00	58.40
	3.06%	*1.88%*	*3.82%*	*8.00%*	*10.83%*	*9.33%*	*8.13%*	*6.96%*
Natural Gas	110.50	130.80	108.90	87.00	65.10	47.10	34.10	24.70
	37.17%	*40.21%*	*27.58%*	*18.46%*	*11.75%*	*7.33%*	*4.62%*	*2.95%*
Import Coal	51.10	39.70	38.00	30.00	22.00	15.90	11.50	8.30
	17.19%	*12.20%*	*9.62%*	*6.37%*	*3.97%*	*2.47%*	*1.56%*	*0.99%*
Domestic Coal	46.40	58.40	58.50	74.70	95.30	121.70	121.70	118.20
	15.61%	*17.95%*	*14.81%*	*15.85%*	*17.20%*	*18.93%*	*16.50%*	*14.10%*
Other Fossil Fuels	1.20	1.60	1.70	1.30	1.00	0.70	0.50	0.40
	0.40%	*0.49%*	*0.43%*	*0.28%*	*0.18%*	*0.11%*	*0.07%*	*0.05%*
Nuclear	0.00	0.00	38.70	38.70	38.70	38.70	38.70	38.70
	0.00%	*0.00%*	*9.80%*	*8.21%*	*6.98%*	*6.02%*	*5.25%*	*4.62%*
Total	297.30	325.30	394.90	471.30	554.10	642.90	737.70	838.50
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table C.19. *Power Generation for MaxLocal-High Scenario, in TWh*

	2017	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydro	58.20	64.70	93.90	104.80	104.80	104.80	104.80	104.80
	19.58%	*19.13%*	*22.04%*	*19.93%*	*16.42%*	*13.74%*	*11.64%*	*9.98%*
Wind	17.90	20.20	48.60	120.90	131.80	134.60	134.60	134.60
	6.02%	*5.97%*	*11.41%*	*22.99%*	*20.65%*	*17.64%*	*14.95%*	*12.81%*
Solar	2.90	3.80	9.60	23.80	59.30	147.40	252.40	350.40
	0.98%	*1.12%*	*2.25%*	*4.53%*	*9.29%*	*19.32%*	*28.03%*	*33.36%*
Other Renewables	9.10	12.10	11.90	24.10	60.00	60.00	60.00	60.00
	3.06%	*3.58%*	*2.79%*	*4.58%*	*9.40%*	*7.86%*	*6.66%*	*5.71%*
Natural Gas	110.50	130.80	108.90	87.00	82.90	105.80	125.00	159.60
	37.17%	*38.68%*	*25.56%*	*16.54%*	*12.99%*	*13.87%*	*13.88%*	*15.19%*
Import Coal	51.10	46.00	38.00	30.00	38.20	48.80	62.30	79.50
	17.19%	*13.60%*	*8.92%*	*5.70%*	*5.98%*	*6.40%*	*6.92%*	*7.57%*
Domestic Coal	46.40	59.00	74.70	95.30	121.70	121.70	121.70	121.70
	15.61%	*17.45%*	*17.54%*	*18.12%*	*19.06%*	*15.95%*	*13.52%*	*11.59%*
Other Fossil Fuels	1.20	1.60	1.70	1.30	1.00	1.20	0.90	1.10
	0.40%	*0.47%*	*0.40%*	*0.25%*	*0.16%*	*0.16%*	*0.10%*	*0.10%*
Nuclear	0.00	0.00	38.70	38.70	38.70	38.70	38.70	38.70
	0.00%	*0.00%*	*9.08%*	*7.36%*	*6.06%*	*5.07%*	*4.30%*	*3.68%*
Total	297.30	338.20	426.00	525.90	638.40	763.00	900.40	1050.40
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table C.20. *Power Generation for MinGHG-Low Scenario, in TWh*

	2017	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydro	58.20	77.50	104.80	104.80	104.80	98.80	88.40	78.10
	19.58%	*24.78%*	*28.66%*	*24.88%*	*21.86%*	*18.34%*	*14.73%*	*11.79%*
Wind	17.90	23.80	59.30	122.20	134.60	134.60	134.60	134.60
	6.02%	*7.61%*	*16.22%*	*29.01%*	*28.08%*	*24.98%*	*22.43%*	*20.31%*
Solar	2.90	3.80	9.60	23.80	59.30	147.40	237.00	323.40
	0.98%	*1.22%*	*2.63%*	*5.65%*	*12.37%*	*27.36%*	*39.49%*	*48.80%*
Other Renewables	9.10	12.10	11.90	29.50	60.00	60.00	58.40	56.80
	3.06%	*3.87%*	*3.25%*	*7.00%*	*12.52%*	*11.14%*	*9.73%*	*8.57%*
Natural Gas	110.50	129.50	93.70	67.80	56.90	41.20	29.80	21.60
	37.17%	*41.41%*	*25.62%*	*16.09%*	*11.87%*	*7.65%*	*4.97%*	*3.26%*
Import Coal	51.10	34.20	24.70	17.90	13.00	9.40	6.80	4.90
	17.19%	*10.94%*	*6.75%*	*4.25%*	*2.71%*	*1.74%*	*1.13%*	*0.74%*
Domestic Coal	46.40	31.00	22.40	16.20	11.80	8.50	6.20	4.50
	15.61%	*9.91%*	*6.13%*	*3.85%*	*2.46%*	*1.58%*	*1.03%*	*0.68%*
Other Fossil Fuels	1.20	0.80	0.60	0.40	0.30	0.20	0.20	0.10
	0.40%	*0.26%*	*0.16%*	*0.09%*	*0.06%*	*0.04%*	*0.03%*	*0.02%*
Nuclear	0.00	0.00	38.70	38.70	38.70	38.70	38.70	38.70
	0.00%	*0.00%*	*10.58%*	*9.19%*	*8.07%*	*7.18%*	*6.45%*	*5.84%*
Total	297.30	312.70	365.70	421.30	479.40	538.80	600.10	662.70
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table C.21. *Power Generation for MinGHG-Mid Scenario, in TWh*

	2017	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydro	58.20	77.50	104.80	104.80	104.80	104.80	104.80	104.80
	19.58%	*23.83%*	*26.54%*	*22.24%*	*18.91%*	*16.30%*	*14.20%*	*12.50%*
Wind	17.90	23.80	59.30	106.20	134.60	134.60	134.60	134.60
	6.02%	*7.32%*	*15.02%*	*22.54%*	*24.28%*	*20.94%*	*18.24%*	*16.05%*
Solar	2.90	3.80	9.60	23.80	59.30	147.40	276.50	350.40
	0.98%	*1.17%*	*2.43%*	*5.05%*	*10.70%*	*22.93%*	*37.47%*	*41.79%*
Other Renewables	9.10	12.10	30.10	60.00	60.00	60.00	60.00	60.00
	3.06%	*3.72%*	*7.62%*	*12.73%*	*10.82%*	*9.33%*	*8.13%*	*7.16%*
Natural Gas	110.50	142.00	104.70	103.20	131.80	139.30	110.10	140.50
	37.17%	*43.67%*	*26.51%*	*21.90%*	*23.78%*	*21.67%*	*14.92%*	*16.76%*
Import Coal	51.10	34.20	24.70	17.90	13.00	9.40	6.80	4.90
	17.19%	*10.52%*	*6.25%*	*3.80%*	*2.35%*	*1.46%*	*0.92%*	*0.58%*
Domestic Coal	46.40	31.00	22.40	16.20	11.80	8.50	6.20	4.50
	15.61%	*9.53%*	*5.67%*	*3.44%*	*2.13%*	*1.32%*	*0.84%*	*0.54%*
Other Fossil Fuels	1.20	0.80	0.60	0.40	0.30	0.20	0.20	0.10
	0.40%	*0.25%*	*0.15%*	*0.08%*	*0.05%*	*0.03%*	*0.03%*	*0.01%*
Nuclear	0.00	0.00	38.70	38.70	38.70	38.70	38.70	38.70
	0.00%	*0.00%*	*9.80%*	*8.21%*	*6.98%*	*6.02%*	*5.24%*	*4.62%*
Total	297.30	325.20	394.90	471.20	554.30	642.90	737.90	838.50
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table C.22. *Power Generation for MinGHG-High Scenario, in TWh*

	2017	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydro	58.20	77.50	104.80	104.80	104.80	104.80	104.80	104.80
	19.58%	*22.92%*	*24.60%*	*19.93%*	*16.41%*	*13.74%*	*11.64%*	*9.98%*
Wind	17.90	23.80	58.50	93.10	134.60	134.60	134.60	134.60
	6.02%	*7.04%*	*13.73%*	*17.70%*	*21.08%*	*17.64%*	*14.95%*	*12.81%*
Solar	2.90	3.80	9.60	23.80	59.30	147.40	272.40	350.40
	0.98%	*1.12%*	*2.25%*	*4.53%*	*9.29%*	*19.32%*	*30.25%*	*33.36%*
Other Renewables	9.10	12.10	30.10	60.00	60.00	60.00	60.00	60.00
	3.06%	*3.58%*	*7.07%*	*11.41%*	*9.40%*	*7.86%*	*6.66%*	*5.71%*
Natural Gas	110.50	147.10	130.80	166.90	213.00	257.20	275.20	351.30
	37.17%	*43.49%*	*30.70%*	*31.74%*	*33.36%*	*33.71%*	*30.56%*	*33.44%*
Import Coal	51.10	42.10	30.50	22.00	16.00	11.50	8.40	6.00
	17.19%	*12.45%*	*7.16%*	*4.18%*	*2.51%*	*1.51%*	*0.93%*	*0.57%*
Domestic Coal	46.40	31.00	22.40	16.20	11.80	8.50	6.20	4.50
	15.61%	*9.17%*	*5.26%*	*3.08%*	*1.85%*	*1.11%*	*0.69%*	*0.43%*
Other Fossil Fuels	1.20	0.80	0.60	0.40	0.30	0.20	0.20	0.10
	0.40%	*0.24%*	*0.14%*	*0.08%*	*0.05%*	*0.03%*	*0.02%*	*0.01%*
Nuclear	0.00	0.00	38.70	38.70	38.70	38.70	38.70	38.70
	0.00%	*0.00%*	*9.08%*	*7.36%*	*6.06%*	*5.07%*	*4.30%*	*3.68%*
Total	297.30	338.20	426.00	525.90	638.50	762.90	900.50	1050.40
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table C.23. *Power Generation for FullRE-Low Scenario, in TWh*

	2017	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydro	58.20	64.70	65.90	77.40	77.40	104.80	104.80	104.80
	19.58%	*20.69%*	*18.02%*	*18.37%*	*16.15%*	*19.45%*	*17.47%*	*15.81%*
Wind	17.90	20.20	41.10	102.30	134.60	134.60	134.60	134.60
	6.02%	*6.46%*	*11.24%*	*24.28%*	*28.09%*	*24.98%*	*22.43%*	*20.31%*
Solar	2.90	3.80	9.60	19.20	47.70	118.80	218.80	317.40
	0.98%	*1.22%*	*2.63%*	*4.56%*	*9.95%*	*22.05%*	*36.47%*	*47.89%*
Other Renewables	9.10	6.10	11.90	24.10	60.00	60.00	60.00	60.00
	3.06%	*1.95%*	*3.25%*	*5.72%*	*12.52%*	*11.14%*	*10.00%*	*9.05%*
Natural Gas	110.50	130.80	108.90	87.00	65.10	43.20	21.30	0.00
	37.17%	*41.83%*	*29.78%*	*20.65%*	*13.59%*	*8.02%*	*3.55%*	*0.00%*
Import Coal	51.10	34.20	38.00	30.00	22.00	13.90	5.90	0.00
	17.19%	*10.94%*	*10.39%*	*7.12%*	*4.59%*	*2.58%*	*0.98%*	*0.00%*
Domestic Coal	46.40	51.30	49.90	41.30	32.80	24.30	15.70	7.20
	15.61%	*16.41%*	*13.65%*	*9.80%*	*6.84%*	*4.51%*	*2.62%*	*1.09%*
Other Fossil Fuels	1.20	1.60	1.70	1.30	0.90	0.50	0.20	0.00
	0.40%	*0.51%*	*0.46%*	*0.31%*	*0.19%*	*0.09%*	*0.03%*	*0.00%*
Nuclear	0.00	0.00	38.70	38.70	38.70	38.70	38.70	38.70
	0.00%	*0.00%*	*10.58%*	*9.19%*	*8.08%*	*7.18%*	*6.45%*	*5.84%*
Total	297.30	312.70	365.70	421.30	479.20	538.80	600.00	662.70
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table C.24. *Power Generation for FullRE-Mid Scenario, in TWh*

	2017	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydro	58.20	64.70	87.90	104.80	104.80	104.80	104.80	104.80
	19.58%	*19.89%*	*22.26%*	*22.24%*	*18.91%*	*16.30%*	*14.20%*	*12.50%*
Wind	17.90	20.20	48.30	120.30	134.60	134.60	134.60	134.60
	6.02%	*6.21%*	*12.23%*	*25.53%*	*24.29%*	*20.94%*	*18.24%*	*16.05%*
Solar	2.90	3.80	9.60	23.80	59.30	147.40	281.10	350.40
	0.98%	*1.17%*	*2.43%*	*5.05%*	*10.70%*	*22.93%*	*38.10%*	*41.79%*
Other Renewables	9.10	6.10	11.90	24.10	60.00	60.00	60.00	60.00
	3.06%	*1.88%*	*3.01%*	*5.11%*	*10.83%*	*9.33%*	*8.13%*	*7.16%*
Natural Gas	110.50	130.80	108.90	87.00	65.10	43.20	21.30	13.60
	37.17%	*40.21%*	*27.58%*	*18.46%*	*11.75%*	*6.72%*	*2.89%*	*1.62%*
Import Coal	51.10	39.70	38.00	30.00	22.00	13.90	5.90	14.70
	17.19%	*12.20%*	*9.62%*	*6.37%*	*3.97%*	*2.16%*	*0.80%*	*1.75%*
Domestic Coal	46.40	58.40	49.90	41.30	68.80	99.70	91.20	121.70
	15.61%	*17.95%*	*12.64%*	*8.76%*	*12.41%*	*15.51%*	*12.36%*	*14.51%*
Other Fossil Fuels	1.20	1.60	1.70	1.30	0.90	0.50	0.20	0.00
	0.40%	*0.49%*	*0.43%*	*0.28%*	*0.16%*	*0.08%*	*0.03%*	*0.00%*
Nuclear	0.00	0.00	38.70	38.70	38.70	38.70	38.70	38.70
	0.00%	*0.00%*	*9.80%*	*8.21%*	*6.98%*	*6.02%*	*5.25%*	*4.62%*
Total	297.30	325.30	394.90	471.30	554.20	642.80	737.80	838.50
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

Table C.25. *Power Generation for FullRE-High Scenario, in TWh*

	2017	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydro	58.20	64.70	103.40	104.80	104.80	104.80	104.80	104.80
	19.58%	*19.13%*	*24.27%*	*19.92%*	*16.42%*	*13.74%*	*11.64%*	*9.98%*
Wind	17.90	20.80	51.70	128.70	134.60	134.60	134.60	134.60
	6.02%	*6.15%*	*12.14%*	*24.47%*	*21.08%*	*17.64%*	*14.95%*	*12.81%*
Solar	2.90	3.80	9.60	23.80	59.30	147.40	323.60	350.40
	0.98%	*1.12%*	*2.25%*	*4.52%*	*9.29%*	*19.32%*	*35.94%*	*33.36%*
Other Renewables	9.10	12.10	24.10	60.00	60.00	60.00	60.00	60.00
	3.06%	*3.58%*	*5.66%*	*11.41%*	*9.40%*	*7.86%*	*6.66%*	*5.71%*
Natural Gas	110.50	130.80	108.90	87.00	96.40	139.00	117.10	240.20
	37.17%	*38.68%*	*25.56%*	*16.54%*	*15.10%*	*18.22%*	*13.01%*	*22.87%*
Import Coal	51.10	46.00	38.00	30.00	22.00	16.00	8.00	0.00
	17.19%	*13.60%*	*8.92%*	*5.70%*	*3.45%*	*2.10%*	*0.89%*	*0.00%*
Domestic Coal	46.40	58.40	49.90	51.70	121.70	121.70	113.10	121.70
	15.61%	*17.27%*	*11.71%*	*9.83%*	*19.06%*	*15.95%*	*12.56%*	*11.59%*
Other Fossil Fuels	1.20	1.60	1.70	1.30	0.90	0.80	0.40	0.00
	0.40%	*0.47%*	*0.40%*	*0.25%*	*0.14%*	*0.10%*	*0.04%*	*0.00%*
Nuclear	0.00	0.00	38.70	38.70	38.70	38.70	38.70	38.70
	0.00%	*0.00%*	*9.08%*	*7.36%*	*6.06%*	*5.07%*	*4.30%*	*3.68%*
Total	297.30	338.20	426.00	526.00	638.40	763.00	900.30	1050.40
	100.00%	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*

D. NUMERICAL RESULTS: GHG EMISSIONS

The GHG emissions for all scenarios are shown in Table D.26.

Table D.26. *GHG Emissions for All Scenarios, in MtCO2e*

Scenario		**2017**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**CAGR 2017-2050**
BaseCase	Low	155.0	151.8	161.2	171.0	210.5	245.5	276.3	301.5	2.0%
	Mid	155.0	165.3	160.6	192.8	245.4	297.3	346.8	391.7	2.8%
	High	155.0	172.6	169.7	216.6	276.4	348.3	420.2	489.3	3.5%
MaxLocal	Low	155.0	151.8	144.5	140.3	140.3	144.5	157.7	149.9	-0.1%
	Mid	155.0	165.3	153.8	152.2	155.3	168.4	157.7	146.2	-0.2%
	High	155.0	172.6	171.0	174.1	208.7	230.6	253.3	287.4	1.9%
MinGHG	Low	155.0	128.8	93.1	67.3	52.3	37.9	27.5	19.9	-6.0%
	Mid	155.0	134.5	98.0	83.4	86.2	82.2	63.7	73.6	-2.2%
	High	155.0	145.2	116.1	116.5	126.1	137.7	140.0	170.0	0.3%
FullRE	Low	155.0	151.8	144.6	116.6	88.7	60.7	32.8	7.7	-8.7%
	Mid	155.0	165.3	144.6	116.6	127.0	141.0	113.2	151.3	-0.1%
	High	155.0	171.9	144.6	127.7	197.4	210.2	182.2	238.0	1.3%

E. GTAP-CGE MODEL: SUPPORTING INFORMATION

The sectoral aggregation used in the GTAP-CGE model is shown in Table E.27.

Table E.27. *Sectoral Aggregation in GTAP-CGE Model*

Sectoral Aggregation	GTAP Code	Goods	Sectoral Aggregation	GTAP Code	Goods
	PDR	Paddy rice		NMM	Mineral products nec
	WHT	Wheat		I_S	Ferrous metals
	GRO	Cereal grains nec		NFM	Metals nec
	V_F	Vegetables, fruit, nuts		FMP	Metal products
	OSD	Oil seeds		MVH	Motor vehicles and parts
	C_B	Sugar cane, sugar beet		OTN	Transport equipment nec
	PFB	Plant-based fibers		ELE	Electronic equipment
	OCR	Crops nec		OME	Machinery and equipment nec
	CTL	Bovine cattle, sheep and goats, horses		OMF	Manufactures nec
	OAP	Animal products nec		WTR	Water
	RMK	Raw milk	ind - industry	CNS	Construction
	WOL	Wool, silk-worm cocoons		TRD	Trade
	FRS	Forestry		CMN	Communication
	FSH	Fishing		OFI	Financial services nec
	CMT	Bovine meat products		ISR	Insurance
	OMT	Meat products nec		OBS	Business services nec
	VOL	Vegetable oils and fats		ROS	Recreational and other services
	MIL	Dairy products		OSG	Public Administration, Defense, Education, Health
	PCR	Processed rice	serv - service	DWE	Dwellings
	SGR	Sugar		OTP	Transport nec
	OFD	Food products nec		WTP	Water transport
agri - agriculture and food	B_T	Beverages and tobacco products	tran - transportation	ATP	Air transport
	OMN	Minerals nec	coal - coal	COA	Coal
	TEX	Textiles	roil - refined oil	P_C	Petroleum, coal products
	WAP	Wearing apparel	oil - crude oil	OIL	Oil
	LEA	Leather products		GAS	Gas
	LUM	Wood products	gas - gas	GDT	Gas manufacture, distribution
	PPP	Paper products, publishing			
ind - industry	CRP	Chemical, rubber, plastic products	elec - electricity	ELY	Electricity

The nesting structures of each sector is illustrated in Figure E.1 to E.7.

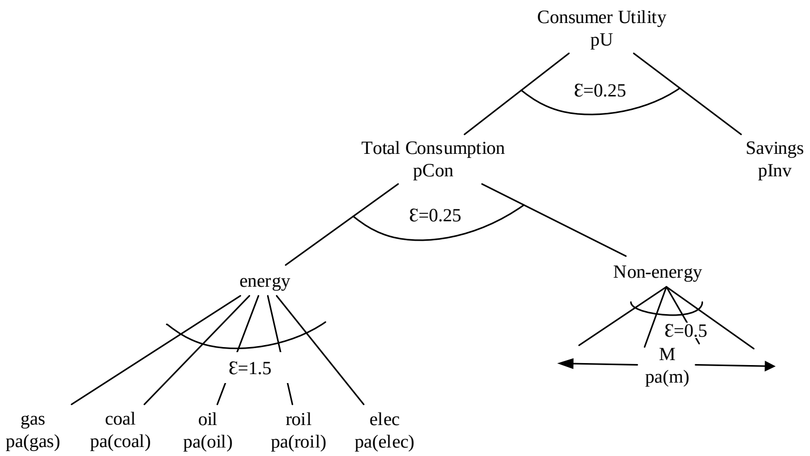

Figure E.1. Nesting Structure of Consumer Utility

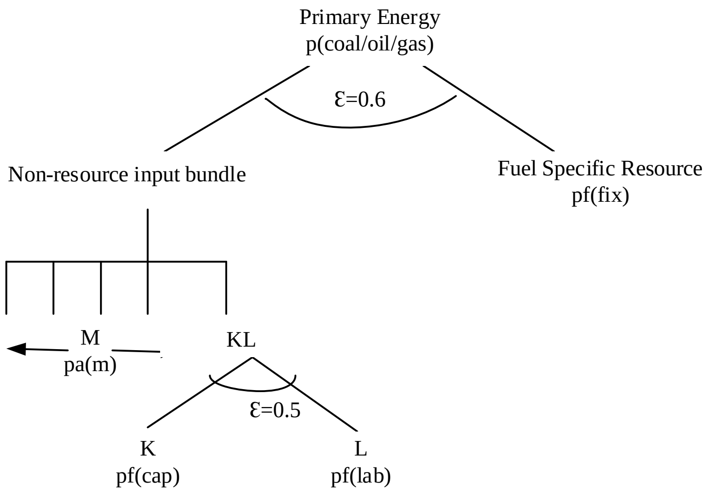

Figure E.2. Nesting Structure of Primary Energy

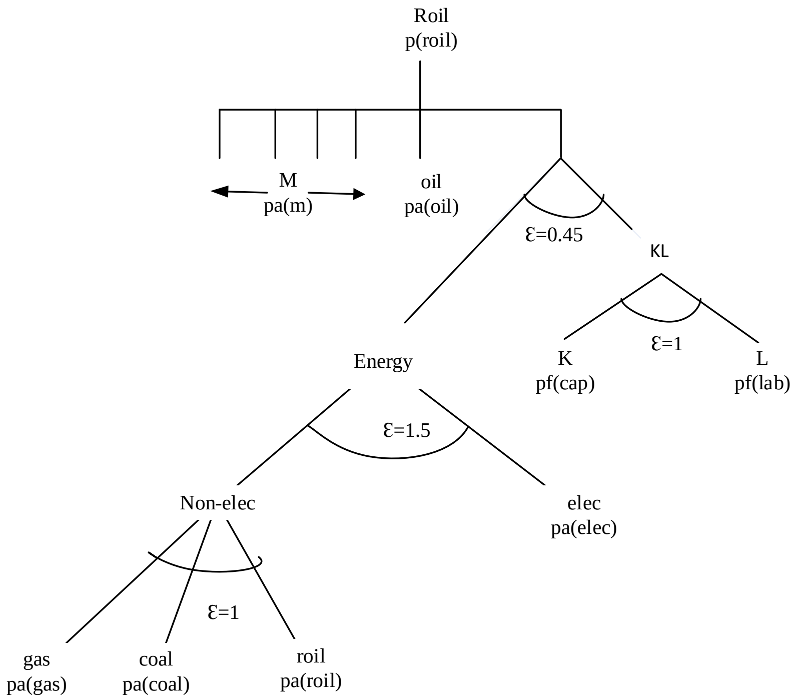

Figure E.3. Nesting Structure of Oil Refinery

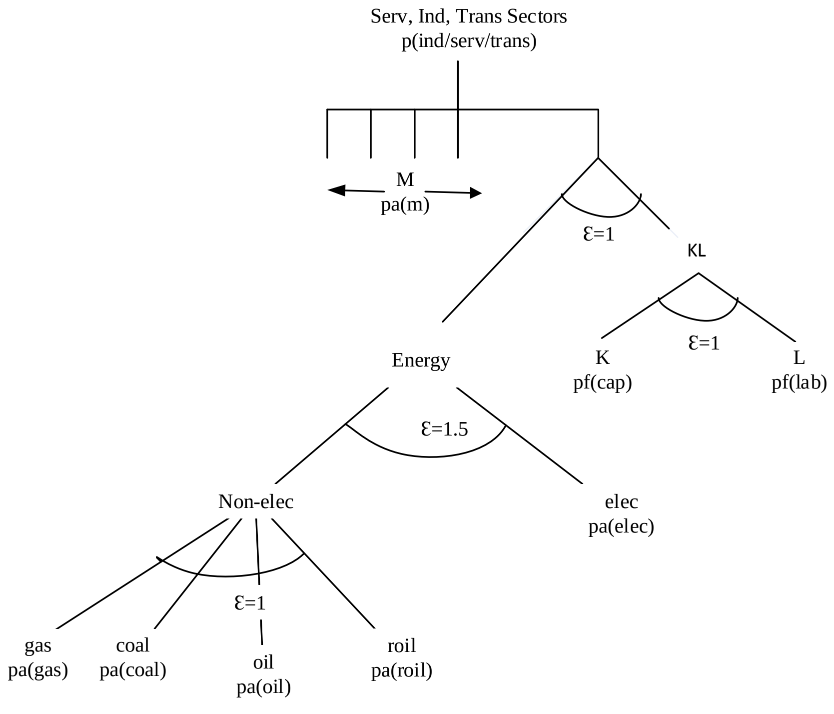

Figure E.4. Nesting Structure of Industry, Service and Transport Sectors

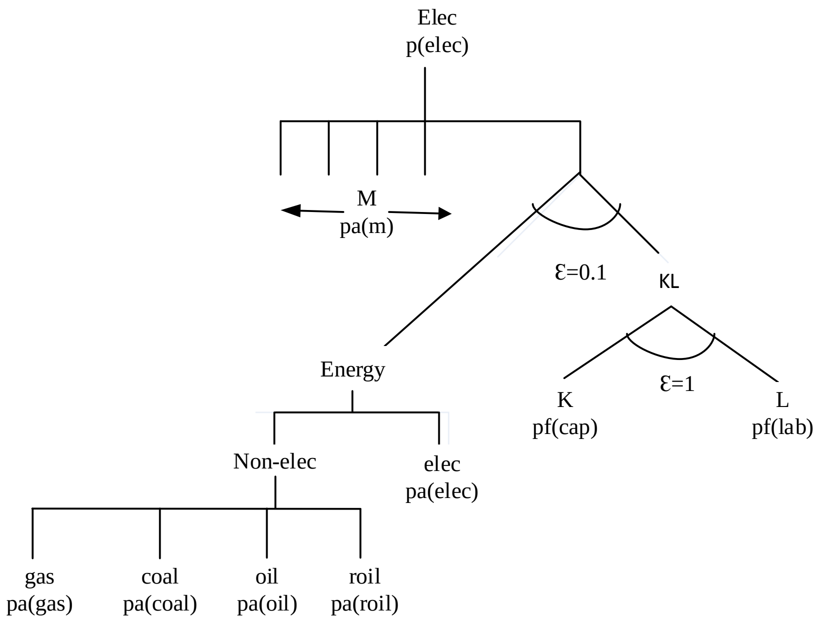

Figure E.5. Nesting Structure of Electricity Sector

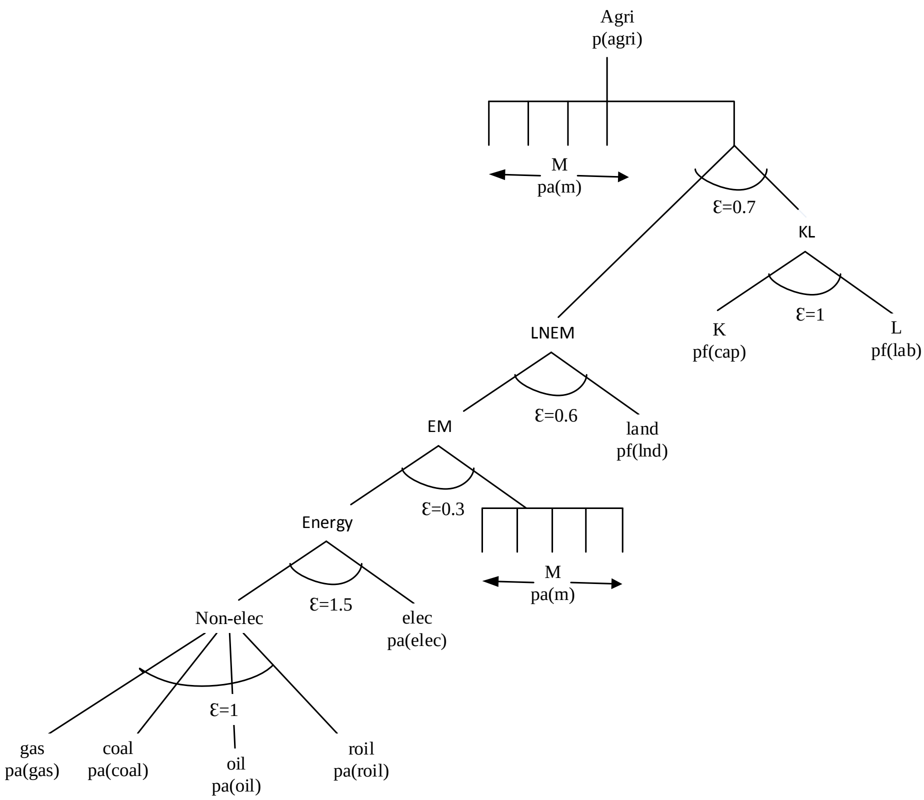

Figure E.6. Nesting Structure of Agriculture

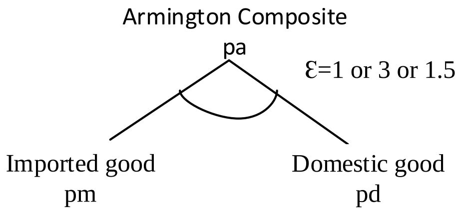

Figure E.7. Nesting Structure of Armington Composite

F. POWER-LP MODEL: SUPPLEMENTAL DATA

Exogenous input used in Power-LP model and the GAMS code for the model are shown below.

Capacity Factor

The capacity factor is assumed to be constant for all period using the value shown in Table F.28.

Table F.28. *Capacity Factor*

Primary Energy Resource of the Technology	Capacity Factor
Hydro	26%
Wind	32%
Solar	20%
Other Renewables	64%
Natural Gas	57%
Import Coal	59%
Domestic Coal	59%
Other Fossil Fuels	36%
Nuclear	92%

Emission Factor

Emission factors for fossil-based technology are defined as follow: natural gas 347.419 Gg CO2 per TWh; import coal 819.790 Gg CO2 per TWh; domestic coal 1,016.425 Gg CO2 per TWh; and other fossil fuels 1,838.048 Gg CO2 per TWh.

Lifetime of Technology

The lifetime of each technology is shown in Table F.29.

Table F.29. *Lifetime of Power Plants*

Primary Energy Resource of the Technology	Lifetime (years)
Hydro	30
Wind	30
Solar	30
Other Renewables	30
Natural Gas	30
Import Coal	30
Domestic Coal	30
Other Fossil Fuels	30
Nuclear	60

GAMS Code

MAIN PROGRAM

```
$title Power Linear Program
*==============================================================================================
Sets
*==============================================================================================
t               years                   /2017
                                         2020
                                         2025
                                         2030
                                         2035
                                         2040
                                         2045
                                         2050/

tt(t)           years                   /2020
                                         2025
                                         2030
                                         2035
                                         2040
                                         2045
                                         2050/

i               power technologies      /Hydro
                                         Wind
                                         Solar
                                         OthRen
                                         NaturalGas
                                         ImpCoal
                                         DomCoal
                                         OthFos
                                         Nuclear/

nuc(i)                                  /Nuclear/

rnw(i)          renewable technologies  /Hydro
                                         Wind
```

```
                                         Solar
                                         OthRen/

local(i)        domestic technologies   /Hydro
                                         Wind
                                         Solar
                                         OthRen
                                         DomCoal/
;
alias(i,j);
*=============================================================================================
Parameters
*=============================================================================================

CapFac(i)       Capacity factor of technology i
InsCap0(i)      Installed capacity of technology i in base year
EleDem(tt)      Electricity demand in year t
Life(i)         Lifetime of technology i in years
DepRate(i,t)    Depreciation rate of technology i in year t
EmisFac(i)      Emission factor (Gg CO2 per TWh) of technology i
RetRate(t)      Max retirement rate of technology i in year t
LB(i,tt)        Lower bound on the installed capacity of technology i in year tt (as a ratio
of total
                installed capacity)
UB(i,tt)        Upper bound on the installed capacity of technology i in year tt (as a ratio
of total
                installed capacity)
LB2(i,t)        Lower bound on the installed capacity of technology i in year tt (as a ratio
of total
                installed capacity in year t-1)
UB2(i,t)        Upper bound on the installed capacity of technology i in year tt (as a ratio
of total
                installed capacity in year t-1)
ActGen0(i)      Actual generation of technology i in base year
ShrGen0(i)      Share of electricity generation in the base year
Output(*,*,*)   Reporting parameter
Loss(tt)          Difference between Net Consumption and Gross Generation (incl. TnD Loss,
internal
                cons and net foreign trade)
;

Loss(tt)                 = 0.16;
ShrGen0(i)               = ActGen0(i)/sum(j, ActGen0(j));
display ShrIC0;

*=============================================================================================
*Capacity factor
*=============================================================================================
CapFac("Hydro")          = 0.26;
CapFac("Wind")           = 0.32;
CapFac("Solar")          = 0.20;
CapFac("OthRen")         = 0.64;
CapFac("NaturalGas")     = 0.57;
CapFac("ImpCoal")        = 0.59;
CapFac("DomCoal")        = 0.59;
CapFac("OthFos")         = 0.36;
CapFac("Nuclear")        = 0.92;
*=============================================================================================
*Base Year Installed Capacity
*=============================================================================================
InsCap0("Hydro")         = 27.2731;
InsCap0("Wind")          =  6.5162;
InsCap0("Solar")         =  3.4207;
InsCap0("OthRen")        =  1.7056;
InsCap0("NaturalGas")    = 26.3206;
```

```
InsCap0("ImpCoal")       =  9.3060;
InsCap0("DomCoal")       =  9.9116;
InsCap0("OthFos")        =  0.74621;
InsCap0("Nuclear")       =  0.0000;
*==============================================================================================
*Base Year Electricity Generation
*==============================================================================================
ActGen0("Hydro")         =  58.218462;
ActGen0("Wind")          =  17.90381511;
ActGen0("Solar")         =   2.889302;
ActGen0("OthRen")        =   9.099789;
ActGen0("NaturalGas")    = 110.4899809;
ActGen0("ImpCoal")       =  51.118093;
ActGen0("DomCoal")       =  46.3582;
ActGen0("OthFos")        =   1.199878;
ActGen0("Nuclear")       =   0.000;
*==============================================================================================
*Net Electricity Demand (2020-2050) input from GTAP-CGE
*==============================================================================================
EleDem("2020")           = 273.281244284532;
EleDem("2025")           = 331.704233155087;
EleDem("2030")           = 395.887570309917;
EleDem("2035")           = 465.383015958638;
EleDem("2040")           = 539.986073883005;
EleDem("2045")           = 619.633499598528;
EleDem("2050")           = 704.232837484739;
*==============================================================================================
*Emission factor
*==============================================================================================
EmisFac("Hydro")         =    0.000;
EmisFac("Wind")          =    0.000;
EmisFac("Solar")         =    0.000;
EmisFac("OthRen")        =    0.000;
EmisFac("NaturalGas")    =  347.419;
EmisFac("ImpCoal")       =  819.790;
EmisFac("DomCoal")       = 1016.425;
EmisFac("OthFos")        = 1838.048;
EmisFac("Nuclear")       =    0.000;
*==============================================================================================
*Lifetime
*==============================================================================================
Life("Hydro")            = 30;
Life("Wind")             = 30;
Life("Solar")            = 30;
Life("OthRen")           = 30;
Life("NaturalGas")       = 30;
Life("ImpCoal")          = 30;
Life("DomCoal")          = 30;
Life("OthFos")           = 30;
Life("Nuclear")          = 60;
*==============================================================================================
*Depreciation rate
*==============================================================================================
DepRate(i,t)             = (1/Life(i))*5;
DepRate(i,"2020")        = (1/Life(i))*3;
DepRate("Solar",t)       = 0;
DepRate("Wind",t)        = 0;

*==============================================================================================
Free Variables
*==============================================================================================
vObj                   Objective
;
*==============================================================================================
Positive Variables
```

```
*==============================================================================================
vEmis(i,t)            Emission due to generation of technology i in year t (Mton)
vAnnEmis(t)           Total emissions in year t (Mton)
vTotEmis              Total emissions throughout 2020-2050 (Mton)
vInsCap(i,t)          Installed capacity of technology i in year t (GW)
vInsCapAct(i,t)       Actively used Installed capacity of technology i in year t (GW)
vAnnInsCap(t)         Total installed capacity in year t (GW)
vNewInsCap(i,t)       Newly installed capacity in year t (GW)
vEleGen(i,t)          Generation by technology i in year t (TWh)
vTotEleGen(t)         Total generation in year t (TWh)
vIdleCap(tt)          Idle Capcity (GW)
;
vInsCap.fx(i,"2017")                       = InsCap0(i);
vEleGen.fx(i,"2017")                       = ActGen0(i);
*==============================================================================================
*Global Assumptions
*==============================================================================================
vInsCap.up("Nuclear",tt)                   =   0;
vInsCap.fx("Nuclear",tt)$(tt.val>2020)     =   4.800;
vInsCap.up("Hydro",tt)                     =  46.000;
vInsCap.up("Wind",tt)                      =  48.000;
vInsCap.up("Solar",tt)                     = 200.000;
vInsCap.up("DomCoal",tt)                   =  23.543;
vInsCap.up("OthRen",tt)                    =  10.7;
vInsCap.lo("Hydro","2020")                 =  28.4;
vInsCap.lo("Wind","2020")                  =  7.2;
vInsCap.lo("Solar","2020")                 =  5.5;
vInsCap.lo("OthRen","2020")                =  2.4;
vInsCap.lo("NaturalGas","2020")            =  26.2;
vInsCap.lo("ImpCoal","2020")               =  8.9;
vInsCap.lo("DomCoal","2020")               =  11.3;
vInsCap.up("OthFos","2020")                =  0.7;
*==============================================================================================
Scalar
*==============================================================================================
Scenario        Selected scenario;
*==============================================================================================
*Scenario Selection (here the BaseCase is selected)
*==============================================================================================
*BaseCase 1
*MaxLocal 2
*MinGHG 3
*FullRE 4

Scenario                 = 1;
$include BaseCase.cas
*$include MaxLocal.cas
*$include MinGHG.cas
*$include FullRE.cas

*==============================================================================================
EQUATIONs
*==============================================================================================
EquObj                 Objective
EquDemSupBal(tt)       Demand is satisfied in year tt
EquInsCap(i,t)         Installed capacity of technology i in year t
EquTotInsCap(tt)       Total installed capacity in year tt
EquEleGen(i,tt)        Generation by technology i in year tt
EquTotEleGen(t)        Total generation in year tt
EquEmis(i,t)           Emission due to generation of technology i in year t
EquAnnEmis(t)          Total emissions in year t
EquTotEmis             Total emissions throughout 2017-2040
EquGenLB(i,tt)         Lower bound on the electricity generation of technology i in year tt
EquGenUB(i,tt)         Upper bound on the electricity generation of technology i in year tt
```

```
EquCnsctvGenLB(i,t)     Lower  bound  on  the  consecutive  total  electricity  generation  of
technology i in
                         year t
EquCnsctvGenUB(i,t)     Upper  bound  on  the  consecutive  total  electricity  generation  of
technology i in
                         year t
EquInsCapAct(i,tt)      Actively used capacity should be lower than total installed capacity
EquIdle(tt)             Idle Capacity
;

EquObj..          vObj          =e=    sum((i,tt)$local(i),vEleGen(i,tt))$(Scenario = 2)
                                       - sum((i,tt),EmisFac(i)*vEleGen(i,tt))$(Scenario = 3)
                                       - 1000*sum(tt,vIdleCap(tt))
                                       + sum((i,tt)$rnw(i),vEleGen(i,tt))$(Scenario = 4);

EquDemSupBal(tt)..      vTotEleGen(tt)      =e=     EleDem(tt)/(1-Loss(tt));
EquInsCap(i,t)$tt(t)..  vInsCap(i,t)        =e=     vInsCap(i,t-1)- DepRate(i,t)*
                                                    vInsCap(i,"2017")+vNewInsCap(i,t);
EquTotInsCap(tt)..      vAnnInsCap(tt)      =e=     sum(i,vInsCap(i,tt));
EquEleGen(i,tt)..       vEleGen(i,tt)       =e=     CapFac(i)*8760*vInsCapAct(i,tt)/1000;
EquTotEleGen(t)..       vTotEleGen(t)       =e=     sum(i,vEleGen(i,t));
EquInsCapAct(i,tt)..    vInsCapAct(i,tt)    =l=     vInsCap(i,tt);
EquGenLB(i,tt)..        vEleGen(i,tt)       =g=     LB(i,tt)*vTotEleGen(tt);
EquGenUB(i,tt)..        vEleGen(i,tt)       =l=     UB(i,tt)*vTotEleGen(tt);
EquCnsctvGenLB(i,t)$(tt(t)and not Nuc(i))..  vEleGen(i,t) =g=   (1-LB2(i,t))*vEleGen(i,t-1);
EquCnsctvGenUB(i,t)$(tt(t)and not Nuc(i))..  vEleGen(i,t) =l=   (1+UB2(i,t))*vEleGen(i,t-1);
EquIdle(tt)..           vIdleCap (tt)       =e=     [sum(i,vInsCap(i,tt)-vInsCapAct(i,tt))];
EquEmis(i,t)..          vEmis(i,t)          =e=     EmisFac(i)*vEleGen(i,t);
EquAnnEmis(t)..         vAnnEmis(t)         =e=     sum(i,vEmis(i,t));
EquTotEmis..            vTotEmis            =e=     sum(tt,vAnnEmis(tt));


Model Power_LP /
EquObj
EquDemSupBal
EquInsCap
EquTotInsCap
EquEleGen
EquTotEleGen
EquEmis
EquAnnEmis
EquTotEmis
EquGenLB
EquGenUB
EquCnsctvGenLB
EquCnsctvGenUB
EquInsCapAct
EquIdle
/

Solve Power_LP maximizing vObj using LP;

Output("Installed Capacity",i,t) = vInsCap.l(i,t);
Output("Active Capacity",i,t) = vInsCapAct.l(i,t);
Output("Generation",i,t) = vEleGen.l(i,t);
Output("Emissions",i,t) = vEmis.l(i,t);
Output("Newly Installed Capacity",i,t) = vNewInsCap.l(i,t);

Execute_unload   'Power_LP Results.gdx'

--------------------------------------------------------------------------------------------
```

BaseCase.Cas

```
--------------------------------------------------------------------------------------------

LB(i,tt)         = (1-0.3)*ShrGen0(i);
```

```
UB(i,tt)         = (1+0.3)*ShrGen0(i);


LB("nuclear",tt)$(tt.val>2020) =0;
UB("nuclear",tt)$(tt.val>2020) =1;

LB2(i,"2020")            = (1+0.1)**3-1;
UB2(i,"2020")            = (1+0.1)**3-1;

*Non RE Maximum annual increase/decrease 5% conservative assumption based on CAGR 2011-2017
LB2(i,tt)$(tt.val>2020)  = (1+0.05)**5-1;
UB2(i,tt)$(tt.val>2020)  = (1+0.05)**5-1;

*RE Maximum annual increase/decrease 20% conservative assumption based on CAGR 2011-2017
LB2(rnw,tt)$(tt.val>2020)  = (1+0.2)**5-1;
UB2(rnw,tt)$(tt.val>2020)  = (1+0.2)**5-1;
```

MaxLocal.Cas

```
LB(i,tt)         = 0.0;
UB(i,tt)         = 1.0;

LB2(i,"2020")            = (1+0.1)**3-1;
UB2(i,"2020")            = (1+0.1)**3-1;

*Non RE Maximum annual increase/decrease 5% conservative assumption based on CAGR 2011-2017
LB2(i,tt)$(tt.val>2020)  = (1+0.05)**5-1;
UB2(i,tt)$(tt.val>2020)  = (1+0.05)**5-1;

*RE Maximum annual increase/decrease 20% conservative assumption based on CAGR 2011-2017
LB2(rnw,tt)$(tt.val>2020)  = (1+0.2)**5-1;
UB2(rnw,tt)$(tt.val>2020)  = (1+0.2)**5-1;
```

MinGHG.cas

```
LB(i,tt)         = 0.0;
UB(i,tt)         = 1.0;

LB2(i,"2020")            = (1+0.1)**3-1;
UB2(i,"2020")            = (1+0.1)**3-1;

*Non RE Maximum annual increase/decrease 5% conservative assumption based on CAGR 2011-2017
LB2(i,tt)$(tt.val>2020)  = (1+0.05)**5-1;
UB2(i,tt)$(tt.val>2020)  = (1+0.05)**5-1;

*RE Maximum annual increase/decrease 20% conservative assumption based on CAGR 2011-2017
LB2(rnw,tt)$(tt.val>2020)  = (1+0.2)**5-1;
UB2(rnw,tt)$(tt.val>2020)  = (1+0.2)**5-1;
```

FullRE.cas

```
LB(i,tt)         = 0.0;
UB(i,tt)         = 1.0;

LB("Nuclear","2050")         = 0.03091;
UB("Nuclear","2050")         = 1.0;

LB2(i,"2020")            = (1+0.1)**3-1;
```

```
UB2(i,"2020")            = (1+0.1)**3-1;

*Non RE Maximum annual increase/decrease 5% conservative assumption based on CAGR 2011-2017
LB2(i,tt)$(tt.val>2020)  = (1+0.05)**5-1;
UB2(i,tt)$(tt.val>2020)  = (1+0.05)**5-1;

*RE Maximum annual increase 20% conservative assumption based on CAGR 2011-2017
LB2(rnw,tt)$(tt.val>2020)  = (1+0.2)**5-1;
UB2(rnw,tt)$(tt.val>2020)  = (1+0.2)**5-1;

vInsCap.fx("Hydro","2050")                          =  46.000;
vInsCap.fx("Wind","2050")                           =  48.000;
vInsCap.fx("OthRen","2050")                         =  10.7;
```

G. LEAP: BASIC ALGORITHM

Energy Consumption

There are typically 4 different ways in the calculation of energy demand in LEAP.

- Final Energy Analysis: $E = AL\,.\,EI$

  Where E=energy demand, AL=activity level, EI=final energy intensity (energy consumed per unit of activity)

  Example: energy demand in the cement industry can be projected based on tons of cement produced and energy used per ton. *Each can change in the future.*

- Useful Energy Analysis: $E = AL.\left(\frac{u}{n}\right)$

  Where u=useful energy intensity, n = efficiency

  Example: energy demand in buildings will change in future as (1) more buildings are constructed [+a] (2) people get richer and heat and cool buildings more [+u], or building insulation improves [-u], or as people switch from less efficient oil boilers to electricity or natural gas [+n].

- Stock Analysis: $E = s\,.\,d$

  Where s=stock, d=device intensity (energy use per device). Stock is modeled endogenously based on existing vintage of devices, sales of new devices and survival profile for devices.

  Example: how quickly will a new energy efficiency standard for refrigerators lead to energy savings based on penetration of new devices and turnover of existing stock?

- Transport Analysis: $E = s\,.\left(\frac{m}{fe}\right)$

  Where m = vehicle miles, fe = fuel economy (MPG)

Allows modeling of vehicle stock turnover. Also allows pollutant emissions to be modeled as function of vehicle miles

Example: model impact of new vehicle fuel economy or emissions standards.

In the study, energy demand of each sector is exogenously calculated in GTAP-CGE model. Thus, the calculation of energy demand in the study:

$$E_{i,t} = AL_{i,t} \, . \hat{E}_{i,t}$$

Where: $E_{i,t}$=energy demand of sector i in year t $AL_{i,t}$=Activity level of sector i in year t and $\hat{E}_{i,t}$ = Projected energy demand of sector i in year t

The activity level for each sector is set as 100%, thus we get:

$$E_{i,t} = \hat{E}_{i,t}$$

Furthermore, the total energy consumption is calculated as:

$$EC_t = \sum_i E_{i,t}$$

Transformation and electricity generation

In LEAP accounting framework, net electricity output should be equal to electricity demand for each year t:

$$NetOutput_t = EC_t$$

In the Transmission and Distribution module the net output is calculated as gross output multiply by electricity losses:

$$NetOutput_t = GrossOutput_t . losses_t$$

The calculation of electricity generation by technology is as follow:

$$GrossOutput_{i,t} = share_{i,t} . GrossOutput_p$$

The share of electricity generation of the technology i in year t, $share_{i,t}$, is taken exogenously from the Power-LP model results.

Costs

The cost calculated in the study is in terms of electricity supply cost. That is, the cost to generate electricity. The costs variable included are: capital, variable and fixed costs. In LEAP, the capital cost is annualized with several methods: Capital Recovery Factor, No Annualization, Straight Line Depreciation, Sinking Fund Depreciation, Declining Balance Depreciation and Double Declining Balance Depreciation. The approaches allow the capital costs to spread over the lifetime of each technology. In the study we opted capital recovery factor, thus the annualized capital costs of technology i is calculated as follow.

$$A_i = P_i \left[\frac{r(1+r)^n}{(1+r)^n - 1}\right]$$

Where: A_i=Annualized capital cost of technology i; P_i=Overnight capital cost of technology i; r=interest rate; n=lifetime of the technology

The annual capital cost of all technology is simply the sum of annualized capital costs of all technology.

$$capital_t = \sum_t A_{i,t}$$

Hence, the total cost calculations are as follow:

Discounted Total Cost:

$$NPV = \sum_t \frac{capital_t + fixed_t + variable_t}{(1+r)^t}$$

Where: NPV=Discounted total cost; capital=capital cost in year t ; fixed=fixed cost in year t; variable=variable costs in year t; r=discount rate

Undiscounted Total Cost:

$$TC = \sum_{t} capital_t + fixed_t + variable_t$$

The cost data used in the model is presented in Table G.30.

Table G.30. *Cost Data in LEAP Model*

Energy Source	**Capital Cost (2010 USD/kW)**	**Fixed Cost (2010 USD/kW)**	**Variable Cost (2010 USD/MWh)**	**Ref.**
Coal	2200	23	3.4	IPCC (2015) median values
Other Fossil Fuels	1100	7	3.2	Assumed to be the same as natural gas combined cycle. IPCC (2015) median values
Natural Gas	1100	7	3.2	IPCC (2015) median values
Other Renewables	3600	99	3.8	IPCC (2015) median values
Hydro	1900	35	0	IPCC (2015) median values
Wind	2100	0	14	IPCC (2015) median values
Solar	3200	20	0	IPCC (2015) median values
Nuclear	4300	0	13	IPCC (2015) median values

Emissions

The carbon emission from energy transformation is calculated as follows:

$$TotEmission = \sum_{s} \sum_{i} \sum_{g} ETP_{g,i} \cdot \frac{1}{f_{g,i,s}} . EF_{g,i,s}$$

where TotEmission is total greenhouse gas emissions, ETP is the energy transformation product, f is the energy transformation efficiency, and EF is the emission factor from one unit of primary fuel type s consumed for producing secondary fuel type g through technology i. The efficiency parameter (f) of each technology is own calculation based on data from (TEIAS, 2019a) and presented in Table G.31.

Table G.31. *Efficiency of Each Power Plant Technology*

Primary Energy Resource of the Technology	Efficiency
Hydro	100%
Wind	100%
Solar	100%
Other Renewables	70%
Natural Gas	50.20%
Coal	35.50%
Other Fossil Fuels	27.40%
Nuclear	100%

CURRICULUM VITAE

PERSONAL INFORMATION

Surname, Name	: Fathurrahman, Fahman
Nationality	: Indonesian
Date and Place of Birth	: 26 July 1987, Bandung
Phone	: +90 536 832 28 90
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EDUCATION

Degree	**Institution**	**Year of Graduation**
MS	METU Earth System Science	2014
BS	ITB Environmental Engineering	2009
High School	SMU Negeri 2 Bandung	2004

WORK EXPERIENCE

Year	**Place**	**Enrollment**
2018	SESRIC	Intern
2016	ASEAN Centre for Energy	Research Intern
2014-2015	GTE Carbon	Carbon Consultant
2011	Mitsubishi UFJ	CDM Consultant

FOREIGN LANGUAGES

Advanced Turkish, Fluent English

PUBLICATIONS

1. Raos, M., Fathurrahman, F., & Protic, M. (2019). Modelling energy consumption of the Republic of Serbia using linear regression and artificial neural network technique. Technical Gazette, Vol. 26, No. 1. DOI: 10.17559/TV-20180219142019

2. Fathurrahman, Fahman. (2016). Measuring the sustainability of energy development in emerging economies. Int. J. Global Environmental Issues, Vol. 15, No. 4, pp.315–345. DOI: 10.1504/IJGENVI.2016.081059

3. Fathurrahman, F., Kat, B., & Soytaṣ, U. (2015). Simulating Indonesian fuel subsidy reform: a social accounting matrix analysis. Annals of Operations Research. DOI: 10.1007/s10479-015-1954-x

HOBBIES

Travelling, Football, Movies, Computer Technologies, Music