SUSTAINABLE CARBON CONSTRAINED ENERGY GENERATION PERSPECTIVES

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY
IN
MECHANICAL ENGINEERING

DECEMBER 2021

Approval of the thesis:

SUSTAINABLE CARBON CONSTRAINED ENERGY GENERATION PERSPECTIVES

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ABSTRACT

SUSTAINABLE CARBON CONSTRAINED ENERGY GENERATION PERSPECTIVES

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December 2021, 283 pages

There is a consensus that climate change, which is about to become a major disaster for humankind, is largely due to anthropogenic activities. Greenhouse gases (dominated by CO_2) emissions play a dominant role there. Majority of the emissions results from energy consumption. Today, mitigating CO_2 emissions consists one of the fundamental missions of the humankind. One such task is to reduce the global energy demand. Enhancing efficiency, recycling, promoting behavioral changes to reduce energy demanding activities are among such measures. In this work, the effectiveness of another set of approaches involving the alteration of energy sources and carriers, while meeting the specified energy demand forecasts has been investigated. Predictions for the energy demand and resulting CO_2 emissions are calculated on economic sectors basis. Materials demand forecasts for the industry sector, passenger and freight activity forecasts for the transport sector, and energy demand forecasts directly for the buildings sector have been collected from the literature. These sources are selected specifically so that no mitigation intended reductions to future demands have been applied. Electricity generated from renewables and nuclear, electrolytic hydrogen, and solar thermal are designated as the new energy carriers and sources. By recommending their penetration rates in all three economic sectors, electricity demand until 2100 has been determined. Data for today’s operating power plants are analyzed and the need for the additional generation capacity is determined. A generation mix, consisting of renewable and nuclear, is proposed and the resulting generation capacity requirement and CO_2 emissions until 2100, are assessed.

Keywords: Climate Change, Greenhouse Gases, Energy Carrier, Renewable Energy, Nuclear Energy

ÖZ

SÜRDÜRÜLEBİLİR KARBON KISITLI ENERJİ ÜRETİM PERSPEKTİFLERİ

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Aralık 2021, 283 sayfa

İnsanoğlu için büyük bir felaket olma yolunda ilerleyen iklim değişikliğinin insan kaynaklı aktivitelerden kaynaklandığı konusunda fikir birliğine varılmış bulunmaktadır. CO_2'in başı çektiği sera gazları salımı en büyük sorumluluğu taşımaktadır. Söz konusu salımların büyük çoğunluğu enerji tüketiminden kaynaklanmaktadır. Günümüzde, salımları azaltma girişimleri insanlık en temel görevlerinden biri olmuştur. Bu yöndeki çalışmaların bir bölümü küresel enerji talebini azaltmak yönündedir. Verimliliğin artırılması, geri dönüşüm, toplumsal ve bireysel davranışlarda enerji tüketimini azaltma yönünde çalışmalar bu kapsamdadır. Bu çalışmada ise, gelecek için öngörülen enerji talebinin, enerji kaynakları ve taşıyıcılarında yenilenme yoluna gidilmesinin, anılan salımların azaltılmasına ne kadar etkili olacağı irdelenmiştir. Enerji tüketimi ve çıkardığı CO_2 salımları, ekonomik sektörler üzerinden incelenmiştir. Endüstride malzeme talepleri, ulaştırmada yolcu ve yük taşıma öngörüleri, binalarda ise doğrudan enerji talepleri literatürden alınmıştır. Bu kaynaklar seçilirken, salımların azaltılmasına yönelik talep kısıntılarının yapılmış olmamasına özen gösterilmiştir. Yenilenebilir ve nükleerden üretilen elektrik, elektrolitik hidrojen ve güneş enerjisi bu çalışmada yeni enerji kaynak ve taşıyıcıları olarak belirlenmiştir. Üç sektör için anılan kaynak ve taşıyıcıların penetrasyon hızları önerilmiş ve buna bağlı 2100 yılına kadar olan elektrik talebi belirlenmiştir. Günümüzde çalışmakta olan güç santralleri ile ilgili bilgi toplanmış, analiz edilmiş ve sonucunda belirlenen talep için eksik kalan elektrik üretim kapasitesi hesaplanmıştır. Bulunan bu ek kapasitenin karşılanmasına yönelik, yenilenebilir ve nükleer santrallerden oluşan bir dağılım önerilmiş ve çıkan elektrik üretim kapasitesinin büyüklüğü ve çıkan CO_2 salımları 2100 yılına kadar hesaplanmıştır.

Anahtar Kelimeler: İklim Değişikliği, Sera Gazları, Enerji Taşıyıcıları,
Yenilenebilir Enerji, Nükleer Enerji

To my family

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to my supervisor Prof. Dr. İlker Tarı for his trust in me, especially after the pause in my studies. The encouragements and the guidance he has provided have inspired me throughout this work.

I would like to thank to Prof. Dr. Derek Baker and Assoc. Prof. Dr. Şule Ergün for their continuous support, advice, and encouragements throughout the study.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

2W/3W:	Two or Three Wheeled Vehicles
AFF:	Agriculture, Forestry, and Fishery economic sector (used by IEA)
AR:	Assessment Report
BAU:	Business As Usual
BF:	Blast furnace
BOF:	Basic Oxygen Furnace
BTX:	Mixed Xylenes
Capex:	Capital Expenditures
CCGT:	Combined Cycle Gas Turbines
CFC:	Chlorofluorocarbon gases
COP:	Coefficient of Performance
DRI:	Direct Reduced Iron
EAF:	Electric Arc Furnace
FLAT:	Scenario in which demands remain constant (flat) beyond the range of the provided data (i.e., beyond 2050 or 2060)
GDP:	Gross Domestic Product
GDP:	Scenario in which demands are proportional to Gross Domestic Product beyond the range of the provided data (i.e., beyond 2050 or 2060)
GHG:	Greenhouse Gases
HDV:	Heavy Duty Vehicles
HHV:	Higher Heating Value (of a fuel)

HTGR: High Temperature Gas Cooled Reactor

HVC: High Value Chemicals

IATA: International Air Transport Association

ICCT: International Council on Clean Transportation

IEA: International Energy Agency

IMO: International Maritime Organization

IPCC: Intergovernmental Panel on Climate Change

ITF: International Transport Forum (under OECD)

LDV: Light Duty Vehicles

LED: Light Emitting Diode

LHV: Lower Heating Value (of a fuel)

LMFBR: Liquid Metal Fast Breeder Reactor

LNG: Liquified Natural Gas

LWR: Light Water Reactor

MDV: Medium Duty Vehicles

MIT: Massachusetts Institute of Technology

NASA: National Aeronautic and Space Administration (of the United States)

NDC: National Determined Contribution (mentioned in Paris Agreement)

NEA: Nuclear Energy Agency (under OECD)

NPP: Nuclear Power Plant

OECD: Organization for Economic Co-operation and Development

OCGT: Open Cycle Gas Turbines

POP: Scenario in which demands are proportional to population beyond the range of the provided data (i.e., beyond 2050 or 2060)

PV: Photovoltaic (used as solar PV to refer to the specific power plant)

PWR: Pressurized Water Reactor

RTS: Reference Technology Scenario (developed by IEA)

SR: Special Report

SUV: Sport Utility Vehicles

UN: United Nations

UNEP: United Nations Environmental Program

VRE: Variable Renewable Energies (used to refer to non-dispatchable renewables such as wind and solar)

WMO: World Meteorological Organization

WRI: World Resources Institute

CHAPTER 1

CLIMATE CHANGE

Climate Change is about to become the most serious problem humankind will face in this century. To clarify, what is being referred to as climate change is the recent increase in the average surface temperature on the Earth. Global warming is another wording that is being used to refer to the same event.

This recent warming trend of our planet's surface is being recorded since 1880, according to NASA [1]. This trend, which is very young when Earth's age is considered, is believed to be associated with human activities. This is why it is also referred to as anthropogenic global warming and is now linked to the greenhouse effect of various gases released into the atmosphere, mostly due to activities performed by humankind.

Gases that are responsible for the greenhouse effect are numerous, however only very few of them reach enough concentration in Earth’s atmosphere to create a detectable effect. Water vapor, CO_2, CH_4, N_2O, and CFCs are among the gases that are considered dangerous for this recent climate change. Water vapor’s release rate to the atmosphere has not been affected by human activities at a level to create substantial changes. This is not the case for other gases mentioned. On a molar basis, the latter gases have a more detrimental effect on the greenhouse formation in Earth's atmosphere; however, CO_2 has been recognized as the largest contributor to global warming, because of its excessive emission rates [2].

Although not all CO_2 emissions are anthropogenic, large quantities started being released into the environment, especially following the industrial revolution, which has initiated in the 19th century. The establishment of the industry resulted in heavy use of fossil fuels (as well as biomass) to supply the energy demand, which emits large quantities of CO_2 to the atmosphere.

In this study, a mitigation strategy to reduce CO_2 emissions through the employment of energy sources that can be classified as zero CO_2 emitters shall be investigated.

1.1. Brief History of Climate Change

The recognition of the existence of the problem took more than two decades, starting from its first public announcement in 1979, at the 1st World Climate Conference [3]. In 1992, more than 190 countries joined an international convention, organized by the United Nations (UN), the aim of which is to fight/cooperate against Climate Change. The first concrete output of the Convention came in 1997, with the release of the Kyoto Protocol [4]. The Kyoto Protocol obliges Convention members to reduce their greenhouse gas emissions. The first commitment period of the Protocol started in 2008 and ended in 2012.

The following achievement of the Convention is the signing of the Paris Agreement. The agreement, which has been adopted by 197 countries, entered into power on November 4, 2016 [5].

The importance of the Paris Agreement lies in the measures that could stop Climate Change to some extent, the World manages to implement them. As of today, 192 parties (191 countries and European Union) have ratified the agreement [6].

The principal clause of the Paris Agreement is embedded in Article 2 item 1a: "*Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels*". Although the agreement itself is an important global step in the effort to prevent Climate Change, it is widely criticized to be relatively weak in the enforcement aspect; it does not contain any penalty clause but relies on the "name and shame" approach. The agreement is "encouraging voluntary actions". The mechanism of the agreement is based on National Determined Contribution

(NDC). It proposes each signatory country announce its current NDC and mitigation plans to decrease the future NDC. It is expected to hear the success stories from every country on each NDC announcement period. However, there is no enforcement in case of a failure to comply. Another clause that requires special attention is Article 28 item 1 that grants permission to the signatory countries to exit the agreement*: "At any time after three years from the date on which this Agreement has entered into force for a Party, that Party may withdraw from this Agreement by giving written notification to the Depositary".*

Despite its weaknesses, The Paris Agreement is still being considered as an ultimate success of the scientists working on Climate Change. It is worth emphasizing the great contribution of the studies by IPCC (Intergovernmental Panel on Climate Change) in this effort.

IPCC has been established in 1988, by the World Meteorological Organization (WMO) and United Nations Environment Programme (UNEP). The mandate of IPCC is "*to provide policymakers with regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation*" [7]. It incorporates 195 member countries and its main activity is to publish reports. The scientists contributing to these reports are being selected through a rather lengthy and immaculate process. The selected scientists are working on a voluntary basis in their contribution to the preparations of the reports. IPCC reports can be classified into two categories: Assessment Report (AR) and Special Report (SR). The Assessment reports are the major publications and "*are composed of the full scientific and technical assessment of climate change, generally in three volumes, one for each of the Working Groups of the IPCC, together with their Summaries for Policymakers, plus a Synthesis Report*". The Special Reports are intended to address specific issues and the latest SR report titled "Special Report on Global Warming of 1.5°C" (SR-1.5) [8] consists one of the major driving forces behind this thesis proposal.

Climate Change 5th Assessment Report (AR-5) [9], published in 2014, emphasized one more time the effects of anthropogenic emissions on climate change. Below are the major findings of the report:

1- Anthropogenic emissions are the reason for Climate Change (extremely likely)
2- Anthropogenic Greenhouse Gas (GHG) emissions are increasing by economic and population growth
3- Continued gas emission will cause further warming
4- The mitigation to limit the warming to below 2°C requires substantial emission reduction and near-zero CO_2 emissions

The importance of AR-5 lies in the consensus among many scientists (coming from 195 different countries) that the major reason for climate change is human-induced GHG emissions. The dominating source of GHG emissions is recognized to be the fossil fuels used for electricity production, followed by their use in transportation and heating.

1.2. Now is the Time to Act

SR-1.5 [8] (the draft of which has been issued in October 2018) clearly indicates that a 1.5°C limit on global warming should be implemented. According to the report, limiting global warming to 2°C is not enough to sustain the current life in the world and unrecoverable changes are expected to occur beyond the 1.5°C limit.

Awareness about climate change has spread in societies thanks to efforts by IPCC, which investigate its scientific causes and potential impacts. Works by IPCC lead to the conclusion that "*it is unequivocal that human influence has warmed the atmosphere, ocean, and land*" [10].

Having established an upper limit for global warming, studies concentrated on determining the remaining amount of CO_2 to be released into the atmosphere. Analyzing many of these studies, IPCC prepared a table for correlating the remaining

CO_2 emissions with climate change in its SR-1.5 [8]. IPCC concluded in this report that "*global warming is likely to reach 1.5°C between 2030 and 2052, if it continues to increase at the current rate (high confidence)*".

The forecasted period for reaching the global warming limit indicates that urgent actions should be taken to mitigate CO_2 emissions. This observation constitutes the fundamental driving force behind this study.

1.3. Literature Review on Mitigation of Climate Change

One effective method to study climate change in the future involves the development of the so-called "scenarios". Predicting the possible evolution of the climate change phenomenon represents an effort that requires the adoption of several (many) assumptions. Forecasting inherently contains a degree of uncertainty, as one cannot be sure about the future conditions. Today, we have learned that global warming is strongly correlated with anthropogenic activities resulting in GHG emissions. A large portion of these emissions consists of energy related emissions. A relatively smaller share belongs to process emissions, resulting mainly from industrial activities. Forecasting future energy uses and industrial activities necessitate the adoption of various assumptions. Depending on the characteristics of the adopted assumptions, the collection of which is referred to as a scenario, different evolution predictions have been obtained in the literature [11] [12] [13] [14] [15].

Having accepted the reality of climate change, one category of works in the literature has concentrated on studying the potential impacts of climate change [16] [17] [18]. A sub-category of works concentrate on physical impacts [19] [20] [21] [22], whereas another sub-category on socio-economic impacts [23] [24] [25] [26]. Although understanding the consequences of global warming is inarguably important, analyses are also required to assess the potential pace of the warming and to develop strategies to eliminate the further deepening of the phenomenon.

Directly related to the present study, there are also numerous efforts that discuss mitigation methods for GHG emissions. One approach involves the proposal of economic measures to reduce future emissions. The concepts of carbon taxing and carbon pricing are the results of such considerations. The effectiveness of such economic measures is a popular subject in such studies [27] [28] [29] [30].

Apart from economic measures, developing strategies to enhance the use of energy carriers with little (or no) emissions to mitigate climate change constitutes an important category of works. Promoting the use of renewables in power generation is a preferred approach [31] [27] [32] [33]. Another mitigation technique recalls the carbon capture [34] [35] [36] [37] [38].

There are many scenarios developed also by various authorities, including IPCC [8], International Energy Agency (IAE) [39] [40] [41], and other scientists [42] [43] [44] [45], intended to mitigate CO_2 emissions by various measures.

Many of the aforementioned scenarios either do not include NPPs or consider only a decreasing number of them in the future. Only a few studies gave importance to NPPs for the future energy generation mix [46] [47] [48]. The three fundamental reasons for the relatively low importance accorded to NPPs may be classified as cost, safety, and public acceptance concerns [49]. Although the discussion of the validity of these allegations is beyond the scope of this study, the author felt the need to point out strongly that the Climate Change threat is real and needs to be addressed immediately. Unless serious measures are taken in the near future, the world is approaching the point of no return. Therefore, the cost is not to be considered in decision-making; after all, with a Climate Change that has a detrimental effect, there would be no point in assessing the cost in the future.

In parallel with the motivations behind this study, a report has been published by MIT in September 2018 [50]. This report, titled "*The Future of Nuclear Energy in a Carbon Constrained World*", is the result of an interdisciplinary effort. It has initiated heated discussions among scientists because it emphasizes the importance of Nuclear Power Plants (NPPs) in reducing CO_2 emissions in the near future.

Although it is well known that NPPs, by their very nature, are low CO_2 emitters, not enough importance is attributed to the fundamental role they may play in the future energy generation mix.

Literature survey on de-carbonization reveals that the importance allocated to nuclear power plants is rather weak. Although very many scenarios have been investigated to study how CO_2 emissions can be reduced to an acceptable limit, most often NPPs are neglected/ignored, at most are taken as one of the variables in the scenario. However, it is apparent that without substantial contributions from NPPs, humanity does not seem to be capable of reducing CO_2 emissions. Recent publications emphasize the importance of NPPs, yet a sound scenario that attributes a major role to NPPs has not been fully analyzed.

1.4. Methodology of the Study

Analysis of the two very recent reports (SR-1.5 and MIT Report) reveals that combining the outcomes of the two into a single study will be a fruitful challenge. The majority of the scenarios studied in the literature survey, consider global warming of 2°C. However, the former report clearly indicates the need to lower this 2°C temperature increase down to 1.5°C. This reduction in the global warming upper limit constitutes the foremost motivation for this study. Second, it is intended to compensate for the lack of importance attributed to NPPs in previous studies.

This study is dedicated to the assessment of whether, through intense use of cleaner primary energy sources and energy carriers, humankind can remain within the emissions limit set by IPCC until the year 2100. To this end, it is necessary, to begin with identifying the current sources of CO_2 emissions. Next, in an unbiased manner, the evolution of each individual source needs to be predicted until 2100. This analysis has been performed by dividing emission sources into economic sectors, as frequently done in the literature.

Emissions from each economic sector have been forecasted by predicting the relative magnitude of activities within the sector in the future and correlating these activities to emissions. The former needs to be evaluated objectively, i.e., independent of any specific effort intended to reduce emissions, reflecting the pure human requirement of services and goods supplied by the sector. To this end, data have been collected from various sources and compared with each other to assess their validity. Rather than employing energy demand forecasts of individual economic sectors, selected data for this study rely on the predictions of the services and goods to be provided, to the possible highest extent.

Data are available correlating economic sectors' activity to their energy consumptions and hence CO_2 emissions. The collected data provide either a current or a very recent picture of the sector. To mitigate CO_2 emissions, in this study, it is proposed to reduce the emission intensity of activities. This has been achieved by more intense use of cleaner energy carriers, which in turn rely on cleaner primary energies. In summary, activities in economic sectors are not planned to be reduced to lower future emissions, rather less emission intensive methods are employed for a given amount of activity. The pace of transition to less emitting technologies constitutes a fundamental part of the set of assumptions adopted in this study, which is referred to as a scenario, as frequently done in the literature.

The selection of cleaner energy carriers proposed in the study results in an increased electricity generation requirement. This further growth in the electricity demand, which is mitigation related, redefines the activity of the power sector. Therefore, treatment of the latter sector has been done following the completion of the analyses of the other economic sectors.

The here proposed mitigation strategy for the power sector is a transition to electricity generation employing renewables (wind and solar PV), together with nuclear energy. The latter is essential, as renewables are renowned for their lack of dispatchability. All the proposed future electricity generation technologies emit zero (or low) CO_2. To assess the emissions from the power sector, until the year 2100, it is required to develop a strategy for the composition of the sector in the future. Conditions imposed on the evolution of the sector constitute the remaining part of the set of assumptions adopted in this study, the scenario. While assessing the contribution of new power plants, it is necessary also to determine the contribution to both electricity generation and CO_2 emissions of the power plants in operation as of today. To this end, data have been collected for the inventory of power plants in operation. Findings from various sources needed to be compared to ensure their validity and data required processing to eliminate erroneous and missing information. Computer codes developed for these purposes are supplied as an open source.

Finally, the effectiveness of the proposed mitigation efforts has been assessed by calculating the cumulative CO_2 emissions from all sectors, according to the scenario developed in this study. This finding is then compared with the limit set by IPCC. Sensitivity analyses are also performed by varying the implementation pace of cleaner energy carriers and the long-term evolution of the goods and services supplied by the economic sectors.

Details of the calculation steps, as well as computer codes employed for processing power plants under operation will be shared as an open source through OpenMETU.

1.4.1. Novelty Brought by the Study

The current study aims at reducing cumulative CO_2 emissions until 2100 below the recently revised limit set by IPCC. Recognizing that the major provenance of the CO_2 emissions is the energy consumption, the intended reduction can be achieved by either reducing the activities in the economic sectors, or increasing the energy efficiency of the employed processes, or finally by employing cleaner energy carriers.

The majority of the studies presented in the literature attack the problem limiting activities in the sectors, namely the demand. Energy efficiency improvements have also been investigated intensively. However, this study is dedicated to the use of cleaner energy carriers (which in turn are produced from clean primary energy sources) while depriving the evolution of the demands for goods and services, as well as the energy efficiency of the processes from all mitigation related efforts. Hence, it is the effectiveness of the sole use of cleaner sources, that has been assessed.

Demands for each economic sector have been collected from various independent sources, compared among, and processed until readied to be used in the study. The evolution of demands is not available in the literature, beyond 30 or 40 years. Hence, extrapolation of these demands constitutes part of the study-specific characteristics.

The study of cumulative emissions until 2100 necessitated the development of a scenario that incorporates the evolution pattern of demands (for goods and services, hence for energy) in economic sectors. In addition, a strategy needed to be developed for the future composition of the power sector. Phasing out of the power plants currently in operation, together with the composition of the "to be constructed" power plants, has been realized according to the author's determination. New power plants have been selected to have a share in renewables increasing gradually to 50%, whereas the remaining electricity demand is fulfilled with nuclear.

1.4.2. New Energy Carriers

Reducing CO_2 emissions requires the substitution of fossil fuels with other energy carriers. Through the evolution of the study, it has been recognized that the use of biomass for heating and cooking applications also constitutes a major source of emissions. In this study, to mitigate the CO_2 emissions, the use of electricity as the preferred energy carrier over fossil fuels and biomass has been proposed. Existence of conditions, where the direct use of electricity has not reached maturity under current technological considerations has been identified. In such cases, it has been recommended to use of electrolytic hydrogen as the second choice for an energy carrier.

Employing electrolytic hydrogen as a carrier to supply thermal energy incorporates a significant inherent inefficiency. The thermal energy intensity of hydrogen cannot exceed its Higher Heating Value (HHV), which is approximately 142 MJ/kg. In the majority of the processes, thermal energy that can be recovered from the combustion hydrogen falls below its Lower Heating Value (LHV), which is 120 MJ/kg. Some improvements in the efficiency of electrolysis of water are expected. Several different technologies are being used and proposed for the future, including alkaline, Polymer Electrolyte Membrane (PEM), and Solid Oxide electrolyzer technologies. It has been concluded that with mature technologies hydrogen production via electrolysis requires an energy intensity of 180 MJ/kg. Therefore, the use of electrolytic hydrogen for thermal energy generation requires 1.5 times (180 MJ/kg versus 120 MJ/kg) more electricity when compared to the direct use of electricity to produce the same amount of heat.

Both uses of direct electricity and electrolytic hydrogen will necessitate an extra electricity generation capacity. To minimize the future emissions, technologies, which are considered zero (or almost zero) CO_2 emitting, have been selected in meeting this additional electricity demand: renewables and nuclear. As will be discussed in detail, the use of electrolytic hydrogen serves also as a storage mechanism, which is known as "hydrogen buffering" in the literature.

1.4.3. Electricity Generation Mix

Priority is given to renewables in electricity generation, as they have a much higher public acceptance over NPPs. However, finding a solution to the power generation solely using renewables is not practical with today’s technologies. Renewables suffer deeply from their lack of dispatchable generation capabilities. They cannot provide reliably the instantaneous electricity demand. Electricity storage has been long discussed, but no mature technology, other than the very limited hydro, is available. Hence, a supporting generation capacity is required: NPPs have been the proposed to fulfill this requirement in this study. This additional capacity is referred to as the dispatchable generation capacity in the literature.

1.4.4. Mature Technologies Only

In this study, while determining the energy generation mix that will reduce the CO_2 emissions, only mature technologies have been employed. This can be justified by underlying that the adopted proposal should represent a feasible strategy, deprived of "fictions". An independent description of the notion of “mature” can be taken from IEA [40]: “*commercial technology types that have reached sizeable deployment and for which only incremental innovations are expected*”. This requirement of the use of mature technologies restricts the choice for the types of both renewable and nuclear power plants.

For renewables, only wind turbines (both onshore and offshore) and solar PV (Photovoltaic) shall only be considered. It may be argued that hydroelectric power plants should be included in the list. However, the latter type has already reached a high penetration worldwide and new constructions will only serve as a life extension of the already operating ones. Solar concentrated power plants have the advantage of storing the energy overnight; however, limited data are available to assess their load factors throughout the world. Therefore, in this study, solar power plants have been modeled as composed of PVs only.

Availability of a mature technology is also limiting the selection of the NPP type to be employed in the analysis. Hence, in the analysis it has been assumed that dispatchable electricity generation will be supplied by Light Water Reactors (LWR). The sub-type that is considered is the Pressurized Water Reactor (PWR), for which humankind has an operating experience, by a large margin when compared to other reactor types. High Temperature Gas Cooled Reactor (HTGR) or Liquid Metal Fast

Breeder Reactor (LMFBR) have a much higher potential in supplying the electricity demand, yet they cannot be considered as mature (as PWRs).

1.4.5. Analysis of the Evolution in Time

The time interval intended for modeling is the period covering the years 2020 to 2100. To make a realistic prediction of the future, a scenario has been developed stripped of all prejudices. In the light of the special report by IPCC [8], it is clear that moderate scenarios cannot satisfy the 1.5°C limit. Therefore, it is intended to develop scenarios aiming at satisfying the 1.5°C criterion.

To perform the cumulative CO_2 emission calculations, targets have been set for the pace of transition from fossil fuel and biomass to new energy carriers of electricity and electrolytic hydrogen. In parallel to the transition to the new energy carriers, electricity generation capacity should grow. Therefore, growth in the new generation energy mix has been modeled accordingly.

Undoubtedly, already operating power plants will continue their operation for quite some time. However, to mitigate the CO_2 emissions, contribution of the fossil-fueled power plants to electricity generation needs to be maintained at lowest possible level. Therefore, a practical target has been set for the current plants in operation. It has been assumed that all coal-fired power plants will be decommissioned by the end of 2030. All other plants will continue their operation until they reach the average plant life of the corresponding type.

1.4.6. Additional Assumptions

It is important to underline that for the sake of this study, carbon capturing and negative CO_2 emission methods have been excluded, on the basis that they lack commercial availability. Proposed carbon capture technologies have not been commercially demonstrated and therefore they have not achieved the required maturity level. Beyond its economic feasibility, carbon capture technologies need to be debated on their technical feasibility. Therefore, the mitigation efforts are restricted to the use of cleaner energy carriers. Carbon capturing in the form of production of biofuels is a viable option, but the availability of the land and climate conditions are beyond the scope of this study.

Similarly, when CO_2 emissions are taken into account, commercial heat supply, which includes district heating, cannot be maintained in its current status. Almost all, commercial heat supply relies on fossil fuels, biomass, or waste combustion, which emit large quantities of CO_2. Therefore, to reduce emissions, all such operations need to be replaced with electric energy carrier, which can readily be converted into heat.

Finally, in this study, the analysis has been restricted to CO_2 emissions only. Therefore, all other gaseous emissions (CH_4, N_2O, and others) that contribute to global warming are left outside the scope of the analysis. Their ongoing production worsens climate change, but their effects are not considered here and the presented mitigation efforts apply to CO_2 emissions only.

Fundamental assumptions in this study are summarized below for ease of referral:

- As new energy carriers, electricity, and electrolytic hydrogen are proposed,
- New power plants will consist of wind turbines (onshore and offshore), solar PV, and NPPs only,
- All coal-fired power plants will be decommissioned by the end of 2030,
- All other power plants currently in operation will be decommissioned at the end of the average lifetime corresponding to the type,
- Commercial heat supply will be substituted by electricity,
- Among GHG, only CO_2 emissions are considered,
- Remediation efforts rely solely on mature technologies,

- Carbon Capture Technologies are excluded from the study.

1.5. Review of the Terminology

Summary of some of the terminology (definitions) frequently used in the literature, which are also adopted here, has been provided, in addition to the list of assumptions to ease the reading of this dissertation. This will eliminate possible misinterpretations of the presented discussion. Following the definition of the GHG emissions, here are the terminology employed frequently in the literature:

Greenhouse gases (GHG) are the gases that trap heat in the atmosphere. [2]. CO_2, CH_4, N_2O, and Fluorinated Gases are the major GHGs.

The carbon budget refers to the cumulative CO_2 emissions that will limit global warming in a given period [8].

VRE stands for Variable Renewable Energies, such as wind and solar PV. The term "variable" is used to express the characteristics of the relevant plants, of not being able to provide electric energy reliably and predictably [46]. Plants with the capability to supply the electricity in a reliable and predictable way, i.e., whenever there is an electricity demand is referred to as **dispatchable** units.

Hydrogen buffering refers to the technology of storing excess electricity production as electrolytic hydrogen. A network of electrolyzer facilities is kept on standby to convert any excess energy in the electric grid to produce hydrogen.

Commercial Heat is the heat sold to a different end user [51]. This includes both district heat applications, as well as the exchange of heat between neighboring industrial facilities.

The analysis of the industry (economic) sector can be best presented with the use of the following notions [52]:

Direct Emissions result from industrial production, excluding those embodied in purchased electricity, heat, and steam. It proves useful to study those under two sub-categories:

- **Energy Related Emissions** result from the combustion of (carbon containing) fuels (including, coal, oil, and natural gas) supplying the energy demand in industrial processes.
- **Process Emissions** result mainly from chemical reactions other than the combustion of fuels, which are accounted for in Energy Related Emissions. Process Emissions originate primarily from calcination reactions (in cement and lime production), production of hydrogen (which enters chemically into the process) from either natural gas or coal, reactions occurring at the electrodes in molten oxide electrolysis (such as the one used for aluminum production).

Indirect Emissions occur during the generation of the electricity, heat, and steam purchased by the industry sector. They are produced in entities separate from the industrial facility of interest.

The concepts of Direct and Indirect Emissions are also useful in understanding the structure of the buildings sector. Similarly, the generation of electricity and commercial (district) heat employed in the buildings are responsible for indirect emissions. However, in the buildings sector, fossil fuels and biomass are mainly used for heating and cooking applications, thus produce direct emissions.

1.6. Structure of the Thesis

Upon expressing the motivation behind and aim of this study, works in chapters dedicated to the specific analysis of economic sectors, responsible for heavy CO_2 emissions are presented. According to a study by IEA [41], economic sectors are ranked as power, industry, transportation, and buildings, in decreasing order for emissions. Shares of sectors in CO_2 emissions in 2020 are given in Figure 1-1.

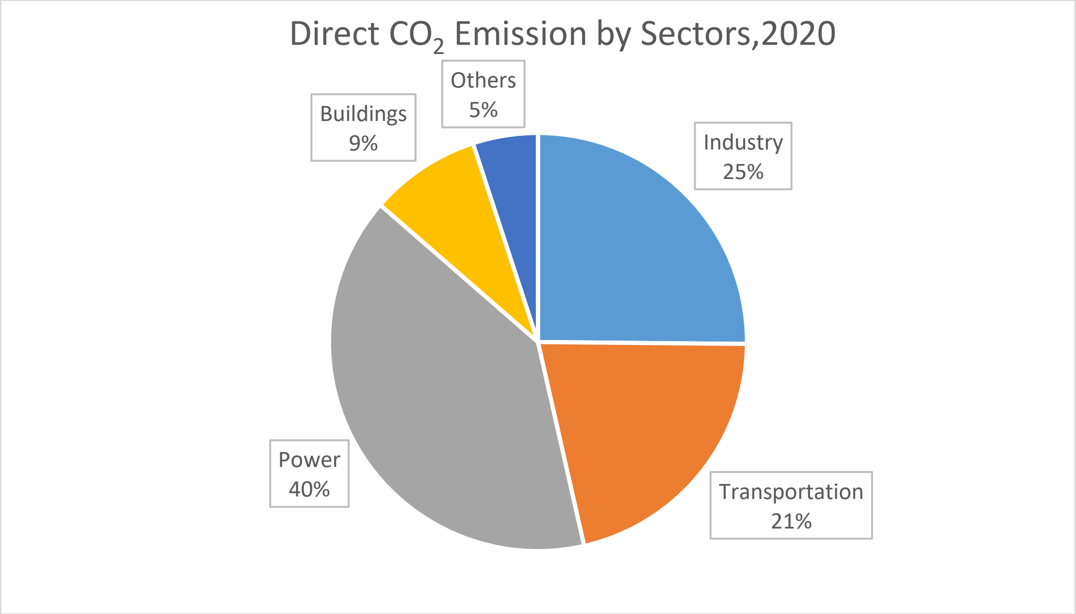

Figure 1-1 Direct CO2 Emissions by Sectors [41]

While investigating each sector, a basic scenario has been developed, which is referred to as REALISTIC. Alternative scenarios are also studied to assess the sensitivity of the results to the adopted assumptions. The first category of alternative scenarios differs from each other by the penetration speed of the newly proposed energy carriers. A slow pace of penetration is analyzed under the RELAXED Scenario, and a fast pace in the AGGRESSIVE Scenario, both in comparison to the basic one, REALISTIC. In the second category, long-term (beyond the last year for which forecast is available) demand trends in the sectors have been modified. All these demand scenarios are modifications of the REALISTIC, with long-term demand being fixed (FLAT), proportional to world population (POP), and proportional to gross domestic product (GDP), in all sectors. All analyses are performed for the period 2020 – 2100.

The following chapter (Chapter 2) is dedicated to the analysis of the industry sector. Demand for fundamental industrial products, which consist of steel, cement, and chemicals, are collected from the literature. Reliable forecasts are available until 2050. Beyond 2050, it has been assumed that demand for industrial products has already reached saturation, therefore the demands will remain fixed in the years after

2050 (as in the case for FLAT Scenario). It has been concluded that, because the required level of maturity has not yet been achieved, direct use of electricity in the industry sector is restricted to some limited applications in the chemical sub-sector and sub-sectors other than steel, cement, and chemical [41]. Hence, electrolytic hydrogen is recommended as the dominant future energy carrier for the sector. Additional electricity demand resulting from the use of electrolytic hydrogen and the extra direct electricity has been determined. Reductions that can be achieved in CO_2 emissions from the sector are then evaluated.

In Chapter 3, the transportation sector has been analyzed. Forecasts for sectoral demand (which is referred to as transport activities) were available until 2050. Beyond 2050, it has been assumed that these activities will grow in parallel to GDP (as in GDP Scenario). To mitigate emissions, the use of both electricity (directly) and electrolytic hydrogen have been proposed in the sector. The additional electricity generation capacity needed for this transition has been determined along with the reductions that can be obtained in CO_2 emissions.

Chapter 4 is allocated to the analysis of the buildings sector, for which forecasts were available until 2060. Beyond 2060, it has been assumed that energy demand in the sector will grow proportionally with the world population (as in the POP Scenario). The use of electrolytic hydrogen does not seem practical for the sector; hence, a transition to direct electricity consumption to meet the energy demand has been proposed. Additional capacity resulting from the transition and the associated saving in CO_2 emissions are evaluated.

In Chapter 5, power plants throughout the world, which are currently in operation, have been analyzed. The time by which each power plant will be decommissioned, has been determined per the assumptions adopted in the study. This allows the forecast of electricity generation by today’s operating plants. Hence, the electricity supply from today's power sector and the resulting CO_2 emissions are evaluated.

Chapter 6 describes the evolution of the power sector. In chapters 2 through 4, additional electricity requirements from economic sectors undergoing a transition to new energy carriers of electricity and electrolytic hydrogen have been determined. To this extra demand, forecasts for the electricity demand (which is independent of the transition to new energy carriers) in all sectors have been added. Thus, a forecast for the overall electricity demand until 2100 has been performed. Chapter 5 provides the amount of electricity that can be supplied by today's power plants. The gap between the demand and supply has been filled with a properly balanced wind turbine, solar PV, and nuclear power plants. Towards the end of the chapter, the future installed capacity that is required for meeting the demand has been presented. Drawbacks of the resulting extremely large capacity have also been investigated.

In Chapter 7, cumulative emissions in various scenarios developed in the study have been analyzed. It has been determined that meeting the 1.5°C global warming limit by 2100 requires additional measures that are not included in this study. Possibility of further measures in reducing the emissions, as well as possible improvements to the present study are discussed at the end of the chapter.

CHAPTER 2

INDUSTRY SECTOR

According to IEA, the industry sector ranks second after the power (Electricity Generation) Sector in CO_2 emissions [41]. IEA estimated that the industry sector alone is responsible for the emission of 8.5 Gt CO_2 in 2018 [53]. This figure reflects only the direct emissions. The intense use of electricity in the industry results in considerable emissions, which are classified under indirect emissions and discussed in the later chapters of this study. To emphasize further the importance of the industry, it is worth mentioning that the sector consumes almost 40% of the World's primary energy source supply [52]. To develop a strategy to reduce CO_2 emissions in the industry, it is essential to identify their sources. This sector contains a large number of sub-sectors with quite distinct emission characteristics [54].

It is not practical to analyze the entire industry sector due to the vast variety of the sub-sectors. Nevertheless, it is important to identify that almost 2/3 of CO_2 emissions from the industry result from three main sub-sectors [52]:

1) Iron and Steel
2) Cement
3) Chemical

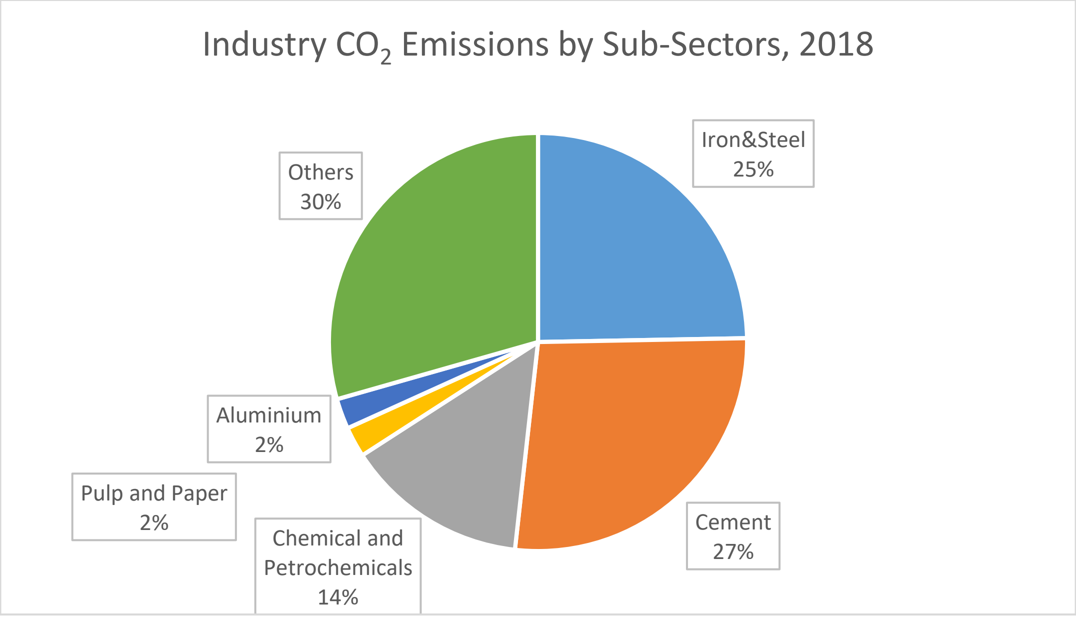

Figure 2-1 Industry CO_2 Emissions by Sub-Sectors, 2018 [53]

The distribution of emissions among sub-sectors, which is shown in Figure 2-1, underlines the importance of the selected three sub-sectors. A strategy developed for these sub-sectors will not only be meaningful in reducing emissions substantially but will also provide guidance for the remaining sub-sectors. The chemical sub-sector is itself very diversified and its analysis will shed light on the possibility of CO_2 emission reduction potentials in almost all other sub-sectors.

The aluminum and paper industries are renowned for being energy intensive sectors, yet they are not analyzed in this study. One major reason, especially valid for the former, is that the share of electricity among energy carriers is already very high. Aluminum production relies on the electrolysis of bauxite, which consumes large quantities of electricity. Emissions from the aluminum industry are extremely small compared to sectors that are analyzed in this study, as can be seen in Figure 2-1. The majority of these emissions are due to process emissions, resulting from the erosion of the employed graphite electrodes. Eliminating or reducing emissions from the aluminum industry will bring only limited improvement, as its contribution to overall emissions is small. Furthermore, such reductions can be achieved by using alternative electrodes, which are not included in the scope of this study. Similarly, the emissions from the paper industry are small enough to be considered for mitigation; hence, the sub-sector is not included in the analysis.

Even though literature includes many suggestions on lowering energy intensity through technological breakthroughs and innovation, to reduce CO_2 emissions, the potential savings are not expected to exceed 20% [9]. Therefore, major changes in the energy arena of the industry sector need to be implemented. In this study, the strategy of switching to primary energy sources, which emit negligible CO_2 have been investigated.

This chapter is structured such that each of the three CO_2 emission dominant sub-sectors is analyzed separately. The fundamental reason behind this division is the diversification in the means of emissions in each sub-sector. The findings in these three sub-sectors have been combined to provide a broader opinion on the entire industry sector.

2.1. Iron and Steel Sub-Sector

OECD and IEA agree on the fact that, when all the sub-sectors are examined, the Iron & Steel sub-sector ranks second in the emission of CO_2, after the Cement sub-sector [52]. However, the author would prefer to begin the investigation with the Iron & Steel Sector, because as will be shown in detail, it incorporates a larger potential in decreasing the CO_2 release rates to the atmosphere.

World Steel Association [55] is considered to be the most reliable supplier of production rate data and many authorities employ their statistics in analyzing the sector. World Steel indicates that in the year 2019, the world's "crude" steel production has been on the order of 1.88 Gt. World Steel also performed studies in determining the energy and CO_2 emission intensities of the sector and concluded that the current value for the latter is on the order of 1.83t CO_2 per ton of crude steel. This figure however contains both direct and indirect emissions in steel manufacturing.

To attack the problem of developing strategies to reduce CO_2 emissions, the nature of these emissions need to be better understood. To this end, studies performed by IEA and OECD, which have investigated the emission aspect in further depth, have been consulted. The conclusion is that the current direct emission intensity of the sub-sector is around 1.4t CO_2 per ton of Crude Steel. Accordingly, 2.6 Gt CO_2 is estimated to be released to the atmosphere, via direct emission pathway. IEA further states that another 1.1 Gt of CO_2 has been emitted in 2019 when indirect emissions are considered [56]. This figure corresponds to an indirect emission intensity of 0.58t CO_2 per ton of Crude Steel. In the present study, indirect emissions will be accounted for while performing the investigation of the Power sector, as they are mainly related to the electricity consumed in steel making. Therefore, in the remaining sections of the chapter, direct emissions only have been scrutinized.

It is important to emphasize that emission rate estimates differ substantially in the literature. The fundamental reason for these discrepancies lies in the selection of emission pathways. Unfortunately, a common terminology is not in place yet, therefore, while analyzing data, it becomes essential to identify the content of the reported emissions. As an example, Worldsteel uses both direct and indirect emissions in their reports, whereas IEA and OECD provide these data separately. In one IEA report [52], it is stated that the Iron & Steel sub-sector is emitting 2.1 Gt CO_2 yearly. However, the IEA report dedicated to the Iron & Steel sub-sector raises this last emission figure to 2.6 Gt CO_2 [56].

The discrepancy between the two figures provided by IEA comes mainly from the inclusion of emissions from coke ovens, in the latter. The vast majority of the coke produced in these ovens is used in the iron & steel industry. Only a very small fraction of the coke is used for electricity or heat generation. Authorities, such as IPCC, tend to classify coke ovens in "other industries", rather than including them in Iron & Steel. Therefore, the yearly emission rate of 2.1 Gt does not include the operation of coke ovens, whereas the 2.6 Gt figure incorporates emissions resulting from the preparation of the fuel for the blast furnace (coal to coke conversion).

In this study, the 2.6 Gt CO_2 yearly emission rate figure has been adopted as a reference, after all, almost all produced coke are used in steelmaking. The suggested mitigation for CO_2 emission reduction will affect both steel manufacturing and coke production.

Process emissions in the Iron & Steel Sector take a small share in direct emissions. IEA estimated that in 2019, 0.3 Gt of the 2.6 Gt CO_2 emissions are process emissions [56]. The two fundamental sources for process emissions are the limestone added to the iron ore to adjust the viscosity of the slag produced in blast furnaces and electrodes used in ferroalloy production. Limestone added to the iron ore transforms into quicklime by releasing its carbon dioxide. Graphite is considered an ideal electrode in molten metal oxide electrolysis applications, due to its high electric conductivity, low cost, and chemical stability. Therefore, just like in aluminum production, ferroalloy production heavily relies on the use of graphite electrodes, which in turn emit large quantities of CO_2.

Steel is among the goods that can be recycled very effectively. Furthermore, it is considered that it has the potential to be recycled indefinitely. Therefore, many scenarios available in the literature emphasized the recycling aspect to reduce CO_2 emissions [57]. Nevertheless, recycling alone cannot meet the future steel demand. Steel manufacturing using scrap steel has much lower energy intensity. Furthermore, the addition of scrap steel to iron produced from ore is a common practice, as it improves the performance of the process [56]. However, collection of the steel for recycling requires also the establishment of an effective network, which may not be established readily, when economical and geopolitical considerations are taken into account. Furthermore, scrap steel may not contain a high level of other materials that can act as impurities depending on the application [58].

IEA and OECD predict that the production of steel from iron ore will continue to be the dominant pathway, especially with the ongoing increase in world population and living standards [56] [59]. The production of steel from iron ore begins with the manufacturing of metallic iron, hence the sub-sector is being referred to as Iron & Steel.

Currently, the majority of the metallic iron produced from ore is obtained in the form of pig iron, which contains a large amount of carbon. Pig iron used in steel production comes from the Blast Furnace-Basic Oxygen Furnace (BF-BOF) pathway. The fundamental energy source in this process is coal. Blast furnaces require high-quality (rich in carbon) coal to operate. In practice, high-quality coals, classified under hard coals or brown coals, undergo a process called coking, before being fed to blast furnaces. The pre-processed coal is referred to as the coke. The carbon abundantly present in coke, interact both with the blown air and the iron ore, via exothermic reactions. These reactions generate the heat required for the operation of the blast furnace and reduce the iron oxide in the ore to the metallic iron. The high concentration in the blast furnace results in the dissolution of the carbon in the produced metallic iron and the finished product is called the pig iron.

BF-BOF pathway relies on the availability of high-quality coal (suitable for coking). Lack of availability of such high-quality coal led to the development of another technology, called the Direct Reduced Iron-Electric Arc Furnace (DRI-EAF). India which is one of the major consumers/producers of iron/steel, currently depends heavily on this relatively new pathway, to produce iron. DRI-EAF uses hydrogen, rather than carbon or carbon monoxide as in the case of the BF-BOF pathway, to chemically reduce iron oxide into metallic iron. Today’s practice is that the hydrogen required in DRI-EAF be produced from natural gas.

The main justification for the production of hydrogen from natural gas is primarily financial. In today's condition, the cheapest hydrogen is produced from natural gas, however, with a great disadvantage of emitting large amounts of carbon dioxide in the process. To reduce CO_2 emissions in the future, the use of the mature DRI-EAF technology is being proposed, however employing electrolytic hydrogen, which in turn relies on the electricity generated from renewable sources and/or nuclear power plants.

Although DRI-EAF has reached a high level of maturity, mostly thanks to the lack of availability of high-quality coals in local markets, is prone to further improvements. Today, DRI-EAF is more selective on iron ore, when compared to BF-BOF technology. DRI-EAF requires that the iron ore be pelletized, hence not all ores can be suitable for use in the pathway. However, these difficulties are expected to be overcome with the future wider use of the technology globally. Also, current operations involve the supply of some carbon monoxide together with hydrogen, as natural gas is being pre-processed. The presence of the former also contributes to the chemical reduction of iron oxide to metallic iron. Therefore, when pure hydrogen is to be used, further modifications or improvements may become necessary. Again, these developments are expected to occur in the course of the spread of the technology.

2.2. Cement Sub-sector

It is accepted that the Cement sub-sector is the most CO_2 emitting sub-sector within the industry [60] [52]. In this study, mitigation in cement is treated after the iron and steel sub-sector, mainly because the majority of the CO_2 emissions in cement production are due to the industrial process itself and are not energy related. Hence, reduction in process emissions cannot be achieved through a switch to carbon-free energy supplies, which constitutes the fundamental objective of this study. Therefore, the room for improvement in CO_2 emissions is restricted to the relatively lower energy related emissions.

Analysis of the cement industry reveals that currently 0.54t CO_2 is being generated on average, for a ton of cement production [61]. These emission intensity figures only reflect the direct emissions from the sector. It has been observed that intensity figures may be higher, however, these sources include the emissions from transportation of the product to the construction sites. The latter term is included in the investigation of the transportation sector in this study.

The relatively smaller mitigation prediction in CO_2 emissions from the cement sub-sector, which amounts to 2.2 Gt CO_2/yr, is primarily due to the large Process CO_2 generation during clinker production, which is the fundamental constituent of cement. It is being predicted that of the 0.54t CO_2 emitted per ton of cement, 0.34t originate from Process emissions [61]. The primary raw material for clinker production is limestone, which may chemically correspond to $CaCO_3$. In today's prevailing technology, limestone is reduced to quicklime (in chemical terms, CaO) in the kiln (the slowly rotating furnace), and thus produced CO_2 is released to the atmosphere. A large portion of the CO_2 emissions occur during this reduction process: the CO_2 resulting from the chemical reduction is released (namely the process CO_2), in addition to the combustion products of the fuel that supplies the necessary heat for the reaction to occur. It is the latter, which is referred to as energy related emissions that are intended to be reduced in this study.

The cement industry relies heavily on coal as a fuel, mainly because of economical reasons. It is also important to emphasize the fuel, consumed in the kiln, burns in an environment where large amounts of alkaline products (lime) are present. This allows the possible capture of the unwanted SO_2 or SO_3 (also referred to as SO_x), which are responsible for both acid rains and greenhouse effects. Furthermore, the presence of sulfates in the clinker is a desired quality, in the production of cement.

The combination of a strongly alkaline environment together with the high combustion temperature in the kiln (which typically operate around 1,450°C) renders cement factories ideal for the consumption of low-quality high sulfur content fuels (such as low-quality coal and petro-coke) and also for incineration of various wastes. These wastes include old tires, waste oils, various municipal wastes, wastewater treatment plant sludge, plastics non-suitable for recycling, and organic wastes. It is a common practice that cement production facilities are regarded as an integral part of waste management systems, especially in developed countries. To this end, it has been assumed that 10% of the energy needed for clinker production will be supplied from waste incineration, even in the future.

2.2.1. Material efficiency suggestions in the literature

Many authorities recognize the cement sub-sector as the most CO_2 emitting sector. To reduce future CO_2 emissions, however, recommendations focus primarily on the reduction of the use of cement in construction, and the reduction of clinker content of cement.

The former goal can be achieved either by increasing the awareness of the adverse effects of the use of concrete in global warming or by increasing the performance of the concrete using the same amount of clinker. The relatively low price of concrete, when compared to other construction materials, makes its unnecessary use or its overuse a common practice. Increasing awareness through education may reduce this unnecessary use of concrete, hence the cement.

The performance of concrete relies heavily on the aggregates employed. IEA emphasizes that when proper aggregates are used and concrete is prepared in controlled conditions, concrete properties are improved [57]. However, increasing the performance of concrete may not be easy. This is because, concrete is produced locally, very close to its final application point. Hence, concrete production centers are widely spread, small-scale utilities, where economic considerations are dominant. Therefore, enforcing the use of quality (but typically more expensive) aggregates or a controlled environment for mixing seems prohibitive.

Another proposed technology to reduce the clinker content of cement is to use alternative materials to clinker, at least to a degree [61]. This approach is the most promising pathway and has already a high level of maturity. Proposed alternative materials include both natural (namely, pozzolanic materials) and anthropogenic products, such as blast-furnace slag and fly ash. All these materials are successfully being added to cement, and a large amount of experience has already been accumulated. The difficulty encountered in the use of these materials lies in their availability. Just like the iron and steel sub-sector, the cement sector is very competitive. Therefore, local production is important to minimize transportation costs. The lack of local availability of the mentioned products limits their use globally. Furthermore, state regulations vary from country to country, again mostly because of economic considerations of the countries, therefore a globally accepted standardization of the slag or pozzolan added types of cement has not been established [61].

2.3. Chemical Sub-sector

The chemical (industry) sub-sector ranks third in terms of CO_2 emissions, following Iron & Steel and Cement sub-sectors. Investigations in the year 2017, performed by OECD and IEA, reveal that the Chemical sub-sector is responsible for 1.5 Gt CO_2 direct emissions [62]. Approximately, 1.3 Gt CO_2 emissions are due to energy-related emissions, whereas the remaining 0.2 Gt CO_2 figure is related to process emissions.

The analysis of the Chemical Sub-sector is more involved than the previous two sub-sectors because it incorporates several different sub-sectors, which in turn are very diversified. In the literature, to resolve the issue, emission dominant sub-sectors of the Chemical sub-sector are being assessed independently. This common procedure has been adopted in this study as well. However, at this point, it is required to present a few terminologies that are frequently employed in the study of the Chemical sub-sector.

Chemicals such as light olefins (ethylene and propylene) and aromatics (benzene, toluene, and mixed xylenes [BTX]), typically called "High-Value Chemicals" (HVCs). HVCs may be considered as being the raw materials for the plastic industry. Because HVCs are being produced from oil and gas, many published statistics rank their production high on CO_2 emissions. However, as oil and gas are employed as feedstock and are not subject to combustion during manufacturing, CO_2 emissions should be treated with care [62]. Together with ammonia and methanol, HVCs constitute an important ensemble in the chemical sub-sector, which is referred to as "Primary Chemicals". Ammonia is indispensable for fertilizer production, which is essential to maintain agriculture at its current level. Methanol, on the other hand, is used throughout the chemical sub-sector, including the manufacturing of plastics.

It is accepted that currently, Primary Chemicals’ production is responsible for 2/3 of the energy consumption in the Chemical Sector, hence 2/3 of the energy related emissions [62]. When process emissions are also considered, roughly 60% of CO_2 emissions result from the production of Primary Chemicals as shown in Figure 2-2. Therefore, mitigation methods employed for primary chemicals can equally be effective for other sub-sectors within the Chemical sector. Using proportionality, potential savings in CO_2 emissions from the entire chemical sub-sector may be estimated. Taking into consideration the vast variety of energy related processes in the sub-sector, it is recommended to switch to hydrogen fuel generated from low/no carbon emitting sources, to reduce emissions in the future. Direct use of electricity may also be an alternative, given the lower process temperatures in the chemical sub-sector, in comparison to Iron & Steel and Cement sub-sectors. However, a mature electricity-based technology to be employed throughout the sub-sector has not been identified. It is not expected that the replacement of conventional fossil fuels with hydrogen will face major technical difficulties.

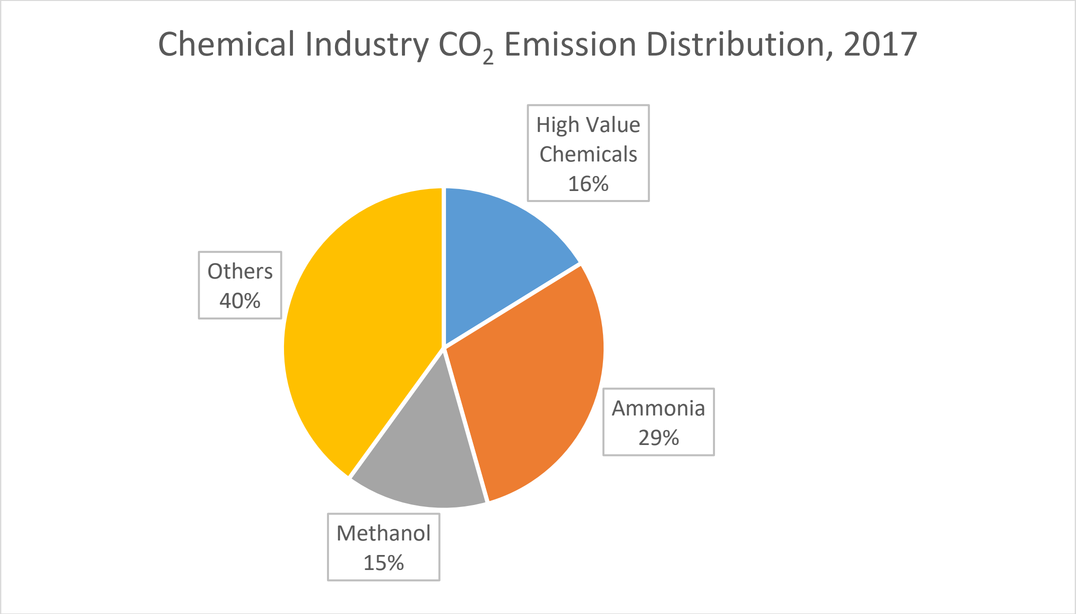

Figure 2-2 CO_2 Emissions of Chemical Subsectors [62]

The Chemical sub-sector contains further diversification within itself. However, analyses in the literature are performed by focusing on HVC, ammonia, and methanol production only, as these three are responsible for more than 2/3 of the energy demand of the sub-sector. Forecasts for the demand of these three products, which are referred to as Primary Chemicals, are taken from IEA [62] until 2050. Similarly, energy intensities are also taken from the same source, reflecting potential improvements in energy efficiencies.

2.3.1. Process CO_2 emissions from ammonia production

In the chemical sub-sector, mitigation can also be achieved in process CO_2 emissions. Process emissions are not as dominant in this sub-sector as in cement. Nevertheless, they are not negligible and methods can be proposed for reducing them, unlike in the latter.

Ammonia production alone is responsible for nearly 65% of process emissions in the sub-sector [62]. The other contributors are very diverse; hence, solely the potential in reducing process emissions from ammonia production has been investigated. The 0.13 Gt CO_2/year figure given in the literature, is not the total CO_2 generated in the yearly ammonia production. The amount of process CO_2 produced in ammonia manufacturing is 0.27 Gt CO_2. However, 0.14 Gt CO_2 resulted in the process, is then captured back in fertilizer production, which is a common practice in the sector. Capture of the CO_2 is done by the alkaline ammonia; to produce urea, a fertilizer favored in agriculture. It is the remaining 0.13 Gt CO_2 that is included in the reports, as direct emissions from ammonia production [63].

It is important to emphasize that the captured CO_2 in urea production, will be released into the atmosphere in a matter of one to two years. Urea, which is spread in the fields, will decompose with time to release its CO_2. The purpose of the employed fertilizer is to supply nitrogen to the plants and CO_2 only plays the role of a carrier. However, the CO_2 released from the decomposition of fertilizers is accounted for in the emissions from agricultural activities, which are excluded from the investigation in this study.

2.4. Methodology in this study

Due to the inherent vast diversity of the industry, the three most CO_2 emitting and also energy demanding sub-sectors are analyzed: Iron & Steel, Cement, and Chemicals. Knowing that these three are responsible for the majority of both CO_2 emissions (65%, [52]) and energy demand (60%, [52]), using their appropriate shares in the industry, releases from the entire industry sector have been estimated by the use of direct proportionality. It is assumed that the indicated shares will remain fairly constant in the future.

To predict future emissions from each sub-sector, first, future individual energy requirements have been identified. Although various forecasts are available in the literature, for the sake of consistency specific forecasts provided by IEA have been selected. IEA, which is working on different scenarios, also assesses the future of each sub-sector in their reports, titled "Roadmaps". To eliminate the effects of additional assumptions that exist in constructing a scenario, material demand for each sub-sector has been extracted. The future demand predictions by IEA that are provided in the appropriate roadmap reports are adopted in this study.

Upon determining the demand for each material (steel, cement, and chemicals), the energy that will be required for the relevant production has been identified. To this end, energy intensities (typically given in GJ/t of final produced material) have extracted, which are also available in the roadmap reports. Energy intensities vary over time, mainly because of technological advances that are expected to occur to enhance the energy efficiency of the production of the good. However, all three sub-sectors have already reached a great deal of energy efficiency. This can be explained by the long experience gained in the sub-sectors. Nevertheless, some room for improvement is still available and is taken into account in this study.

Forecast data for both material demand and energy intensity are available only until 2050. There exist big uncertainties for beyond; hence, reports do not include the relevant predictions. To perform CO_2 emission calculations until 2100 and assess whether the World can remain within the carbon budget corresponding to the 1.5°C global warming limit given by IPCC [8], forecasts have been extended beyond 2050. To this end, a linear growth rate has been adopted from 2050 to 2100. This growth can be associated with Gross Domestic Product (GDP) or with the population increase rate. In the basic scenario of this study, which is referred to as REALISTIC Scenario, it has been assumed that material demand will remain constant after 2050. One justification for this assumption is that humankind will reach a level of saturation in its use of materials, by adapting behavioral changes to achieve sustainability on Earth. In performing the sensitivity analyses, the possibility of a growth in demand beyond 2050 has been taken into account, as will be discussed in detail.

Energy intensity predictions are also available until 2050 [56], [61], and [62]. It has been assumed that these energy intensities will reach saturation by 2050 when almost all technical improvements have already been implemented. Therefore, energy intensities are taken to be constant beyond 2050, in all studied scenarios.

Using the material demand for each sub-sector, along with the energy intensity forecasts, the associated energy needs have been identified. As will be discussed in detail for each sub-sector, the predicted energy requirements should be supplied by some primary energy source. For comparison purposes, future CO_2 emission rates, based on the assumption that today's energy sources and technologies will remain valid even in the future, have also been evaluated. This scenario, which is referred to as the Business As Usual (BAU), will represent the forecast of emissions when no specific action has been taken to reduce CO_2.

To mitigate CO emissions, the use of alternative technologies and energy sources has been proposed in this study. In the specific case of industry, direct use of electricity does not seem to be a viable option, mainly because no mature technology running on electric energy exists. There are experimental studies, which will be discussed, in which either direct use of electricity or concentrated solar energy can be employed, however, they are not taken into consideration in the fundamental scenario, REALISTIC. The only reliable method that can be identified to reduce CO_2 emissions is to switch to hydrogen energy. This hydrogen will be produced via electrolysis, using electricity generated by renewables and NPPs.

To finalize emission calculations, certain targets have been set for the replacements of fossil fuels with electrolytic hydrogen. This is done by specifying the share that hydrogen will reach by the years, 2030, 2050, 2070, and 2100. Linear interpolation has been employed for determining the hydrogen share in years between. It is also assumed that from today until 2030, no change will occur in the operation of the sector, after all, transition to the new fuel is to occur with time, especially when large capital costs that exist in the sector are considered.

2.4.1. Proposed evolution of the Iron & Steel Sub-Sector

The literature contains many studies on and suggestions for the use of hydrogen and electricity in ironmaking [64] [65]. Recently, the feasibility of fossil-free iron production has been demonstrated in Sweden. [66] In this study, the basic scenario for reducing CO_2 emissions in the iron & steel industry involves a complete switching to the DRI-EAF pathway globally, from today's dominating BF-BAF pathway. Such a switch will allow the use of hydrogen as the reduction agent, as opposed to carbon, in the production of metallic iron from the ore. If the required hydrogen can be generated using electrolysis and the electricity be supplied from renewables and nuclear, a very low carbon emitting iron & steel industry will be achieved.

When realistic predictions are to be made, one needs to bear in mind that the investment costs of blast furnaces are high. Furthermore, the iron and steel industry operates under very competitive conditions, where profit margins are extremely slim. In addition, strategic importance needs to be allocated to this sub-sector, therefore many countries will be reluctant to shut down their operating facilities. This is why; it has been assumed in this study that the “business as usual” will dominate the sub-sector in the near future [40] [67]. Accordingly it has been assumed that the current full dependence on fossil fuels of the sub-sector will remain until 2030. Then, the transition will begin in 2030 to be completed in 2100. Targets for the use of electrolytic hydrogen, which are specified for the years 2030, 2050, 2070, and 2100, are presented in Table 2-1.

Table 2-1 Penetration Targets of Electrolytic Hydrogen in the Iron & Steel Industry (REALISTIC Scenario)

Year	H_2 Share (Energy)
2020-2029	0%
2030	10%
2031-2049	Linear interpolation
2050	50%
2051-2069	Linear interpolation
2070	75%
2071-2099	Linear interpolation
2100	100%

Accordingly, in the REALISTIC Scenario, it has been modeled that the hydrogen share to remain zero until 2030 and then jumps to the first target set for the year 2030. Beyond 2030, the evolution follows linear interpolation paths to reach its next target. Share values determined accordingly in the REALISTIC Scenario are presented graphically in Figure 2-3.

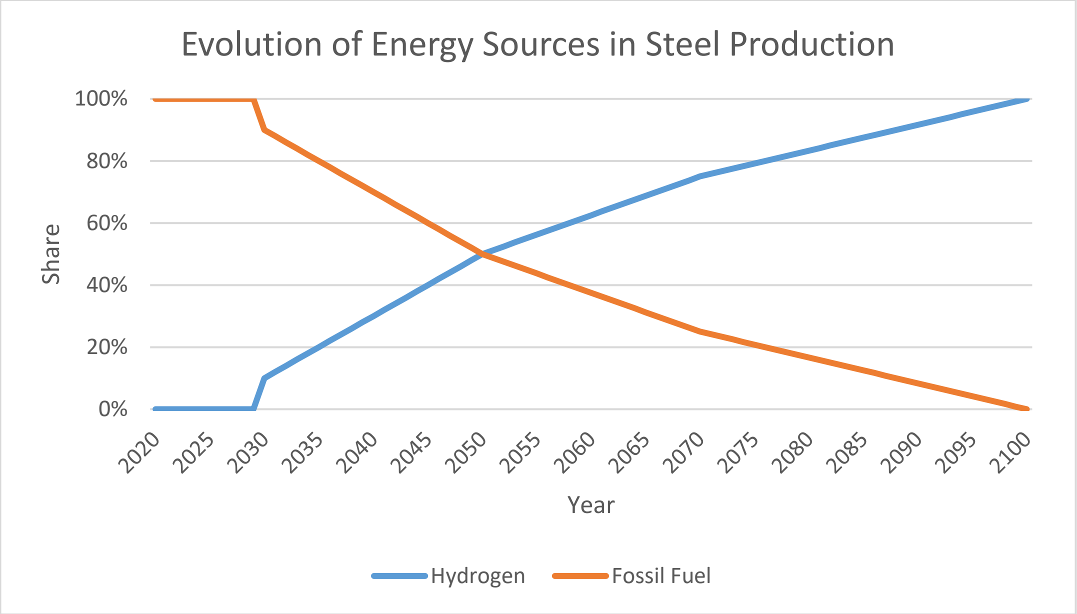

Figure 2-3 Evolution of Energy Sources in Steel Production

Share of energy carriers are denoted by $sh(H2, steel, yr)$ and $sh(fos, steel, yr)$, corresponding to electrolytic hydrogen and fossil fuels, respectively. In the developed model, they satisfy the relation:

$$sh(H2, steel, yr) + sh(fos, steel, yr) = 100\% \qquad (2\text{-}1)$$

2.4.2. Proposed evolution of the Cement Sub-Sector

It has been assumed that cement production techniques will remain fairly unchanged in the future [40]. This lead to the conclusion that the direct process CO_2 emissions in cement production cannot be eliminated. Therefore, the only amelioration can be achieved in the direct energy-related CO_2 emissions. Currently, the lion’s share in energy supply to cement production belongs to coal (almost 2/3) [68], China, which has the largest production rate of cement in the World, heavily rely on its cheap coal for its production.

The clean energy source intended for implementation in the cement sub-sector would be hydrogen. Hydrogen, although its combustion may cause many technical difficulties in practice, is expected to be readily employed in today’s operating kiln, thus replacing the coal and natural gas. Given that strategies can be developed to generate the employed hydrogen with little CO_2 emission, the cement industry's energy related direct CO_2 emissions can be eliminated. However, the author foresees that this elimination cannot be complete, due to fact that cement factories will continue to serve as waste incineration centers, as being part of future waste management strategies.

Today's waste management strategies encourage the use of some municipal waste, old tires, and similar waste as a fuel for clinker production. This also seems inevitable; as societies keep producing these wastes and one of the best management strategies includes the incineration of them in clinker production. However, IEA predicts that the share of such wastes, in supplying thermal energy to clinker will be limited to 10%. Hence, it has been assumed that in the long term, thermal energy would be supplied 90% from hydrogen produced using nuclear technology or renewables and 10% from wastes.

As in the case of the iron and steel sub-sector, the low-profit margins and high investment costs prohibit an immediate change in the sector globally. Transportation costs can readily surpass production costs, as cement is a relatively cheap material on a mass basis. Given that local production of cement is and will remain important due to economic considerations, and countries may not be very willing to rely completely on imports because of geopolitical considerations, it is not expected that a transition to hydrogen can be performed in the near future.

Accordingly it has been assumed that the current full dependence on fossil fuels of the sub-sector will remain until 2030. Then, the transition will begin in 2030 to be completed in 2100. Targets set for the use of electrolytic hydrogen, which are specified for the years 2030, 2050, 2070, and 2100, are given in Table 2-2.

Table 2-2 Penetration Targets of Electrolytic Hydrogen in the Cement Industry (REALISTIC Scenario)

Year	H_2 Share (Energy)
2020-2029	0%
2030	10%
2031-2050	Linear interpolation
2050	50%
2051-2069	Linear interpolation
2070	75%
2071-2099	Linear interpolation
2100	90%

In the REALISTIC Scenario, the share of hydrogen has been modeled to remain zero until 2030, before jumping to the first target set for the year 2030. Beyond 2030, the evolution follows linear interpolation paths to reach its next target. Share values evaluated accordingly are presented graphically in Figure 2-4.

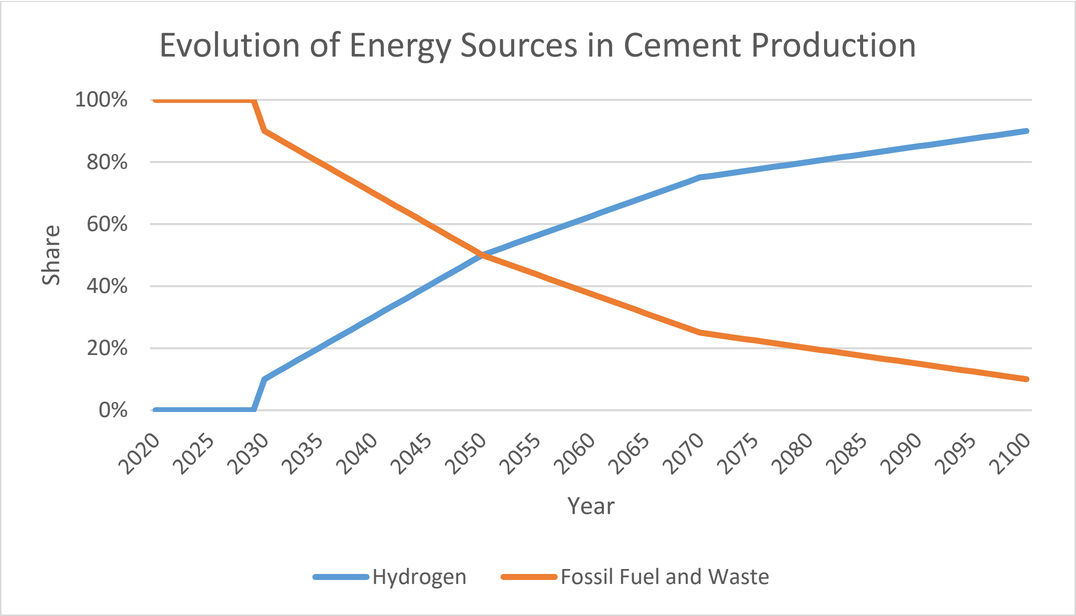

Figure 2-4 Evolution of Energy Sources in Cement Production

Share of energy carriers are denoted by $sh(H2, cement, yr)$ and $sh(fos, cement, yr)$, corresponding to electrolytic hydrogen and fossil fuels (which include waste), respectively. In the model, they satisfy the relation:

$$sh(H2, cement, yr) + sh(fos, cement, yr) = 100\% \tag{2-2}$$

2.4.3. Proposed evolution of the Chemical Sub-Sector

The major gain in CO_2 emissions reduction in the Chemical Sub-sector can be achieved by altering the energy supply. In this study, it has been proposed to replace fossil fuels with electrolytic hydrogen to reduce CO_2 emissions. A switch from fossil fuels to electrolytic hydrogen is not expected to be technically challenging, because the chemical sub-sector operates at relatively moderate (lower) temperatures when compared to Iron & Steel and Cement sub-sectors. Considering the relatively simpler furnace designs in the chemical sub-sector, a faster transition to the new fuel has been adopted, when compared to the Iron & Steel and Cement sub-sectors.

Nevertheless, one needs to bear in mind that economic viability imposes serious obstacles [69].

In comparison to the former two sub-sectors, targets that are more ambitious may be and have been set in the chemical industry. Penetration of electrolytic hydrogen as an energy carrier will begin with a jump in 2030, followed by linear growths between the successive targets set for 2050, 2070, and 2100. These selected targets are summarized in Table 2-3.

Table 2-3 Penetration Targets of Electrolytic Hydrogen as an Energy Carrier in the Chemical Industry (REALISTIC Scenario)

Year	H_2 Share (Energy)
2020-2029	0%
2030	20%
2031-2049	Linear interpolation
2050	60%
2051-2069	Linear interpolation
2070	90%
2071-2099	Linear interpolation
2100	100%

Proposed evolution of the new fuel in the REALISTIC Scenario graphically has been presented in Figure 2-5.

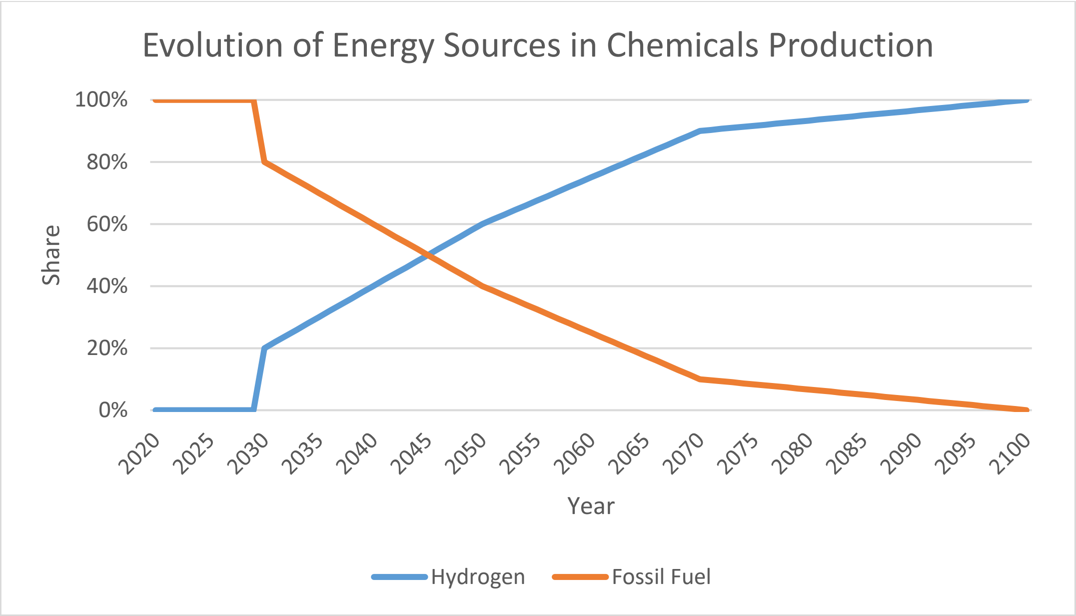

Figure 2-5 Evolution of Energy Sources in Chemicals Production

Shares of energy carriers are denoted by $sh(H2, chem, yr)$ and $sh(fos, chem, yr)$, corresponding to electrolytic hydrogen and fossil fuels, respectively. In the model, they satisfy the relation:

$$sh(H2, chem, yr) + sh(fos, chem, yr) = 100\% \qquad (2\text{-}3)$$

To mitigate process CO_2 emissions in the chemical sub-sector, substitution of fossil fuel based hydrogen production with electrolytic hydrogen has been proposed. The analysis has been restricted to ammonia production, which dominates the process emissions within the sub-sector.

The current state of the are art ammonia production relies on the Haber process, in which H_2 and N_2 react under suitable conditions to produce ammonia. Mainly because of economic reasons, currently, H_2 employed in the process is obtained using fossil fuels. Either coal gasification techniques are being used or natural gas is being subjected to incomplete combustion to produce the necessary hydrogen.

In this study, in Haber processes, the use of hydrogen generated from no/low carbon sources has been proposed. The main production method will be electrolysis using the electricity from renewables and nuclear. The technology is already mature as it uses H_2 directly. However, the production of urea may not be practical when electrolytic hydrogen is employed, because currently, CO_2 capture relies on the high concentration of CO_2 in the gas mixture resulting from partial combustion of fossil fuels used to generate hydrogen. However, this problem may be overcome by switching to the use of nitrogen-based fertilizers other than urea.

As in the case of energy carriers for the sub-sector, targets have been set for the replacement of hydrogen produced from fossil fuels with electrolytic hydrogen, for the years 2030, 2050, 2070, and 2100. They are summarized in Table 2-4.

Table 2-4 Penetration Targets of Electrolytic Hydrogen as Feedstock in the Ammonia Industry (REALISTIC Scenario)

Year	H_2 Share (Feedstock)
2020-2029	0%
2030	20%
2031-2049	Linear interpolation
2050	60%
2051-2069	Linear interpolation
2070	90%
2071-2099	Linear interpolation
2100	100%

Thanks to its low modification requirements for the use of electrolytic hydrogen, it is expected that the penetration of electrolytic hydrogen would be faster, when compared to the Iron & Steel and Cement sub-sectors. The proposed transition to electrolytic hydrogen is presented graphically in Figure 2-6.

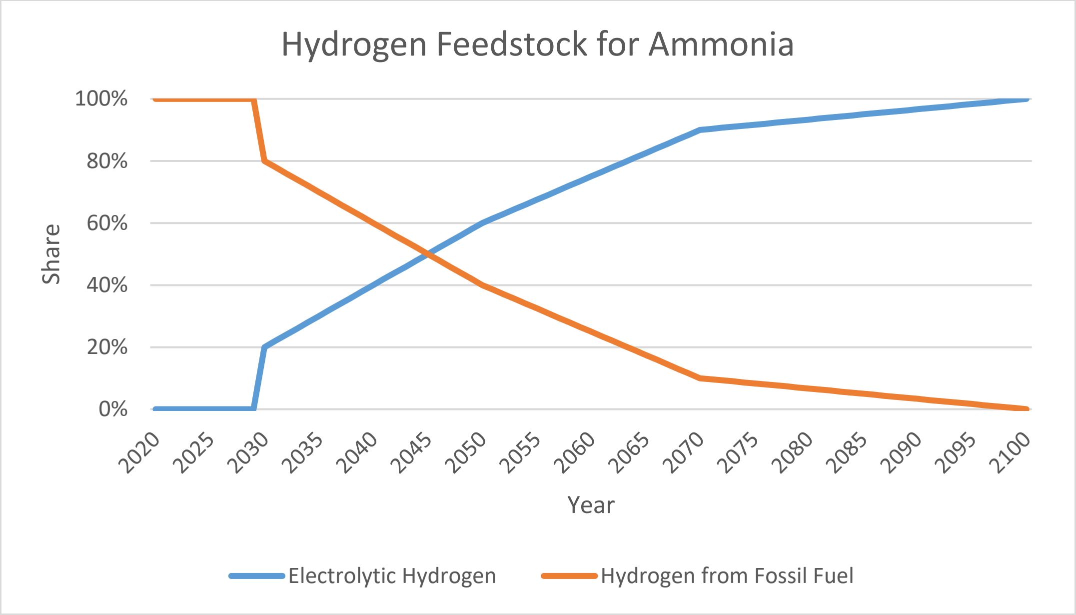

Figure 2-6 Hydrogen feedstock of Ammonia

The share of electrolytic hydrogen in the ammonia industry is denoted by $sh_p(H2, NH3, yr)$ in formulae employed in this study.

2.5. Additional Installed Capacity Requirements and CO₂ Savings

Upon determining the evolution of the share of electrolytic hydrogen in supplying the energy demand of the three sub-sectors, the analysis proceeds with calculating the additional electricity demand that will be created and the reduction achieved in the CO_2 emissions.

Details of the calculations for each of the three sub-sectors are presented below. These calculations are based on the fundamental assumptions adopted in this study, which define a scenario, namely the REALISTIC Scenario.

2.5.1. Iron and Steel Sub-Sector

Production forecasts for steel are taken from IEA [56]. The demand (hence, the supply) for steel is given for today and the year 2050 and summarized in Table 2-5.

Table 2-5 Steel Demand Data

Year	Steel Demand (Gt)
2019	1,875
2020-2049	Linear interpolation
2050 and beyond	2,500

Until 2050, linear interpolation has been performed to evaluate the yearly demands. In the REALISTIC Scenario, it has been assumed that the so-far continuing increase in steel use will cease in 2050. By the time which, humankind will recognize that it has reached the sustainability limit of the supply of steel. Either alternative materials will partially replace steel (as it did happen in the history for other materials) or recycling and more effective use of the steel will become dominant. In the sensitivity analysis, alternative demand evolution trends beyond 2050 shall be investigated. The evolution of the steel demand between 2020 and 2100 (in solid lines for the years where interpolation is used and in dashed lines for the extrapolation) is given in Figure 2-7.

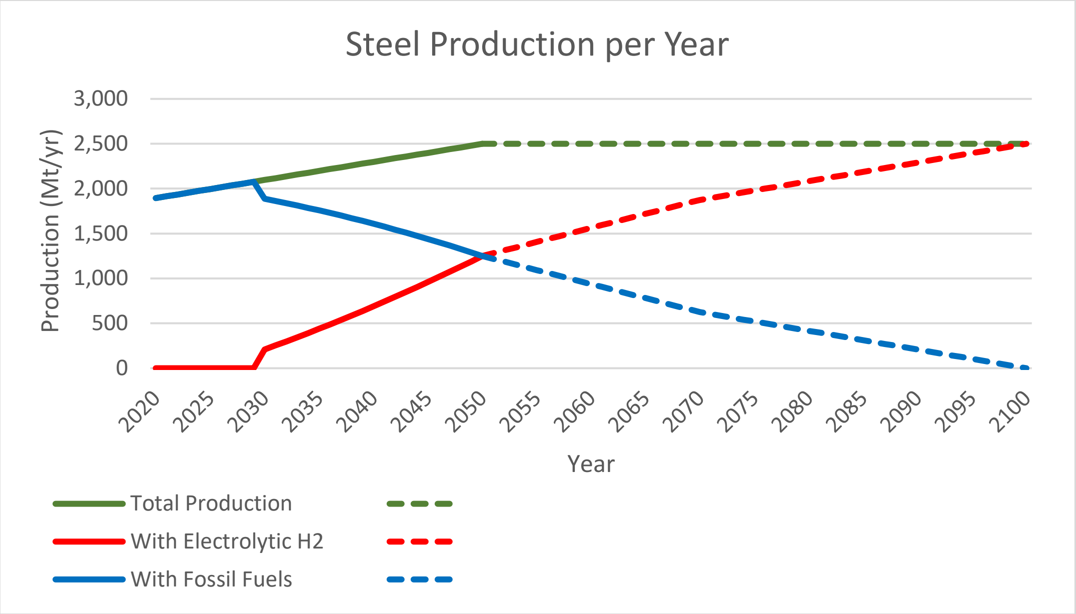

Figure 2-7 Steel Production Rate Forecast until 2100

Yearly steel demand forecasts are denoted by $dem(steel, yr)$ in formulae developed in this study.

Once the yearly steel production has been identified, to estimate the amount of CO_2 emissions that can be prevented in the future, by making a transition from BF-BOF to DRI-EAF technology, the amount of energy consumed in the production of steel needs to be examined. Studies performed by IEA indicated that an average of 19 GJ of energy is needed to produce a ton of crude steel [56]. The majority of the energy demand is currently supplied by coal, hence lies the CO_2 emission dominance of the steel industry. It is elaborated that, this primary energy intensity of steel production may be reduced down to 16 GJ/t by the year 2050, thanks to the expected increase in the efficiency/performance of steel production (that will almost certainly occur in time). However, as already a great deal of improvement has been achieved in energy efficiency since the 1960s [70], no further reductions are expected. Linear interpolation has been performed for the years 2020-2050 and the energy intensity is taken to be constant beyond 2050. Energy intensity values are summarized in Table 2-6.

Table 2-6 Energy Intensity in the Iron & Steel Industry

Year	Energy Intensity (GJ/t of Steel)
2020	19
2021-2049	Linear interpolation
2050 and beyond	16

Energy intensity in the steel sub-sector is therefore a function of years in the future, denoted by $E_{int}(steel, yr)$, in formulae.

Next, the future thermal energy demand for steel production ($E_{th}(steel, yr)$) has been determined by plugging in the steel demand and energy intensity into the formula:

$$E_{th}(steel, yr) = dem(steel, yr) * E_{int}(steel, yr) \tag{2-4}$$

Using the targeted share of electrolytic hydrogen in the corresponding year, the energy supplied by the hydrogen energy carrier ($E_{th}(H2, steel, yr)$) has been evaluated:

$$E_{th}(H2, steel, yr) = sh(H2, steel, yr) * E_{th}(steel, yr) \tag{2-5}$$

Electric energy required for the electrolysis of hydrogen has been taken to be 180 MJ/kg. Thus produced hydrogen will provide only 120 MJ/kg, which is the Lower Heating Value of hydrogen (in steel manufacturing, recovering the latent heat of formed water does not seem practical). From the consumption rate of hydrogen, additional electricity demand to produce the needed electrolytic hydrogen ($E_{elec}(add, steel, yr)$) has been deduced:

$$E_{elec}(add, steel, yr) = \frac{180\frac{MJ}{kg}}{120\frac{MJ}{kg}} E_{th}(H2, steel, yr) \tag{2-6}$$

$$\Rightarrow E_{elec}(add, steel, yr) = 1.5 * E_{th}(H2, steel, yr)$$

It turns out that the potential savings from CO_2 emissions by a transition to electrolytic hydrogen come with a heavy price, however. It appears that extra electricity generation capacities of 1.57 PWh, 8.33 PWh, 12.50 PWh, and 16.67 PWh are needed in 2030, 2050, 2070, and 2100, respectively, for being able to supply the necessary hydrogen. The evolution of the forecasted electricity demand is shown in Figure 2-8.

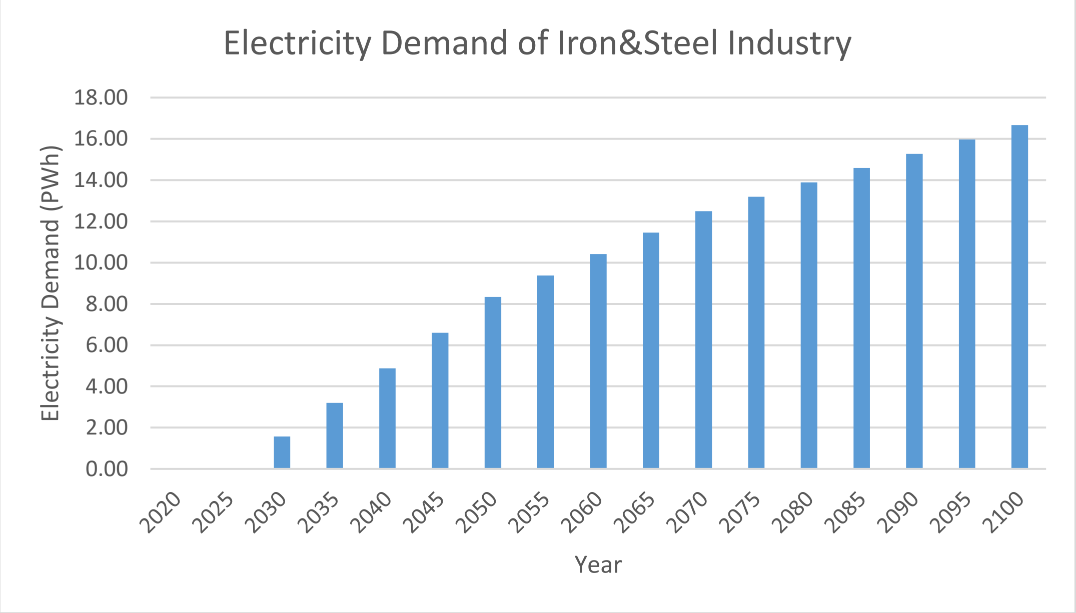

Figure 2-8 Electricity Demand of Steel Industry

Knowing that currently 1.4 ton of CO_2 are emitted per ton of steel, of which 1.25 ton correspond to energy related emissions, and the energy intensity of steelmaking is 19 GJ/t of steel [56], it has been evaluated that $q_{en}(steel) = 0.06579$ ton of CO_2 will be released per GJ of thermal energy delivered by fossil fuels in the iron & steel sub-sector. Therefore, energy related CO_2 emission rates ($Q_{en}(steel, yr)$) in the future can be calculated using the formula:

$$Q_{en}(steel, yr) = q_{en}(steel) * sh(fos, steel, yr) * E_{th}(steel, yr) \qquad (2\text{-}7)$$

For comparison purposes, CO_2 emission rates under the Business As Usual conditions, i.e., when no transition to electrolytic hydrogen occurs, have also been evaluated. In such case, all thermal energy would be supplied by fossil fuels; hence, the yearly emission rate ($Q_{en,BAU}(steel, yr)$) is given by:

$$Q_{en.BAU}(steel, yr) = q_{en}(steel) * E_{th}(steel, yr) \tag{2-8}$$

Abandoning the BF-BOF pathway will also result in a reduction of process emissions. The addition of limestone to iron ore is a common practice in the operation of blast furnaces. While switching to the DRI technology, this need of adding lime to the iron ore will also be eliminated. However, in this study, it will not be correct to assume that all process emissions can be abolished in the sub-sector. It seems that the production of ferroalloys will still use graphite electrodes, which emit CO_2 gases. However, the use of alternatives electrodes does not constitute a subject of this study. Therefore, it has been assumed that the process emission intensity of steelmaking, which is currently 0.15 t CO_2 per ton of steel, will be reduced by a factor of ½ upon switching to the DRI technology. The intensity of process emissions, denoted by, $q_{pro}(steel, yr)$ is used to evaluate future process emissions. In the developed scenarios, it has been assumed that:

$$\begin{cases} q_{pro}(steel, yr) = 0.15 \dfrac{t\ CO_2}{t\ steel}, for\ yr < 2050 \\ q_{pro}(steel, yr) = 0.075 \dfrac{t\ CO_2}{t\ steel}, for\ yr \geq 2050 \end{cases} \tag{2-9}$$

Yearly process emissions from steelmaking ($Q_{en}(steel, yr)$) can be evaluated as:

$$Q_{pro}(steel, yr) = dem(steel, yr) * q_{pro}(steel, yr) \tag{2-10}$$

To assess the gain in CO_2 emissions, process emissions under BAU conditions have also been evaluated, where $q_{pro}(steel, yr) = 0.15 \frac{t\ CO_2}{t\ steel}$ for all years. The reason for the coefficient to remain constant under BAU conditions is the dominance of the BF-BOF pathway over DRI-EA.

Total yearly emission rates from steelmaking are found by summing energy related and process emission rates. The results, which are presented graphically in Figure 2-9, show that the CO_2 emission rates are 2.54 Gt/yr, 1.50 Gt/yr, 0.85 Gt/yr, and 0.19 Gt/yr, for the years 2030, 2050, 2070, and 2100, respectively. Similarly, emission rates under BAU conditions are evaluated to be 2.79 Gt/yr and 2.82 Gt/yr, for 2030 and 2050 (and beyond), respectively.

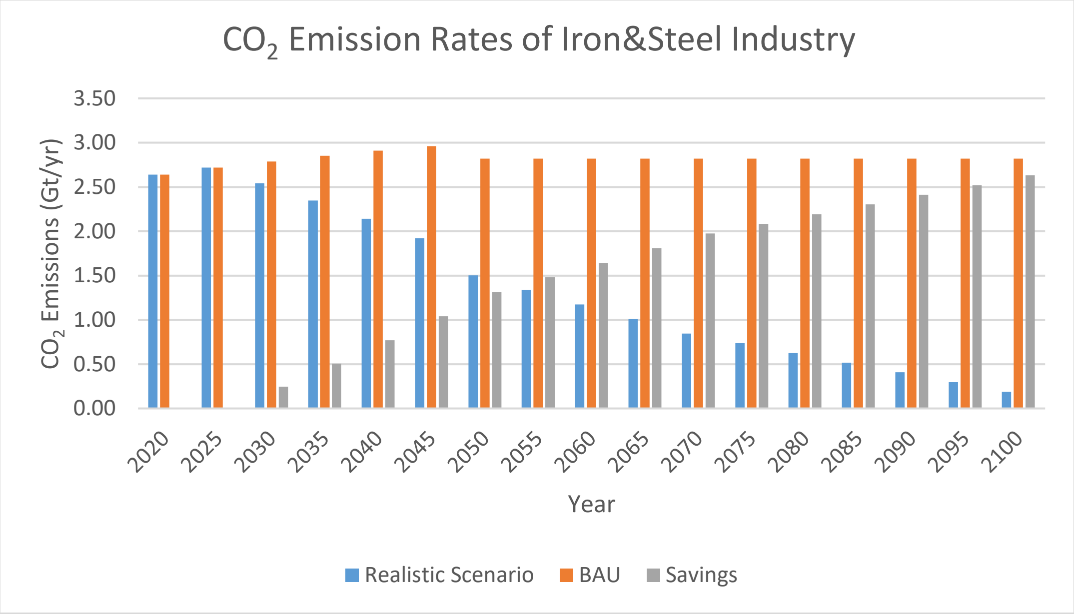

Figure 2-9 CO_2 Emission Rates of Iron & Steel Industry

Thus achieved a reduction in (both energy related and process) CO_2 emissions are evaluated by comparing the CO_2 emission rates of the REALISTIC Scenario and the BAU. If no transition to the DRI-EF pathway occurs, that is if BAU continues, it has been found that around 230 Gt CO_2 emissions would occur between 2020-2100, from ironmaking. However, in the REALISTIC Scenario, emissions will be reduced down to 110 Gt CO_2, in the same period. Hence, approximately, 120 Gt CO_2 emissions can be saved until 2100.

2.5.2. Cement Sub-Sector

Many mitigation efforts mentioned in the literature lay beyond the scope of this study, as they either intend to decrease the use of concrete, or the cement content of the concrete, or the clinker content of the cement. The effort in this study is to reduce CO_2 emissions, through the use of less CO_2 emitting primary energy sources, rather than lowering the use of goods throughout the World.

The yearly consumption and hence production rates for cement have been estimated by IEA, until the year 2050 [61] and are presented in Table 2-7.

Table 2-7 Cement Demand Data

Year	Cement Demand (Gt)
2019	4,200
2020-2049	Linear interpolation
2050 and beyond	4,700

It is relatively difficult to make an estimation beyond. Linear interpolation has been performed between 2020 and 2050 demands. To be able to make predictions on CO_2 emissions and possible savings until 2100, some forecasts need to be made beyond 2050. In the basic scenario developed in this study (REALISTIC), it has been assumed that the yearly production rate of cement will remain invariant beyond 2050. This reasoning is parallel to that in Steel & Iron sub-sector. Thus evaluated cement demand in the future is presented graphically in Figure 2-10.

Yearly cement demand forecasts are denoted by $dem(cement, yr)$ in the formulae of this study.

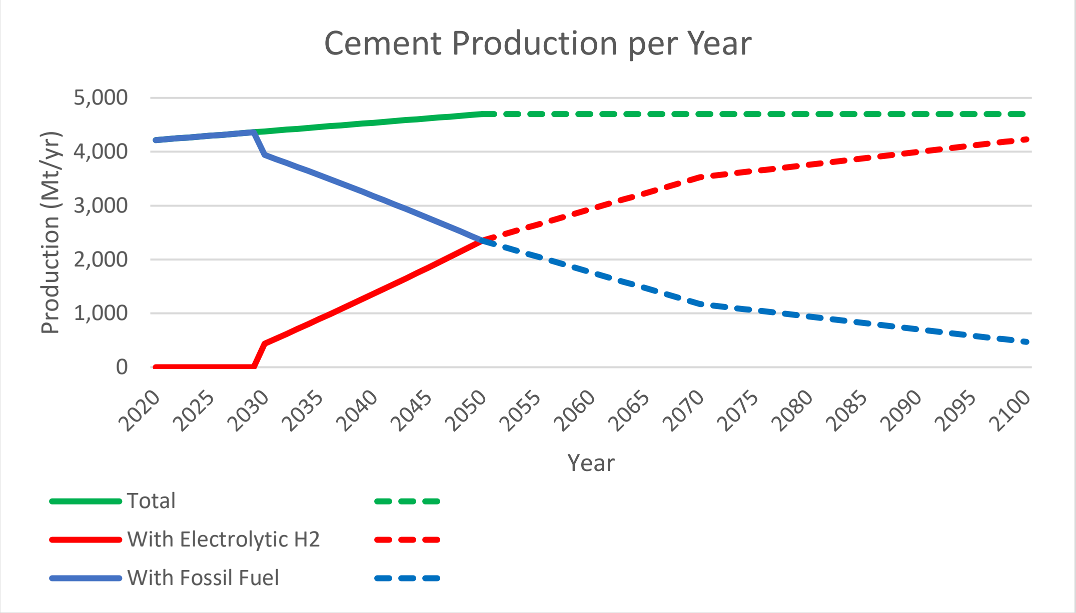

Figure 2-10 Cement Production Rate Forecast until 2100

The thermal energy intensity of the clinker is currently around 3.5 GJ/t clinker [68]. This intensity is expected to decrease by 10% by 2050. This is mainly because of the implementation of the best available technology throughout the world. However, a further decrease is not expected. The clinker content of the cement is around 65% and is expected to remain relatively constant in the future. Therefore, energy intensity has been taken to be 2.275 GJ/t of cement for 2020 and 2.112 GJ/t for 2050 and applied linear interpolation for years in between as indicated in Table 2-8.

Table 2-8 Energy Intensity in the Cement Industry

Year	Energy Intensity (GJ/t of Cement)
2020	2.275
2021-2049	Linear interpolation
2050 and beyond	2.112

Energy intensity in the cement sub-sector is therefore a function of years in the future, denoted by $E_{int}(cement, yr)$ in formulae employed in this study.

Future thermal energy demand for cement production ($E_{th}(cement, yr)$) has been then determined, by plugging in the cement demand and energy intensity into the formula:

$$E_{th}(cement, yr) = dem(cement, yr) * E_{int}(cement, yr) \tag{2-11}$$

Using the targeted share of electrolytic hydrogen in the corresponding year, energy supplied by the hydrogen energy carrier has been ($E_{th}(H2, cement, yr)$):

$$E_{th}(H2, cement, yr) = sh(H2, cement, yr) * E_{th}(cement, yr) \tag{2-12}$$

From the consumption rate of hydrogen that supplies the thermal energy, additional electricity demand to produce the needed electrolytic hydrogen ($E_{elec}(add, cement, yr)$) has been deduced, as previously done for steelmaking:

$$E_{elec}(add, cement, yr) = 1.5 * E_{th}(H2, cement, yr) \tag{2-13}$$

It has been calculated that extra electricity generation capacities of 0.40 PWh, 2.07 PWh, 3.1 PWh, 3.72 PWh are needed, in 2030, 2050, 2070, and 2100, respectively, for being able to supply the necessary hydrogen. The evolution of the forecasted electricity demand is shown in Figure 2-11.

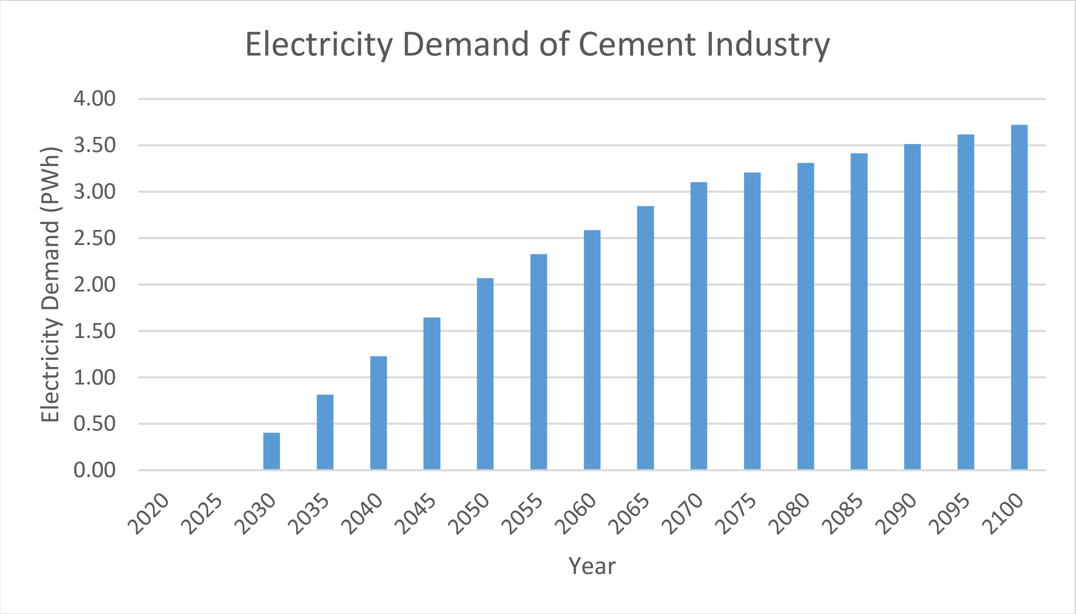

Figure 2-11 Electricity Demand of Cement Industry

Unlike the Iron & Steel sector, however, process emissions play a dominant role in the cement sector. Because no action can be taken within the scope of this study, direct process emissions will remain intact. The achieved reduction potential in CO_2 emissions from the Cement Sector is far inferior to that of Iron & Steel.

Given that currently 0.54 ton of CO_2 are emitted per ton of cement, of which 0.2 ton correspond to energy related emissions (hence the remaining 0.34 ton are process emissions), and the energy intensity is 2.275 GJ/t, it has been evaluated that $q_{en}(cem) = 0.087912$ ton of CO_2 will be released per GJ of thermal energy delivered by fossil fuels and incinerated waste. Therefore, energy related CO_2 emission rates ($Q_{en}(cem, yr)$) in the future can be calculated using the formula:

$$Q_{en}(cem, yr) = q_{en}(cem) * sh(fos, cement, yr) * E_{th}(cement, yr) \qquad (2\text{-}14)$$

For comparison purposes, CO_2 emission rates in the Business As Usual conditions, i.e., when no transition to electrolytic hydrogen occurs have also been evaluated. In such case, all thermal energy would be supplied by fossil fuels and waste; hence, the yearly energy related emission rate ($Q_{en,BAU}(cem, yr)$) is given by:

$$Q_{en,BAU}(cem, yr) = q_{en}(cem) * E_{th}(cement, yr) \tag{2-15}$$

Our CO_2 emission mitigation strategy does not affect the process emissions in the cement sub-sector. For both the REALISTIC Scenario that has been developed in this study and BAU, yearly process emission rates are identical and can be determined by the following formula:

$$Q_{pro}(cem, yr) = dem(cement, yr) * 0.34\ t\ CO_2/t \tag{2-16}$$

Total yearly emission rates from the cement sub-sector are found by summing energy related and process emission rates. The results, which are presented graphically in Figure 2-12, show that the CO_2 emission rates are 2.26 Gt/yr, 2.03 Gt/yr, 1.82 Gt/yr, and 1.69 Gt/yr, for the years 2030, 2050, 2070, and 2100, respectively. Similarly, emission rates under BAU conditions are evaluated to be 2.34 Gt/yr and 2.47 Gt/yr, for 2030 and 2050 (and beyond), respectively.

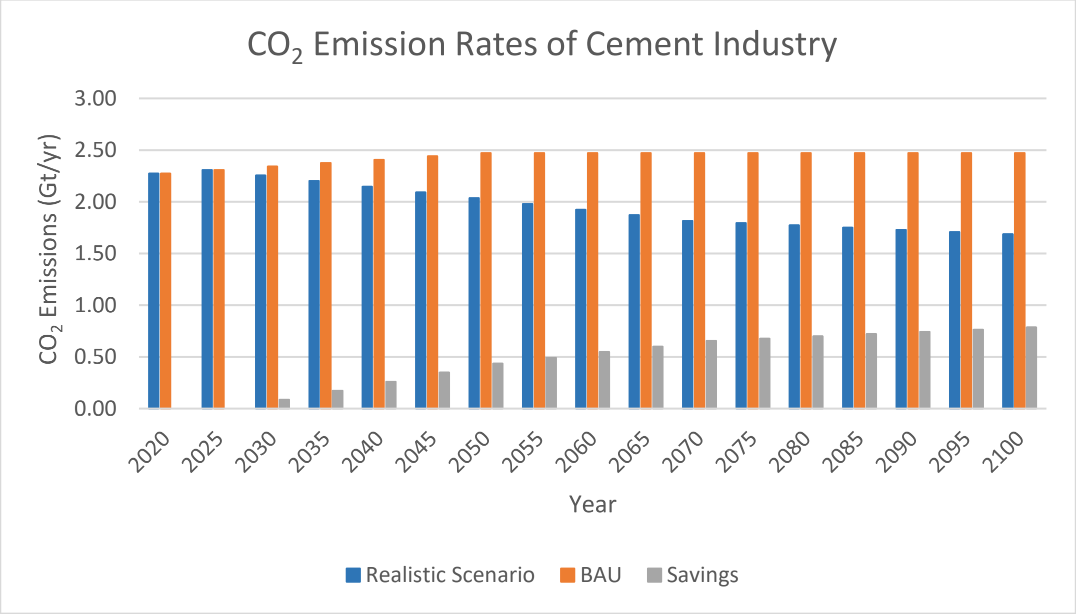

Figure 2-12 CO_2 Emissions of Cement Industry

The achieved reduction in (both energy related and process) CO_2 emissions are evaluated by comparing the CO_2 emission rates of the REALISTIC Scenario and the BAU. If BAU continues, it has been found that 197 Gt CO_2 emissions would occur between 2020-2100. When predictions in the REALISTIC Scenario realize, however, emission will be reduced down to 159 Gt CO_2. Hence, approximately, 38 Gt CO_2 emissions can be saved until 2100.

2.5.3. Chemical Industry Sub-Sector

To assess the amount of CO_2 emissions and possible savings on them, forecasted data by IEA [62] on the yearly consumption/production rates of the primary chemicals have been employed. The yearly demand for each primary chemical is given for the years 2017 and 2050, which are listed in Table 2-9. Linear interpolation has been performed to estimate the demand between 2020 and 2050. Beyond 2050, in parallel with other sub-sectors, it has been assumed that demand remain will remain invariant in the REALISTIC Scenario. Further variations are studied while performing sensitivity analyses.

Table 2-9 Chemical Industry Demand Data

Year	HVC Demand (Mt)	NH_3 Demand (Mt)	CH_3OH Demand (Mt)
2017	220	180	100
2018-2049	Linear interpolation		
2050 and beyond	400	245	180

The evolution of the demand for primary chemicals between 2020 and 2100 is shown graphically in Figure 2-13 through Figure 2-15. In the formulae of this study, these demand values are referred to as $dem(HVC, yr)$, $dem(NH_3, yr)$, and $dem(CH_3OH, yr)$, respectively.

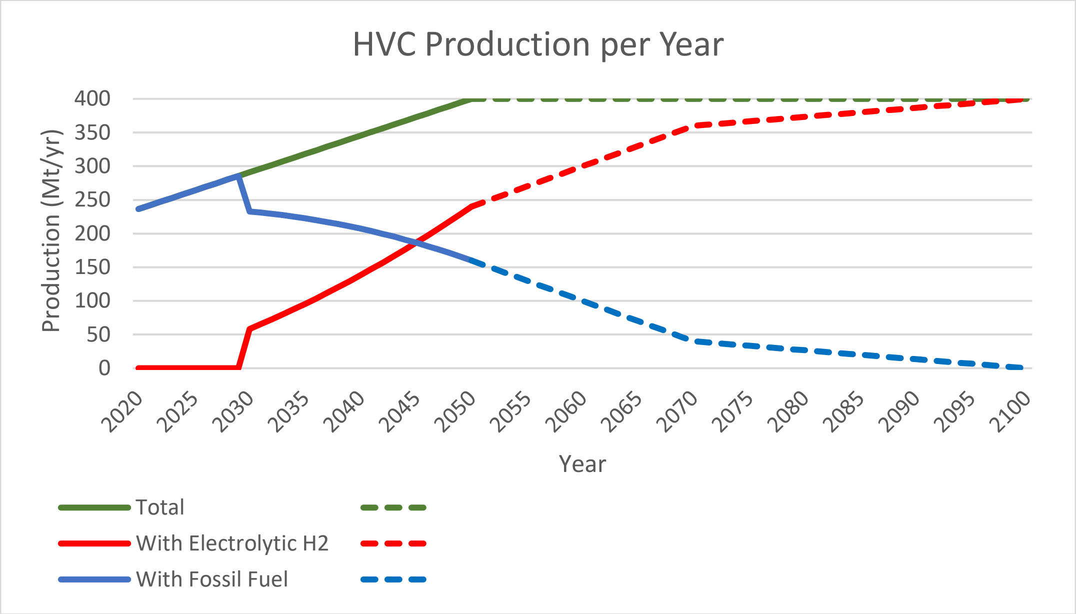

Figure 2-13 HVC Production Forecast Rate until 2100

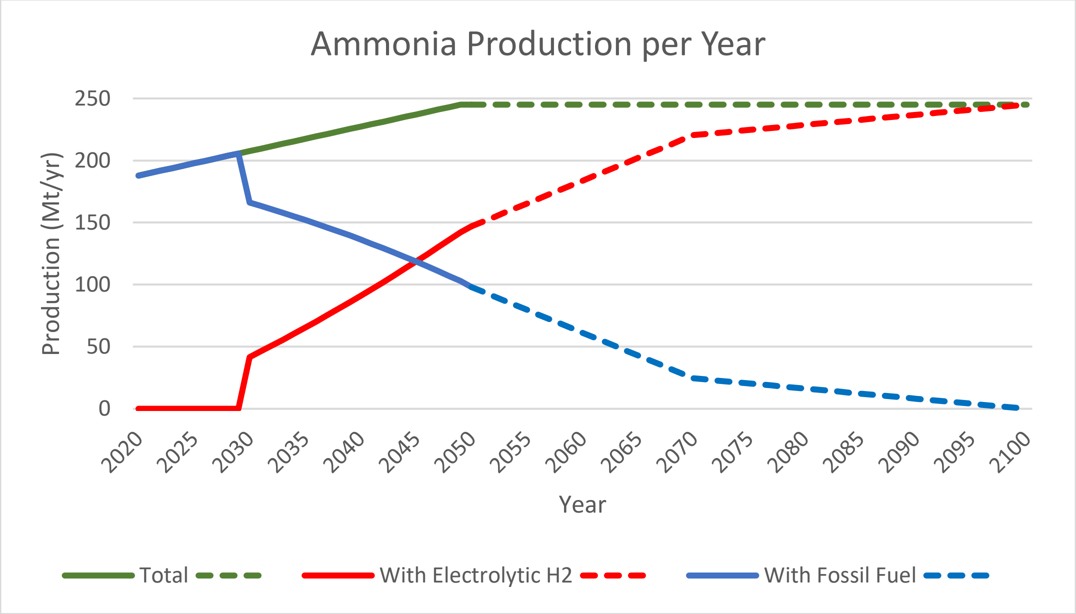

Figure 2-14 Ammonia Production Rate Forecast until 2100

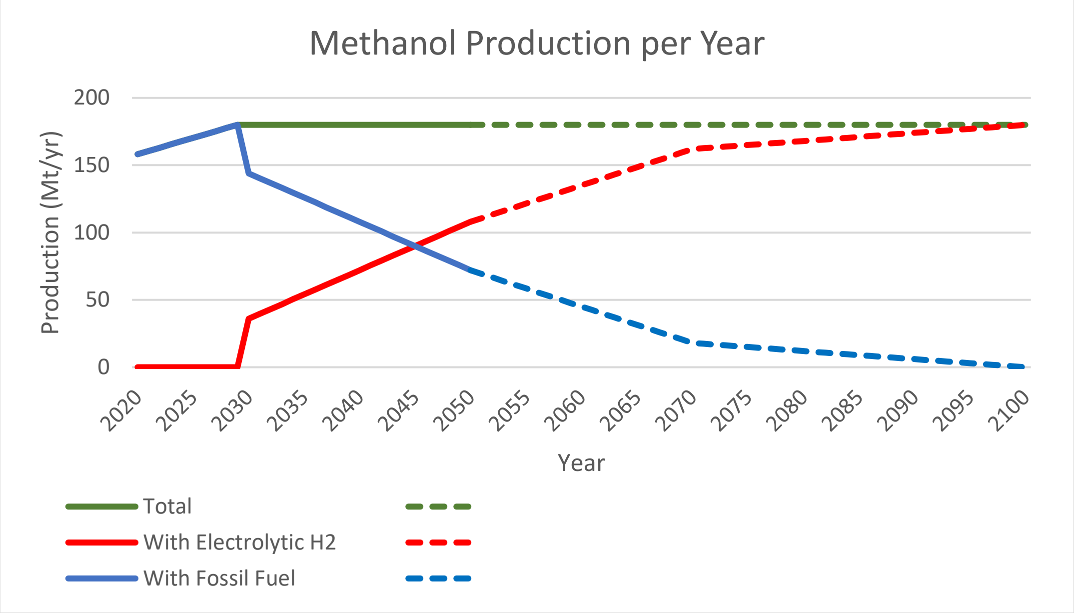

Figure 2-15 Methanol Production Rate Forecast until 2100

IEA has also analyzed the energy intensities of these primary chemicals. Based on the continuous development and improvements in the technology, predictions for the energy intensity of each primary chemical have been provided by IEA, until the year 2050 [62]. Currently, energy consumed in the production of a ton of HVC has been estimated to be 5.6 GJ, whereas for a ton of ammonia it is 25.1 GJ, and for a ton of methanol 23.6 GJ. These intensity figures are expected to gradually decrease with time, to reach 4.0, 19.0, and 20.2 GJ/t by 2050, respectively. It has been assumed for the sake of this study that the intensities reached by 2050 will reflect a practical limit (a level of maturity) and remain constant until 2100. Energy intensities employed in this study are summarized in Table 2-10.

Table 2-10 Energy Intensities in the Chemical Industry

Year	Energy Intensity (GJ/t of Product)		
	HVC	NH_3	CH_3OH
2017	5.60	25.10	23.60
2018-2029	Linear interpolation		
2030	5.30	22.80	22.80
2031-2049	Linear interpolation		
2050 and beyond	4.00	19.00	20.20

Energy intensities in the chemical sub-sector are therefore functions of years, which denoted by $E_{int}(HVC, yr)$, $E_{int}(NH3, yr)$, and $E_{int}(CH3OH, yr)$ in formulae employed in this study, respectively.

Future thermal energy demand for each sub-sector within the chemical industry ($E_{th}(subsec, yr)$) have been determined by plugging in the appropriate demand and energy intensity values into the formula:

$$\begin{cases} E_{th}(subsec, yr) = dem(subsec, yr) * E_{int}(subsec, yr) \\ \qquad subsec = \{HVC, NH3, CH3OH\} \end{cases} \tag{ 2-17}$$

Thermal energy demand for primary chemicals production is then given by:

$$E_{th}(prim, yr) = \sum_{subsec} E_{th}(subsec, yr) \tag{ 2-18}$$

Using the targeted share of electrolytic hydrogen in the corresponding year, energy supplied by the hydrogen energy carrier ($E_{th}(H2, chem, yr)$) has been determined:

$$E_{th}(H2, chem, yr) = sh(H2, chem, yr) * E_{th}(prim, yr) \tag{ 2-19}$$

Electricity needed to produce the hydrogen energy carrier ($E_{elec}(H2, chem, yr)$) has been evaluated as in the case of steelmaking:

$$E_{elec}(H2, chem, yr) = 1.5 * E_{th}(H2, chem, yr) \tag{2-20}$$

Recalling that primary chemicals (HVC, ammonia, and methanol) are responsible for 2/3 of thermal energy consumption within the chemical industry, the thermal energy demand of the miscellaneous sub-sectors ($E_{th}(misc, yr)$) has been estimated using the formula:

$$E_{th}(misc, yr) = \frac{1}{2} * E_{th}(prim, yr) \tag{2-21}$$

The thermal energy of the miscellaneous sub-sectors may be supplied by the combustion of electrolytic hydrogen as well. However, this process being rather inefficient and operating temperatures in the relevant sub-sectors are lower when compared to HVC, ammonia, and methanol production. Therefore, the direct use of electricity to supply the required thermal energy seems more reasonable [41]. It has been concluded that an extra electric generation capacity will be needed for the miscellaneous sub-sectors ($E_{elec}(misc, yr)$), which is equivalent to thermal energy demand:

$$E_{elec}(misc, yr) = E_{th}(misc, yr) \tag{2-22}$$

However, correct evaluation of the overall electric demand of the chemical sector cannot be restricted to energy supply. According to the REALISTIC Scenario, electrolytic hydrogen will also be used as a raw material (feedstock) for the production of ammonia using the Haber process. Targeted shares of electrolytic hydrogen in the REALISTIC Scenario are used to determine the amount of electrolytic hydrogen to be used as feedstock $dem(H2, feed, yr)$, according to the relation:

$$dem(H2, feed, yr) = dem(NH3, yr) * sh_p(H2, NH3, yr) * \frac{3}{17} \tag{2-23}$$

Where 3/17 represents the mass fraction of hydrogen in ammonia. Hence, the additional yearly electricity demand of the entire chemical industry

($E_{elec}(add, chem, yr)$), which results from CO_2 mitigation efforts, is given by the relation:

$$E_{elec}(add, chem, yr) = E_{elec}(H2, chem, yr) + E_{elec}(misc, yr) + dem(H2, feed, yr) * 180\ MJ/kg \tag{2-24}$$

It has been calculated that extra electricity generation capacities of 1.39 PWh, 4.59 PWh, 6.89 PWh, 7.66 PWh are needed, in 2030, 2050, 2070, and 2100, respectively, for being able to supply the necessary hydrogen. The evolution of the forecasted electricity demand is shown in Figure 2-16.

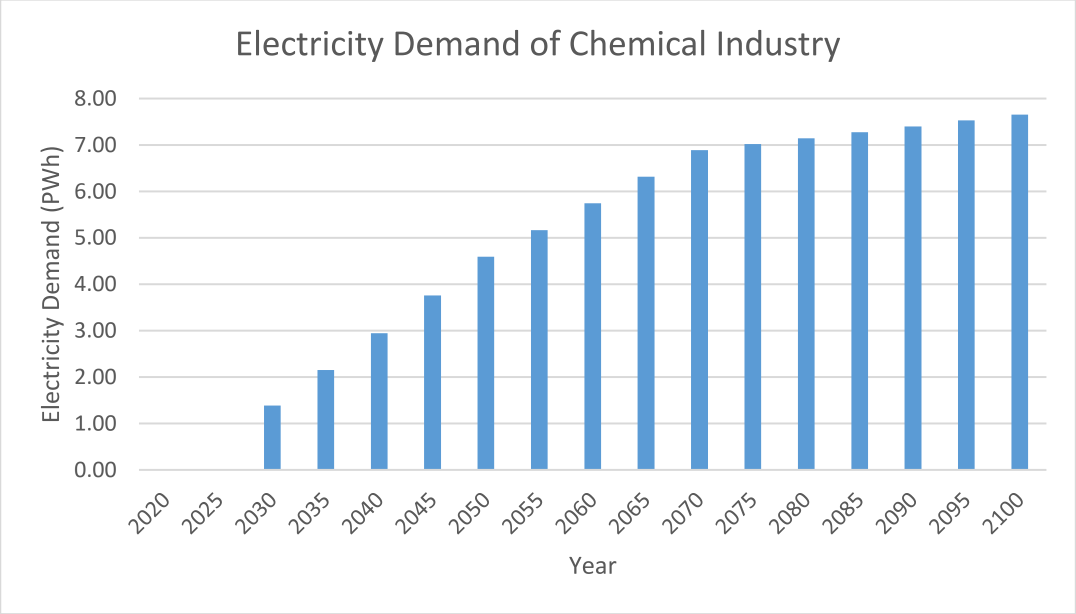

Figure 2-16 Electricity Demand of Chemical Industry

To assess the reduction potential in CO_2 emissions from the chemical industry, both energy related and process emissions have been investigated. It has been calculated that on the average $q_{en}(prim) = 0.09852$ ton of CO_2 will be released per GJ of thermal energy delivered by fossil fuels in the sub-sectors of primary chemicals. Therefore, energy related CO_2 emission rates for the production of primary chemicals ($Q_{en}(prim, yr)$) in the future can be calculated using the formula:

$$Q_{en}(prim, yr) = q_{en}(prim) * sh(fos, chem, yr) * E_{th}(prim, yr) \tag{2-25}$$

For comparison purposes, CO_2 emission rates under the Business As Usual conditions, i.e., when no transition to electrolytic hydrogen occurs have also been evaluated. In such case, all thermal energy would be supplied by fossil fuels; hence, the yearly energy related emission rate ($Q_{en,BAU}(prim, yr)$) is given by:

$$Q_{en,BAU}(prim, yr) = q_{en}(prim) * E_{th}(prim, yr) \tag{2-26}$$

Unlike in the case of the cement industry, the CO_2 emission mitigation strategy has a positive effect on process emissions in the chemical industry. It has been reported that 0.13 Gt CO_2 is currently being emitted for 180 Mt NH_3 production, where almost all hydrogen is derived from fossil fuels [62]. It has been assumed that this ratio will remain fixed in the future, for hydrogen produced from fossil fuels. Therefore, process emissions from the ammonia industry ($Q_{pro}(prim, yr)$), which constitute almost all process emissions from primary chemicals production, can be evaluated using the relation:

$$Q_{pro}(prim, yr) = \frac{0.13\ Gt\ CO_2}{180\ Mt} * sh(fos, chem, yr) * dem(NH3, yr) \tag{2-27}$$

This expression, which is valid for the scenario of interest (namely, the REALISTIC Scenario), takes the following form under BAU conditions:

$$Q_{pro,BAU}(prim, yr) = \frac{0.13\ Gt\ CO_2}{180\ Mt} * dem(NH3, yr) \tag{2-28}$$

CO_2 emission rate from primary chemicals ($Q(prim, yr)$) is then the sum of energy related and process emission rates:

$$Q(prim, yr) = Q_{en}(prim, yr) + Q_{pro}(prim, yr) \tag{2-29}$$

To assess the yearly emission rates from the entire chemical sub-sector, the information that 60% of emissions within the sector result from primary chemicals production has been used [62]. Assuming that this ratio will remain constant in the future, yearly emission rates ($Q(chem, yr)$) for the entire chemical industry have been evaluated, using the formula:

$$Q(chem, yr) = Q(prim, yr)/0.6 \qquad (2\text{-}30)$$

Similarly, emission rates under BAU conditions are given by the relations:

$$Q_{BAU}(prim, yr) = Q_{en,BAU}(prim, yr) + Q_{pro,BAU}(prim, yr) \qquad (2\text{-}31)$$

$$Q_{BAU}(chem, yr) = Q_{BAU}(prim, yr)/0.6 \qquad (2\text{-}32)$$

The results, which are presented graphically in Figure 2-17, show that the CO_2 emission rates are 1.41 Gt/yr, 0.77 Gt/yr, 0.19 Gt/yr, and 0.00 Gt/yr, for the years 2030, 2050, 2070, and 2100, respectively. Similarly, emission rates under BAU conditions are evaluated to be 1.76 Gt/yr and 1.92 Gt/yr, for 2030 and 2050 (and beyond), respectively.

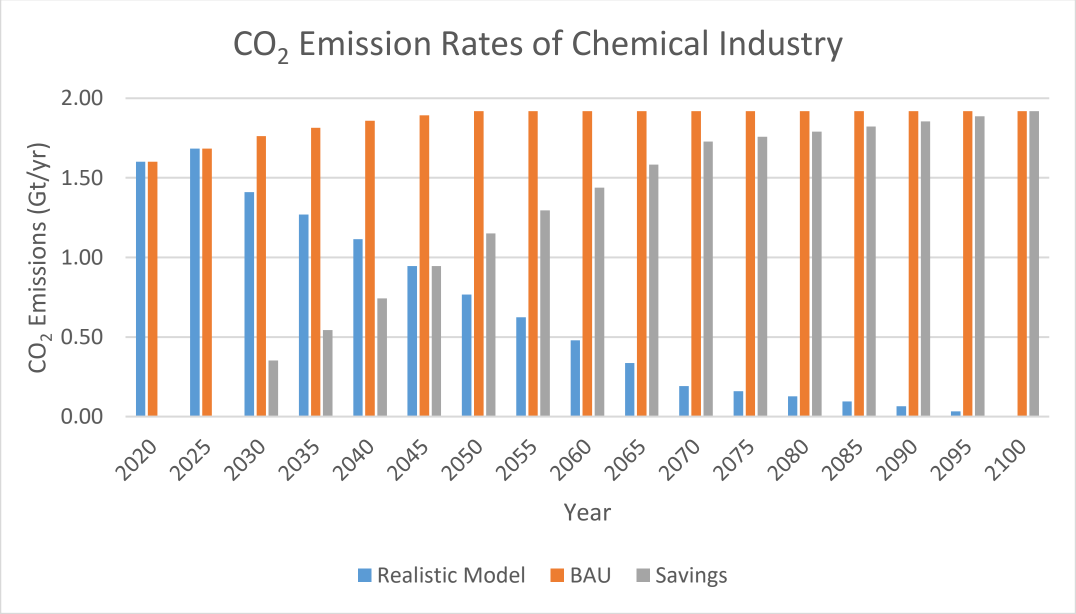

Figure 2-17 CO_2 Emissions of Chemical Industry

Our calculations indicate that BAU conditions imply a release of 77.28 Gt CO_2, between 2020-2100. A transition to electrolytic hydrogen, as described in this study, will reduce CO_2 emissions from the three sub-sectors down to 26.68 Gt CO_2, during the same period. Therefore, there exists a potential for saving almost 50 Gt CO_2 emissions.

This last figure of 50 Gt CO_2 emission savings represents the savings from energy related emissions. However, in the chemical sub-sector, there remains the potential of further reducing CO_2 emissions, by lowering process emissions. This is quite opposite of the cement sub-sector. The savings from process emissions come mainly from the supply of electrolytic hydrogen (versus the use of syngas) for ammonia production. Switching to electrolytic hydrogen as feedstock for ammonia further reduces emissions from the sector. BAU approach indicates that 13.67 Gt CO_2 process emissions will occur between 2020-2100. These process emissions can be reduced down to 4.55 Gt CO_2 with the use of electrolytic hydrogen, thus generating a further savings of almost 9 Gt CO_2.

When the entire chemical industry is analyzed, it has been found that under BAU conditions, emissions will sum up to approximately 152 Gt CO_2. The use of electrolytic hydrogen according to the REALISTIC Scenario will reduce this last figure to 52 Gt CO_2, hence an overall savings of 100 Gt CO_2 can be reached, between 2020 and 2100.

2.5.4. Assessment of the Entire Industry Sector

The fundamental scenario adopted in the study (REALISTIC) implies that the replacement of fossil fuels by electrolytic hydrogen in all three sub-sectors (steel, cement, and chemicals) will require an additional electricity demand. This demand reaches a substantial level, namely 28.05 PWh in 2100.

Recalling that the three most CO_2 emitting sub-sectors (iron & steel, cement, chemical) consume almost 2/3 of the energy in the industry, electricity requirement of the entire industry sector may be predicted. It is argued that in the remaining sub-sectors, temperature requirements are lower when compared to the former three sub-sectors. Hence, rather than employing electrolytic hydrogen as an energy carrier, the use of direct electricity to supply the thermal energy demand [41] has been recommended in this study. It is important to underline that no detailed analysis is available to justify the use of direct electricity in the remaining sub-sectors, other than the lower temperature requirements,

In the case where electrolytic hydrogen was to be employed as the energy carrier in the remaining sub-sectors, the electricity of requirement would have been half of the sum of electricity requirements of the three sub-sectors. However, the use of electrolytic hydrogen incorporates an inherent 2/3 energy efficiency (because, it delivers 120 MJ/kg (LHV), whereas requires 180 MJ/kg to be generated). Thus, the use of direct electricity in supplying the necessary thermal energy will require an energy equivalent to 2/3 of the latter amount. Hence, under the following assumptions, additional electric energy requirement of the sub-sectors, excluding iron &steel, cement, and chemical sub-sectors, ($E_{elec}(add, other, yr)$) have been determined using the formula:

$$\begin{cases} E_{elec}(add, other, yr) = \frac{1}{3} * \sum_{sec} E_{elec}(add, sec, yr) \\ \qquad sec = \{steel, cement, chem\} \end{cases} \tag{2-33}$$

The yearly additional electric energy requirements of the industry sector ($E_{elec}(add, ind, yr)$), resulting from the CO_2 mitigation efforts, are expressed as:

$$E_{elec}(add, ind, yr) = \frac{4}{3} * \sum_{sec} E_{elec}(add, sec, yr) \tag{2-34}$$

The extra electricity production that the REALISTIC Scenario requires, which is present graphically in Figure 2-18, reaches 4.48 PWh, 19,99 PWh, 29.99 PWh, and 37.39 PWh, in the years 2030, 2050, 2070, and 2100, respectively.

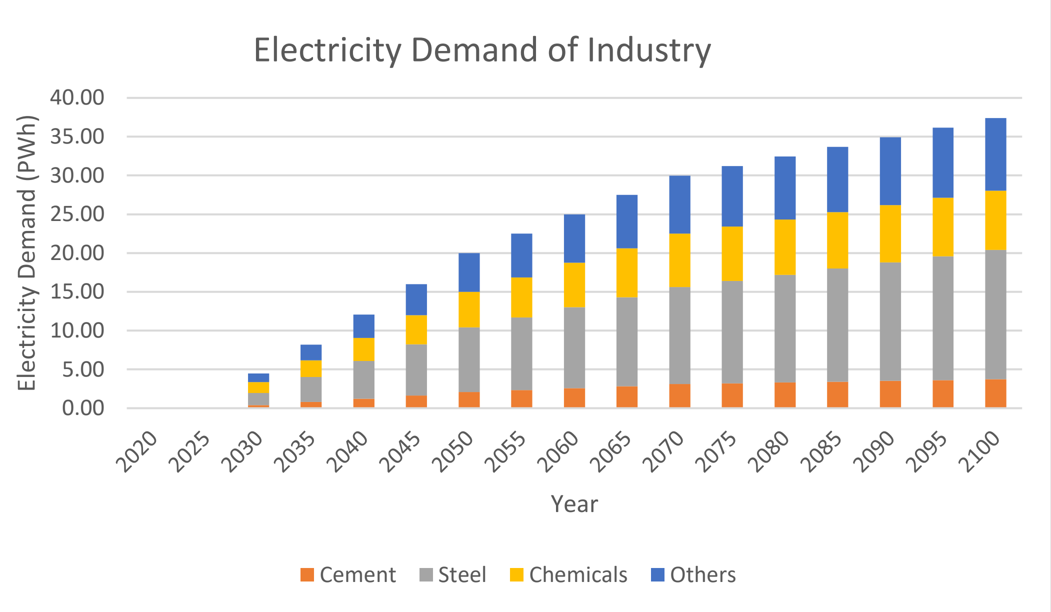

Figure 2-18 Electricity Demand of the Industry

With the transition to electrolytic hydrogen, as an alternative fuel in the industry sector, large savings in CO_2 emissions can be achieved. As in the case of electric energy requirements calculations, proportionality constant has been employed to estimate the savings in the sectors. 2/3 of the emissions arise from the three sub-sectors that are analyzed in this study, and assuming that this constant remains invariant in time, evolutions from the industry (to include other sub-sectors, which have not been investigated so far) have been evaluated.

The evolution of CO_2 emissions predicted in both REALISTIC and BAU Scenarios between 2020 and 2100 are presented graphically in Figure 2-19. It has been calculated that 9.31 Gt CO_2, 6.46 Gt CO_2, 4.28 Gt CO_2, and 2.81 Gt CO_2 are emitted in the years 2030, 2050, 2070, and 2100, respectively. It is worth underlining that even in 2100, 1.69 Gt CO_2 and 0.19 Gt CO_2, will still be emitted in the cement and steel industries, respectively, in the REALISTIC Scenario. Both of these emissions are process emissions, which cannot be eliminated by altering the energy carrier. The remaining 0.94 Gt CO_2 comes from 2/3 allocation of all emissions to the remaining sub-sectors. This can be justified by noting that, still some process emissions will occur in the remaining sectors of the industry.

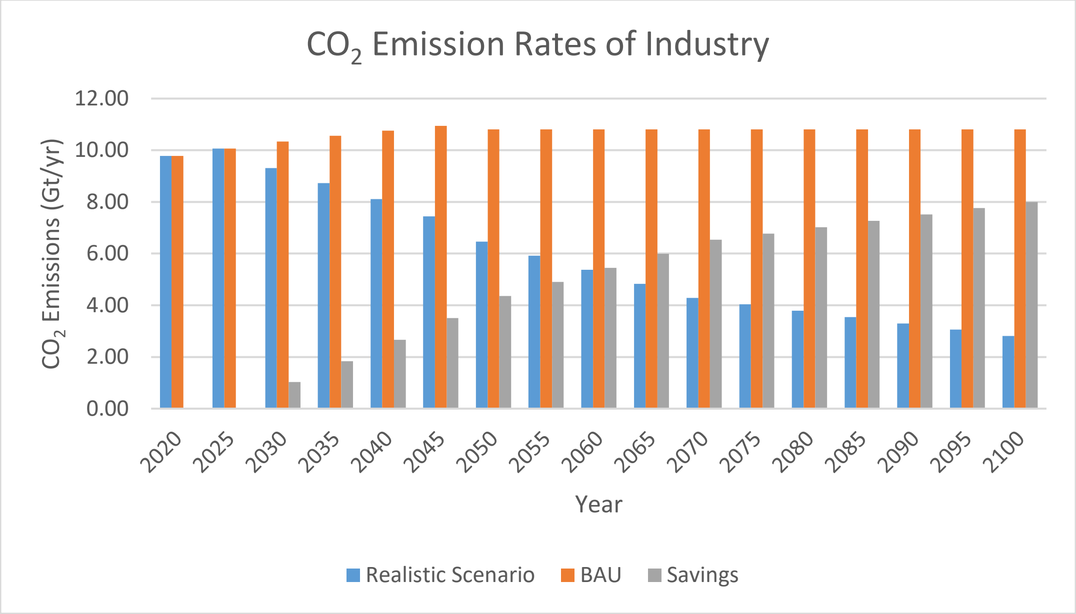

Figure 2-19 CO_2 Emissions by the entire Industry

It has been predicted that according to the REALISTIC Scenario, the industry will be emitting a total of 481.56 Gt CO_2 between 2020 and 2100. In the same period, if no precautions are taken to reduce the emissions, i.e., under the BAU Scenario; a total of 866.4 Gt CO_2 will be released to the atmosphere. Therefore, by employing electrolytic hydrogen in the sector, under the REALISTIC Scenario there exists a potential to save approximately 385 Gt CO_2 emissions.

To better analyze the origin of these emissions, contribution of each sub-sector is presented individually in Figure 2-20.

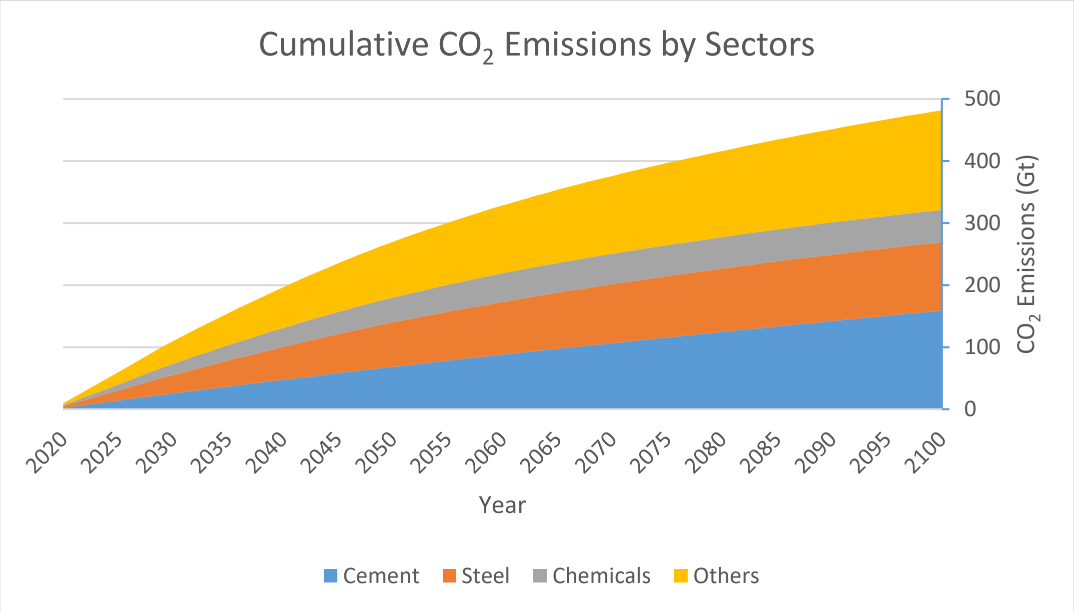

Figure 2-20 Cumulative CO_2 Emissions by Steel, Cement and Chemical sub-sectors

2.6. Possible Further Improvements

To mitigate CO_2 emissions from the industry sector, replacement of fossil fuels with electrolytic hydrogen has been proposed in this study. The needed electricity will then be supplied by a mixture of renewables and NPPs. However, thermodynamically, the process of generating electricity to perform electrolysis of water to produce hydrogen, which is then used in chemical reactions, is rather inefficient. A considerable amount of irreversibility occurs in the electrolysis and the lack of practicality in recovering the higher heating value of hydrogen are the primary sources of this inefficiency. Nevertheless, the fundamental principle of employing mature technologies only in this study implies that the sole other option is to use electrolytic hydrogen.

However, alternative solutions are available or may become available in the future. Further suggestions may be proposed to reduce CO_2 emissions in each sub-sector that has been investigated so far.

2.6.1. Iron & Steel Sub-sector

To eliminate irreversibilities and lack of full recovery of heating potential of hydrogen, direct use of electricity may be considered, without employing hydrogen as a carrier. In the specific case of the Iron & Steel Sub-sector, there exists a potential for converting iron ore to metallic iron, by direct use of electricity. There are ongoing efforts along these lines: The United States of America based company, Boston Metal [71] is working in collaboration with the Massachusetts Institute of Technology (MIT) to develop the Molten Oxide Electrolysis technology, in which the molten iron ore will undergo electrolysis to produce metallic iron.

In this study, Molten Oxide Electrolysis is not included in the scenario, owing to the fact that it has not matured yet. Nevertheless, this relatively new technology has a bright future, as it can be regarded as a variant of electrolytic aluminum production, which is practically the only technology employed throughout the World. Electrolysis in the aluminum sector has a very long history and has already reached a very high degree of maturity. Therefore, it may not be wrong to assume that in the future, all iron production, just like aluminum, will be based on direct electrolysis of the ore.

2.6.2. Cement Sub-sector

It may be argued that electricity can be directly used in the calcination process, which is the fundamental process in clinker production. Efforts have been made along these lines. However, due to the electrically insulating characteristic of the raw materials in clinker production, electric heating did not prove practical. There are also efforts in developing direct solar calcination processes [72] [73]. In the future, there may be developments in the use of electricity and/or direct solar thermal for calcination, but as of today these technologies cannot be classified as "mature", hence cannot be included in this study, according to the adopted assumptions.

2.6.3. Chemical Sub-sector

The relatively lower operating temperatures in the chemical sub-sector (when compared to Iron & Steel and Cement Sub-sectors) may allow the full recovery of the Higher Heating Value (HHV) of the electrolytic hydrogen. Even though irreversibilities inherent to electrolysis persist, employing HHV versus LHV will bring important savings, as the former is 142 MJ/kg, whereas the latter is 120 MJ/kg. However, without knowing the details of the entire industry, which is diversified, it may not be correct to assume that HHV can be used as a representative figure. To remain on the conservative side and to leave space to further improvements, in this study the LHV of electrolytic hydrogen has been used to determine the electric energy demand of the sector, after switching to this new fuel.

Direct use of electricity as a thermal energy source will reveal a higher thermodynamic efficiency when compared to its use for electrolysis and employing thus produced hydrogen. In the case of the chemical sub-sector, the inherent diversity of the sector makes it difficult to assess whether direct use electricity can be employed. Therefore, the applicability of direct electricity to sub-sectors other than primary chemicals production has been ruled out. Potential use of direct electricity in the primary chemicals sub-sector has been left as a possible further improvement.

2.7. Sensitivity Analysis for Industry

The analysis so far is based on the set of assumptions, which constitute the scenario that is referred to as REALISTIC. This scenario represents a rather ambitious effort to reduce CO_2 emissions. Yet, it is based on precautionary measures that can be realized with acceptable financial penalties. To assess the effectiveness of the adopted assumptions involved in the REALISTIC Scenario, two other scenarios have been proposed, in which the targeted transitional shares to electrolytic hydrogen in 2030, 2050, 2070, and 2100 are altered.

Realization of the transition to electrolytic hydrogen will come with financial burdens. Governments and owners of the industrial facilities will initially pay the price, but in the end, this will be transmitted to all individuals. It would not be wrong to assume that there will be resistance to financially contributing to the changes. Therefore, a second scenario has been devised in which the transition occurs at a slower pace, affected by this resistance. This scenario is named the RELAXED Scenario.

With the ever-growing awareness about global warming, the urgency in reducing CO_2 emissions may be recognized by humankind in the near future. In such a case, ignoring all financial aspects a transition to electrolytic hydrogen may be realized within technical limits. This represents a scenario more ambitious than the REALISTIC, which is referred to as the AGGRESSIVE Scenario.

Differences among the three Scenarios developed in this study are summarized in Table 2-11, where the electrolytic hydrogen share targets in each analyzed sub-sector are given for the years 2030, 2050, 2070, and 2100. Until 2030, just like in the REALISTIC Scenario, it has been assumed that BAU prevails; hence, no transition to electrolytic hydrogen occurs.

Table 2-11 Summary of Scenario Assumptions

Scenario	Year	H_2 Share (Energy) Cement	H_2 Share (Energy) Steel	H_2 Share (Energy) Chemical	H_2 Share (Process) NH_3
REALISTIC	2030	10%	10%	20%	20%
	2050	50%	50%	60%	60%
	2070	75%	75%	90%	90%
	2100	90%	100%	100%	100%
RELAXED	2030	5%	5%	10%	10%
	2050	30%	30%	50%	50.%
	2070	60%	60%	75%	75%
	2100	90%	100%	100%	100%
AGGRESSIVE	2030	30%	25%	30%	30%
	2050	90%	100%	100%	100%
	2070	90%	100%	100%	100%
	2100	90%	100%	100%	100%

The evolution of the electricity demand (to produce the needed electrolytic hydrogen) in the three sub-sectors that have been analyzed, according to three comparative scenarios (REALISTIC, RELAXED, and AGGRESSIVE) is presented in Figure 2-21. Accepting that the 2/3 energy share of the three sub-sectors remains almost constant in the future; the evolution of the electricity demand for the entire industry sector can be deduced.

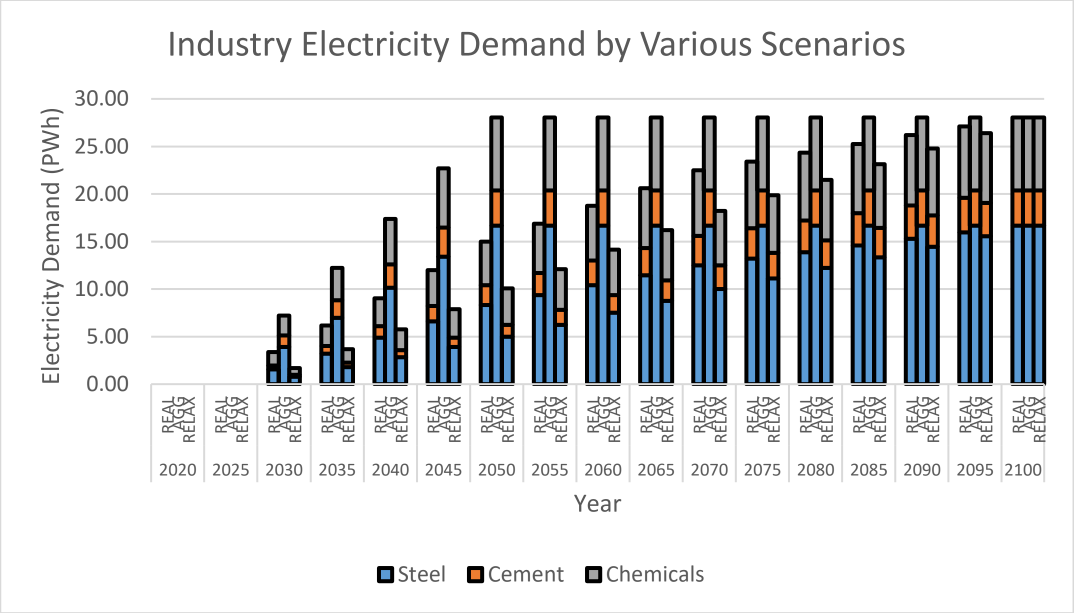

Figure 2-21 Electricity Demand of Steel, Cement and Chemical Sub-sectors by Various Scenarios

Analysis of Figure 2-21 reveals that the electricity generation projected for the year 2100 in the REALISTIC Scenario needs to be reached much earlier (namely by 2050) to achieve the maximum savings in CO_2 emissions (AGGRESSIVE Scenario).

In addition to the created electricity demand, in Figure 2-22, CO_2 emission rates from the three sub-sectors have been presented, in three different scenarios and in comparison with the BAU.

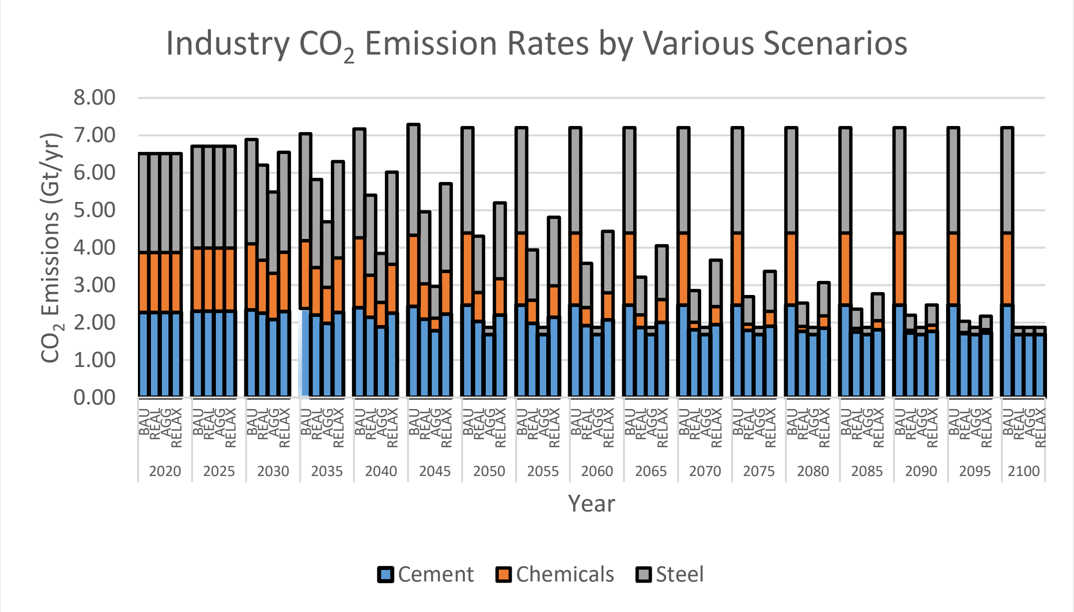

Figure 2-22 CO_2 Emissions of Steel, Cement and Chemical Sub-sectors by Various Scenarios

Because the three sub-sectors represent the entire industry sector (with a factor of 2/3), cumulative CO_2 emissions from the sector have also been estimated. Combining this cumulative emission with the ones from other sectors that are going to be analyzed in the following chapters, information about whether humankind may remain within the carbon budget until 2100 as specified by IPCC [8] can be inferred. This will be the final discussion in this study, which is left to the end. Sub-sectors that have not been analyzed in the study, are considered to contribute half of the sum of three sub-sectors (Iron & Steel, Cement, and Chemicals), as the latter three are responsible for 2/3 of the emissions. The results are shown graphically in Figure 2-23.

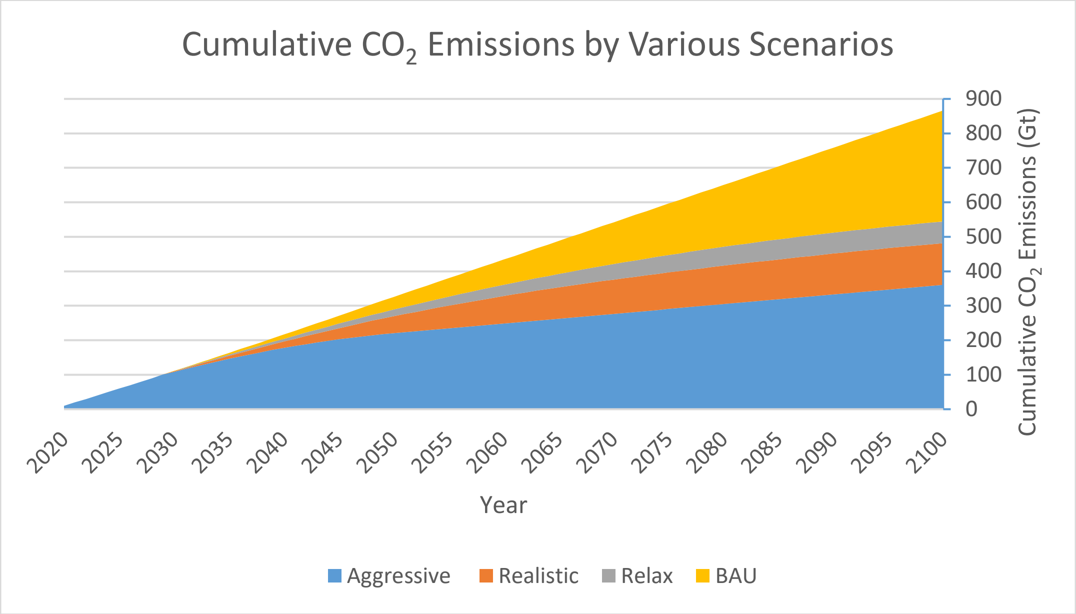

Figure 2-23 Cumulative CO_2 Emissions of Industry by Various Scenarios

Analysis of Figure 2-23 reveals that, CO_2 emissions from 2020 to 2100 can be reduced down to 360.85 Gt employing the AGGRESSIVE Scenario. The base scenario adopted, the REALISTIC Scenario, will imply 481.56 Gt CO_2 emissions in the same period. The possibility of further reducing the emissions by almost 120 Gt comes with a large investment in electricity generation: the electric power generation of 2100 in REALISTIC Scenario, should be realized in 2050.

On the other hand, according to the RELAXED Scenario, 544.18 Gt CO_2 will be emitted in the period 2020-2100. These emissions still represent a saving of approximately 322 Gt from the BAU, which is when no actions are taken for reduction.

While investigating the industry sector, it has been assumed that the material demands will reach maturity by 2050; hence, beyond this year the demands will flat out. However, there exists a large degree of uncertainty in the long term. Therefore, further analyses have been performed, employing two different variants of the REALISTIC Scenario, in which the demand beyond 2050 grows linearly with the

Gross Domestic Product (GDP) and Population Growth. GDP growth rate is taken from OECD's predictions, whereas population growth rate from UN.

Accordingly, GDP yearly linear growth rate is taken to be 2.2710% between 2050 and 2060. From 2060 to 2070, this linear rate is reduced to 2%. Forecasts beyond 2070 are not available. To be able to perform the calculations, it has been presumed that the linear growth is maintained even beyond 2070. To achieve this goal, a linear growth has been set from 2070 to 2100, with a yearly linear growth rate of 1.6667%.

The population growth rates are taken from the UN, which provides various statistics about the forecasts. The median of these forecasts has been selected, hence the yearly linear growth rates are 0.43% between 2050-2060, 0.3% between 2060-2070, and 0.13% beyond 2070.

Assuming that there exists an increase in material demands beyond 2050 (with either GDP or population), the evolution of electricity demand and CO_2 emissions from the three sub-sectors, as well as the cumulative CO_2 emission from the entire industry sector are presented in Figure 2-24 through Figure 2-26.

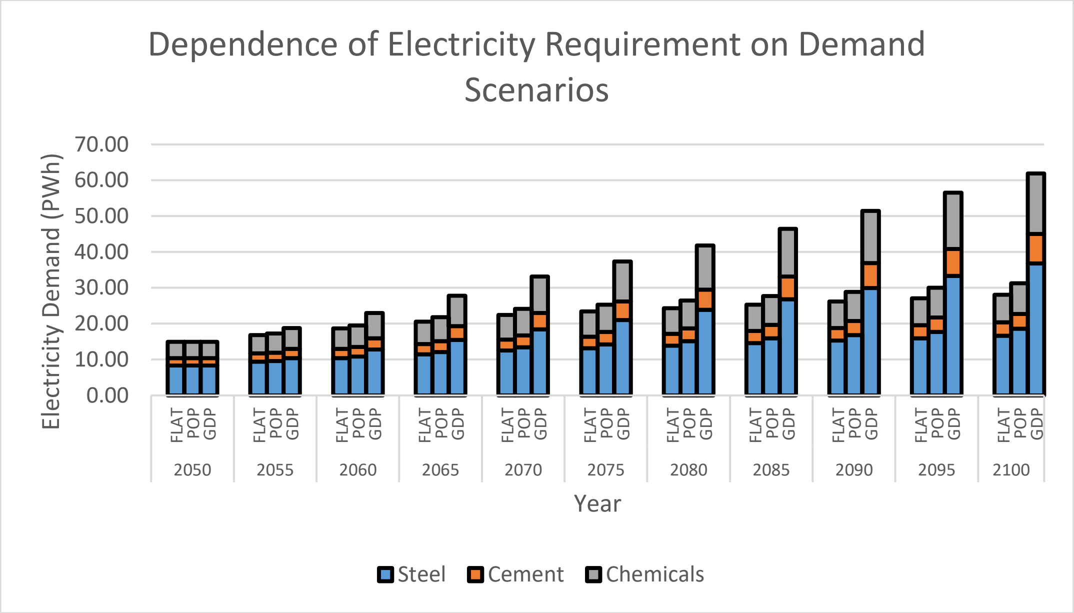

Figure 2-24 Electricity Requirement of Steel, Cement and Chemical Sub-sectors by Demand Scenarios

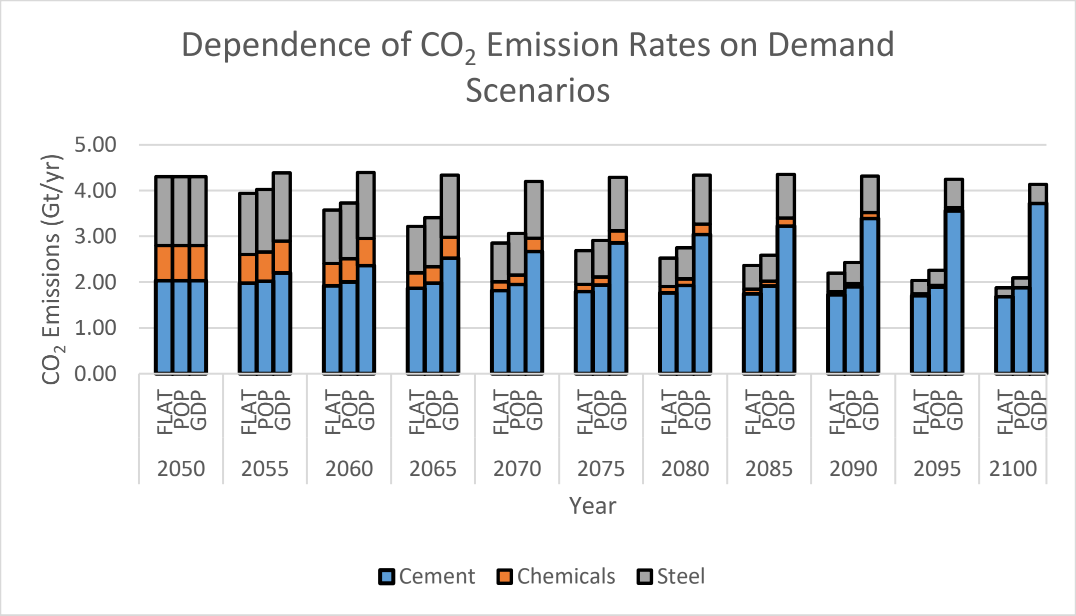

Figure 2-25 CO_2 Emissions of Steel, Cement and Chemical Sub-sectors by Demand Scenarios

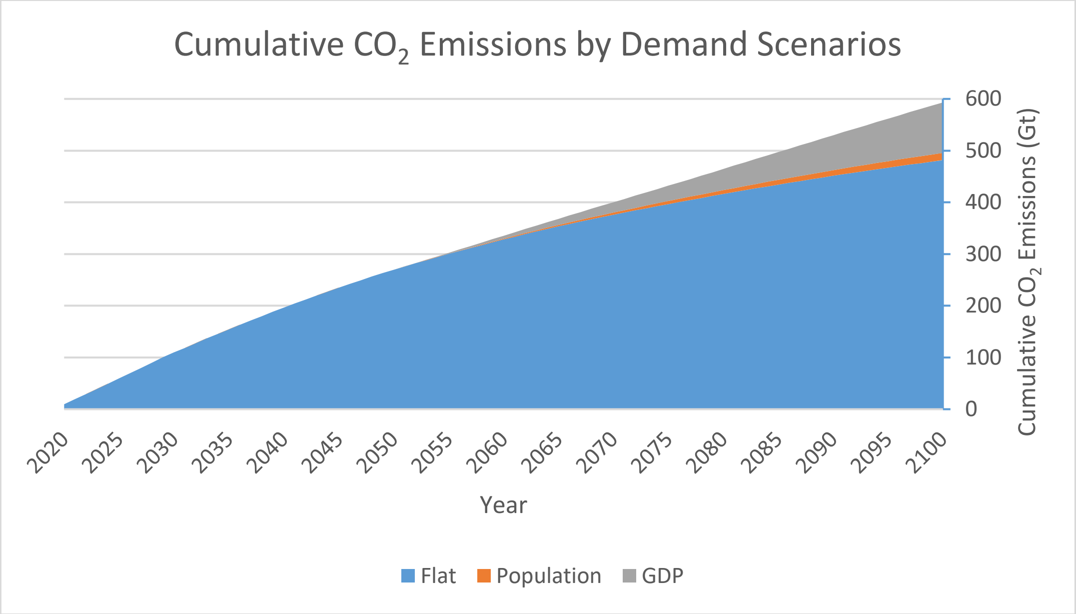

Figure 2-26 Cumulative CO_2 Emissions by Steel, Cement and Chemical Sub-sectors by Demand Scenarios

It is worth noting that a possible material demand growth with population has no major impact on CO_2 emissions. This insensitivity can be attributed to the high level of transition to electrolytic hydrogen that has been reached at an early stage in the REALISTIC Scenario (by 2050). The larger growth with GDP has a more pronounced effect, mostly dictated by process emissions from the cement sector, to which no remedy can be proposed through the use of alternate energy carriers.

2.8. Summary and Novelty of the Approach

Forecasts for materials demands in the three sub-sectors (cement, iron & steel, and chemicals) have been collected from the literature, which were available until 2050 or 2060. Upon comparing data from different sources, those provided by IEA in their RTS Scenario have been selected to be used to identify the energy demand from today until 2050. The long-term material demand has been extrapolated until 2100. In the specific case of industry, this evolution has been adopted to be flat. Current and future energy intensities of the production of each material have been identified, leading to the determination of the yearly energy demand of the industry sector from 2020 to 2100. Thus evaluated energy demand values are specific to the present study.

Following the determination of the energy requirement of the sector, through intense use of electrolytic hydrogen primarily, assisted by direct electricity, a strategy has been developed to mitigate direct CO_2 emissions from the sector. Both selection of the two energy carriers (electrolytic hydrogen and direct electricity) and their adopted pace of penetration form the unique characteristics of the present study. Combined with yearly demand forecasts that are extended until 2100, they form part the basic scenario developed in the study: REALISTIC.

Additional electricity requirement resulting from the proposed mitigation efforts has been evaluated, together with the savings that can be achieved in emissions. To assess the sensitivity of the results to the adopted assumptions, Calculations are performed not only in the basic REALISTIC Scenario but are also repeated under various alternative scenarios, which are also developed in the present study.

CHAPTER 3

TRANSPORTATION SECTOR

Currently, CO_2 emission rates from transportation sector and industry sector are very close. IEA statistics rank the former third with a 21% share of CO_2 emissions, the latter second with only a 25% share [41]. The built-in diversity within the industry sector requires identification of the sub-sectors to analyze the possible remediation efforts to reduce CO_2 emissions. In the case of the transportation Sector, the number of emitters, namely the number of vehicles, is much larger when compared to industry sector. Nevertheless, they can be categorized into few groups and some average emission rates may be assigned to individual groups.

Transportation sector is widely studied in the literature in efforts to determine means of reducing CO_2 emissions [74], [75], [76], [77]. However, the difficulty of gathering data from this large number of emitters results in inconsistencies among the findings. In the case of industry, collecting production statistics is relatively straightforward. Whereas, in the case of transportation, estimating the current rate of transportation throughout the world becomes almost impossible. Therefore, to produce transportation statistics, it is apparent that some assumptions are being made, leading to the aforementioned inconsistencies.

To study the sector, the first step is to identify a proper unit to measure the transportation activity. It is almost agreed by all sources to employ the two units: passenger-km and ton-km, the former to measure passenger, whereas the latter freight activities. Especially passenger activity proves difficult to be measured, as it is largely performed by individuals themselves. Freight activity also incorporates many players; hence, the existence of small-scale players (such as, in-city transporters), from which collecting reliable data is a difficult task, causes large uncertainties in measuring the magnitude of the activity. However, statistics for maritime freight transport (shipping), which dominates the sub-sector, are collected by a single authority (IMO) and considered quite accurate by many authorities.

Another major difficulty in selecting the proper statistics and forecasts to be employed in this study is the different importance allocated to sub-sectors. Some authorities prefer to make urban-domestic-international classification of the activities, whereas others select the distinction between private and public transportation means. In this study, focus is on the CO_2 emissions and means of reducing them in the near future by employing mature technologies, rather than suggesting or promoting behavioral changes to reduce the activity itself, such as shifting towards public or shared transportation modes.

Upon studying the statistics provided by many respected authorities in the sector, ICCT (International Council on Clean Transportation) [78] [79], IEA (International Energy Agency) [77], OECD/ITF (International Transport Forum) [80], SHELL [81], statistics and forecasts provided by ITF have been selected to form a basis to this study. Validity and consistency of the listed statistics have also been confirmed by comparing them to data supplied by sub-sectorial authorities such as IMO (International Maritime Organization) [82] and IATA (International Air Transport Association) [83].

Currently, the transportation sector depends heavily on liquid hydrocarbons as fuel. Therefore, regardless of the means of classification provided in statistics, the total fuel consumption rate evaluated based on them should match the sales of petroleum products. It has been assumed that the petroleum products consumption rate provided by SHELL is correct, as the company is among the top suppliers in the world and keeps the market under strong surveillance. The transport activity figures and the associated energy intensities taken from ITF, match the supply informed by SHELL. This further validates the consistency of the data by ITF, which are employed in this study.

Current characteristics of the transportation sector has been investigated, as well as the forecasts of the activities under two main categories: Passenger transport and freight transport. The analysis of the sector has been initiated with a detailed study of the former. Its current structure has been analyzed, leading to an estimation of how it will change in the near future, followed by the suggestions on CO_2 emission reduction strategies and calculations of the potential effects of such strategies.

3.1. Passenger Transportation

Recalling that there exist many different ways of grouping passenger transportation activities, any classification under urban, non-urban, domestic, or international activities have been disregarded. However, identifying the means of transportation is essential, as their energy intensities, future energy sources are quite diverse. Accordingly, passenger transport activities have been grouped based on their modes: road, rail, aviation, and maritime transportation.

In terms of CO_2 emissions, energy (fuel) consumption, and passenger activity measured in passenger-km, maritime transportation is almost non-existent. Even though this has been a surprising fact for the author of this study, numerous sources agree on the relatively small, even negligible share of maritime passenger transportation. Furthermore, studies do not predict any significant growth in the future. Therefore, maritime passenger transport has not been included to the present analysis.

Lion’s share in CO_2 emissions belongs to road passenger activity. Allocation of vehicle types to road passenger activity is essential because the energy intensity of vehicles differs widely from one to another. Some sources prefer to make a distinction between passenger cars and large passenger cars (SUVs - Sport Utility Vehicles) as their energy intensities are substantially different. However, it is relatively difficult to determine, in passenger-km, the activity carried out by each type. In this study, therefore three different vehicle categories have been used to analyze the road passenger transport: passenger cars (or, simply cars, including

SUVs), 2W/3W (two or three-wheeled vehicles, majority of which are motorcycles), and buses.

Within the road passenger activity, cars (predominantly driven by individuals) are responsible for 85% of the emissions in 2015, according to the statistics provided by ITF [80]. This share drops to 75% in analyses performed by ICCT [84]. Nevertheless, it is beyond dispute that cars dominate the energy consumption, as well as CO_2 emissions in road passenger transport.

Unlike in the case of road passenger transport, available statistics for rail and aviation transport activities are very reliable. Especially in the aviation sector, a single authority (namely, IATA) collects and keeps passenger data. The number of entities that perform aviation transport (airlines) is far less when compared to the number of car drivers, rendering data collection much easier. Similar conditions partly apply to rail passenger transport. When non-urban, domestic, and international passenger activities are involved, again, the number of operators is limited and reliable data can be gathered. Important deviations or uncertainties are present in urban rail passenger transportation, however, performed mainly by municipalities. Distances traveled by urban passengers are not typically registered, therefore data in terms of passenger-km contain an inherent uncertainty.

It has been noted that rail, even when urban transportation is included, does not play an important role in overall passenger transportation. Several authorities underline the importance of increasing rail's share, as it is an energy efficient mode [85], [86]. However, in this study, the analysis of how behavioral characteristics of societies can be changed to reduce energy consumption, hence CO_2 emissions has not been performed. Rather, forecasts by reputable authorities on the intensity of each transport method have been adopted, new CO_2 emission reduction measures have been proposed through the switch to less emission intensive primary energy sources.

Aviation, on the other hand, plays a more important role in passenger transport (25% larger according to ITF [80], whereas 50% for ICCT [84], measured in passenger-km), when compared to rail. Taking into account its higher energy intensity, compared to rail, aviation is the second most CO_2 emitting sub-sector, after road, in passenger transport.

To underline the relative importance of each mode within the passenger transport activities, their contributions are presented in Figure 3-1.

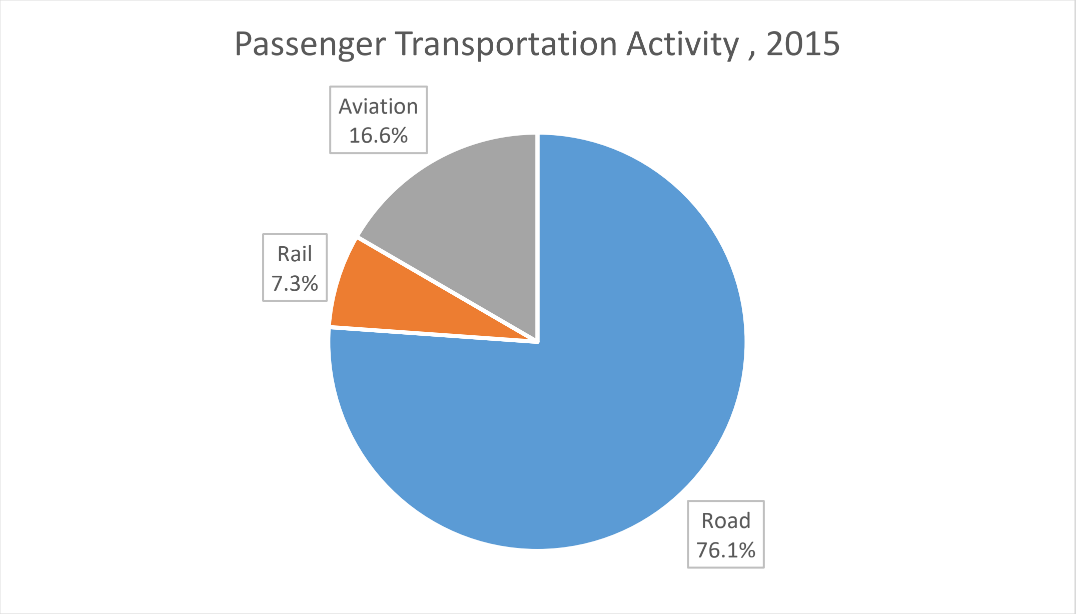

Figure 3-1 Share of Each Mode within the Passenger Transport Activity

3.2. Freight Transportation

In parallel to passenger transport, freight transportation activities have also been analyzed in four different modes: road, rail, maritime, and aviation. In the case of passenger transport, maritime had a negligible contribution, whereas, in freight transport, aviation has a similarly insignificant share. Nevertheless, ITF provided a forecast for aviation freight transport, which have has been included in this study, even though its contribution is small.

Further parallelism exists with passenger transport, as road dominates CO_2 emissions with a 70% share according to ITF 2015 statistics [80]. ICCT’s estimate for this share is also very close to this figure for the same year: 67% [84]. Statistics that are available in the literature for road freight transport incorporate varying categorizations in terms of vehicles. Taking into account the uncertainties and difficulties in collecting data, differentiation between vehicle types (either Heavy Duty Vehicles or Medium Duty Vehicles) has been performed and the entire road freight transportation has been investigated as a whole, as performed by ITF.

The important distinction from passenger transport is the overwhelming weight of the maritime activities in freight transport. Measured in ton-km, maritime constitutes more than 70% of all freight transport activities. However, thanks to its lower energy intensity, maritime ranks second in CO_2 emissions within freight transport.

Statistics for rail freight transport are also quite reliable, as urban rail systems operated by municipalities do not contribute to freight transportation, unlike in passenger transport. However, the volume of rail freight transportation remains small. Authorities, including IEA, emphasize the importance of promoting growth in rail freight to reduce energy consumption and thus CO_2 emissions [85], [87]. Nevertheless, the focus of the present investigation is not on how different transportation modes can be optimized, but rather how CO_2 emission reductions can be achieved in each mode by intensifying the use of renewables and nuclear energy.

To underline the relative importance of each mode within the freight activities, their contributions have been presented in Figure 3-2.

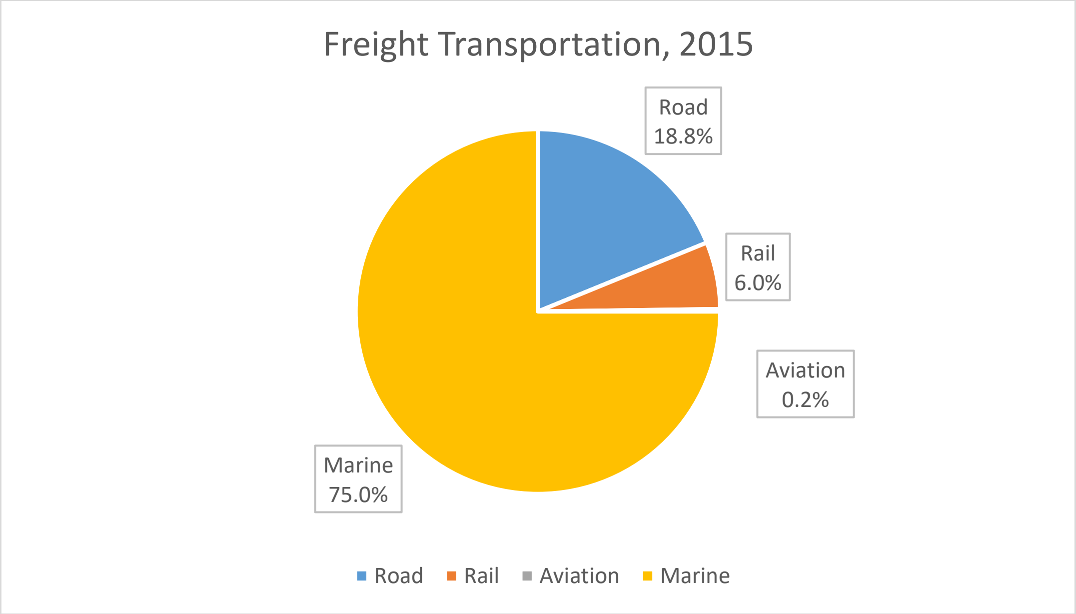

Figure 3-2 Share of Each Mode within the Freight Activities

3.3. Methodology in this study

To analyze the current structure of the transportation sector, mainly statistics provided by ITF have been employed. Forecasts for sub-sectors have also been provided by ITF and are used in this study. It is important to remind that forecasts performed by various authorities contain considerable deviations. Each authority developed its own scenario (or even scenarios) to demonstrate the effectiveness of its CO_2 emission mitigation strategies. The intension in this study is not making suggestions on how social behaviors can or should be modified to lower energy consumption and thus CO_2 emissions. In other words, the more extensive use of energy efficient transport modes, such as rail, or enhancing public or shared transportation are not being promoted. Therefore, forecasts by ITF for transport activities throughout the world have been adopted. These data have been processed to eliminate uncertainties due to different categorizations employed in their collection. Upon studying the suggestions available in the literature for the use of alternate energy carriers to reduce CO_2 emissions, penetration pace of direct electricity and electrolytic hydrogen has been estimated in the sector.

Forecasts provided by ITF extend to 2050, with figures given for years 2015, 2030, and finally for 2050. Linear interpolation has been performed for years in between. OECD, the mother organization of ITF, also provided forecasts until 2060 for Gross Domestic Product (GDP). It is widely accepted that transport activity is directly proportional to GDP. OECD estimated that between 2050 and 2060, GDP would grow linearly with a yearly rate of 2.2710%. The predictions are that the growth rates tend to decrease in the long term. Hence, between 2060 and 2070 a 2% yearly linear growth rate has been proposed. Producing a reasonable model beyond 2070 becomes very difficult due to the large level of uncertainties. Nevertheless, analysis of the forecast by OECD reveals that it is based on a gradual decrease in the yearly growth rate in GDP. Hence, it has been assumed the linear growth prediction for the 2060-2070 period will continue at the same pace; hence, a linear growth with a 1.6667% yearly rate is used for calculations from 2070 until 2100.

Many sources speculate on potential energy efficiency improvements in vehicles, and consider these developments in estimating future CO_2 releases [74], [84], [88]. Whereas, in this study it has been preferred to reduce the proposed improvements in energy intensity (hence energy efficiency) of the engines powering the vehicles, to obtain a more realistic forecast. One reason is that, especially in the case of internal combustion engines, humankind has a very long experience with them, and many technological improvements have already been implemented. Second, it is expected that the use of internal combustion engines will cease in the future, mainly because of CO_2 emission concerns, therefore even if improvements become available, their impact will not be significant. For electric propulsion, it is important to note that it is already close to its theoretical limit. The energy intensities that are adopted are given in the presentation of each mode in the following sections.

Energy intensity of vehicles are denoted by $Eint_X(mode, carr, yr)$ where the variables; $mode = \{LDV, 2W, Bus, HDV, rail, avia, mar\}$ is associated with the road (LDV, 2W/3W, Bus, and HDV), rail, aviation, and marine modes, $carr = \{elec, fos, H2\}$ with direct electricity, fossil fuel, and electrolytic hydrogen energy carriers, and $yr = \{2015, \ldots, 2100\}$ with the years, respectively. The index $X = \{P, F\}$ corresponds to passenger transport and freight activities, respectively.

To scrutinize further the methodology, how the share of each energy carrier employed by vehicles in the future has been modeled are presented in this section. To this end, arguments and forecasts provided by ITF [80], ICCT [84], and in a paper by Khalili et al. [74] have been combined. In doing so, one needs to bear in mind that the proposed technology for each energy carrier has already reached an acceptable level of maturity. The expected and/or proposed changes in energy carriers for each transportation mode have been presented separately, below.

Shares of energy carriers are denoted by $sh_X(mode, carr, yr)$, where identical variables in energy intensities are employed.

3.3.1. Proposed Evolution of Road Transport

Road dominates the CO_2 emissions both in passenger and freight transport. Analysis of road passenger transport is particularly difficult, due to the excessive number of vehicles operated by individuals with almost no organizational relation. Similarly, road freight becomes almost untraceable when the final distribution channel of goods (to consumers) is included, to which many independently operated vehicles contribute.

Upon studying statistics from various sources in the literature, it has been identified that there exists no common opinion on how freight transport is shared among Heavy Duty Vehicles (HDV), Medium Duty Vehicles (MDV), and even Light Duty Vehicles (LDV). Each vehicle type has substantially different energy intensity (measured in energy per ton-km). Similarly, allocating an average energy intensity to passenger cars proves difficult. Some (including IEA) tends to provide better estimates on average intensities by differentiating vehicle types, like cars and SUVs [89]. However, the distribution of passenger transport measured in passenger-km in sub-categories is largely unknown.

In this study, upon selecting the statistics and forecasts by ITF, the effectiveness in reducing CO_2 emissions of the use of alternate energy carriers has been assessed. The current situation is that, even though electric vehicles are available on the market, becoming more and more popular, and heavily being advertised, their present share is almost non-existent. Therefore, for practical purposes, the sole energy source for road transportation consists of fossil fuels (petroleum products and natural gas). The employed statistics begin from 2015 and a 100% share to petroleum products among energy carriers has been allocated in this year.

For a long time, there have been discussions on the possible use of hydrogen as an energy carrier in road transport. However, the large volume occupied by hydrogen, even when considerably compressed, proves its use almost prohibitive. Unlike Liquefied Petroleum Gas (LPG), hydrogen's critical temperature (which is close to $-240^{o}C$) is well below the ambient temperature; hence, liquefaction is not an option. This study relies only on proven mature technologies; therefore, the use of hydrogen in the future is restricted to HDVs only, which can accommodate large volumes for an energy carrier. Hence, the targeted share of hydrogen have been selected to be 10% in 2030, 30% in 2050, reaching 40% in 2070 and leveling off thereafter, in freight transport.

Electric as an energy carrier will dominate road transport in the developed scenario. Currently, the development of electric trucks (especially HDVs) is behind electric cars [88]. Therefore, a faster penetration of electric energy into passenger transport than freight has been predicted. An even faster penetration is expected in the case of motorcycles, which are referred to as 2W/3W, in this study. Buses, typically owned by organizations, rather than individuals are expected to be electrified earlier than cars [90]. This can happen only if governments can and will enforce bus owners and operators to switch to electric energy to reduce CO_2 emissions. Such enforcement cannot be applied to the general public, however, who owns the majority of private cars. Nevertheless, governments can and should promote the use of electric energy in private cars, as policymakers.

Current and targeted shares of energy carriers in road transport are summarized in Table 3-1 and Table 3-2. The evolution of the road transport activities is also shown graphically in Figure 3-3 through Figure 3-6.

Table 3-1 Shares of Energy Carriers in Road Passenger Transport (REALISTIC Scenario)

	LDV		2W/3W		Bus	
Year	Electric	Fossil	Electric	Fossil	Electric	Fossil
2015	0%	100%	0%	100%	0%	100%
2016-2029	Linear interpolation					
2030	30%	70%	50%	50%	40%	60%
2031-2049	Linear interpolation					
2050	80%	20%	90%	10%	90%	10%
2051-2069	Linear interpolation					
2070-2100	100%	0%	100%	0%	100%	0%

Table 3-2 Shares of Energy Carriers in Road Freight (REALISTIC Scenario)

Year	Electric	H_2	Fossil
2015	0%	0%	100%
2016-2029	Linear interpolation		
2030	20%	10%	70%
2031-2049	Linear interpolation		
2050	50%	30%	20%
2051-2069	Linear interpolation		
2070-2100	60%	40%	0%

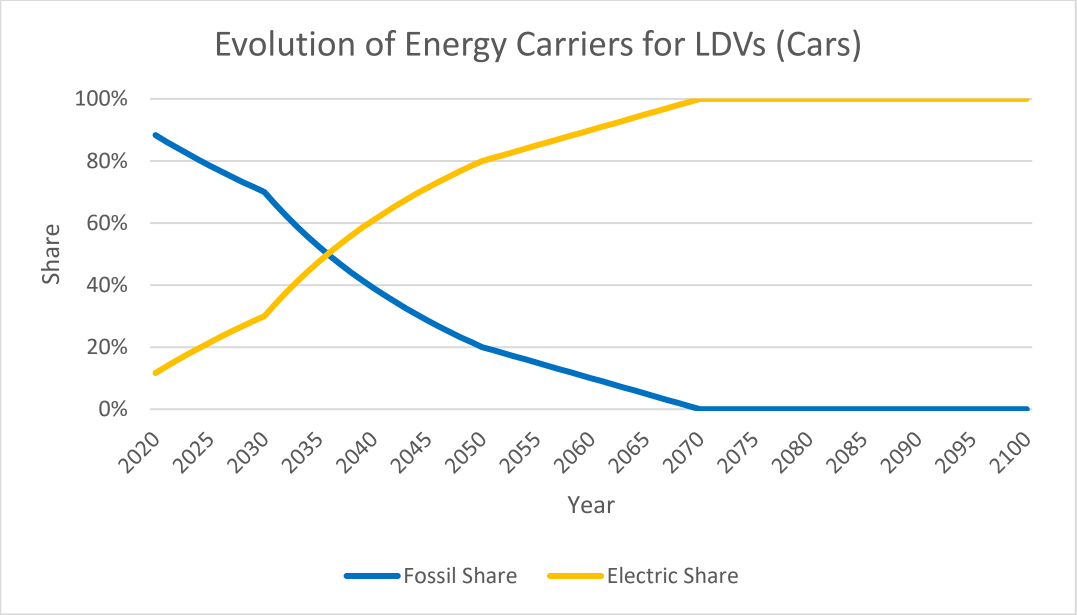

Figure 3-3 Evolution of Energy Carriers for LDVs

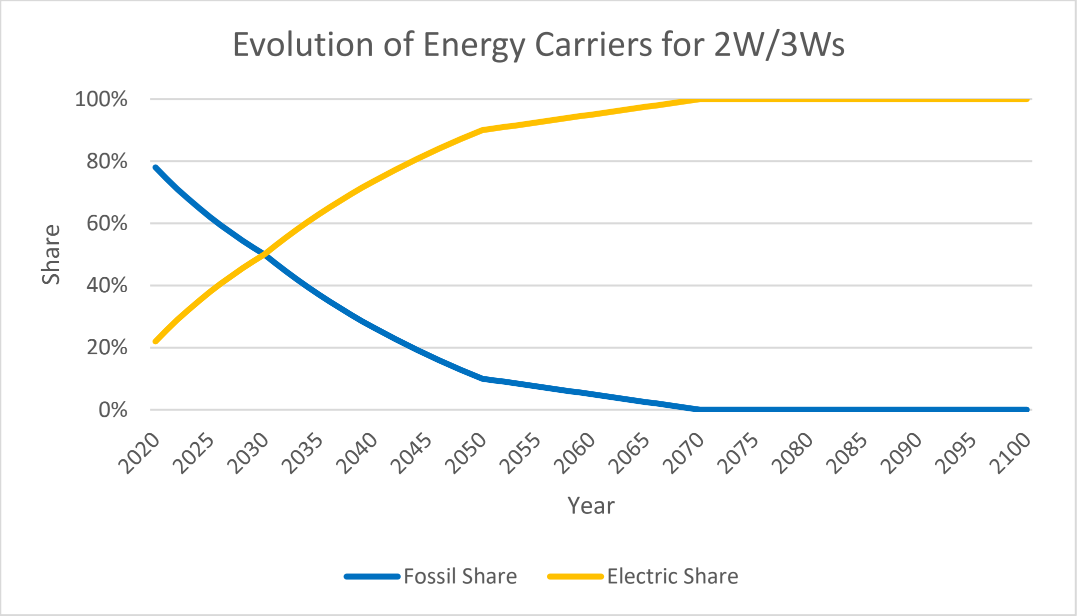

Figure 3-4 Evolution of Energy Carriers for 2W/3Ws

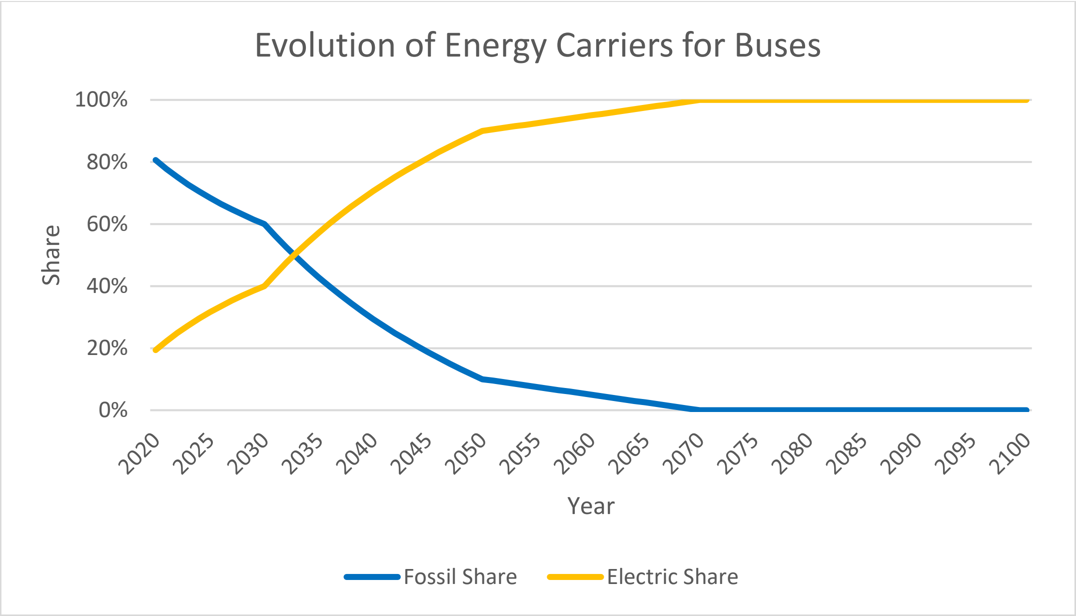

Figure 3-5 Evolution of Energy Carriers for Buses

Share of energy carriers in road passenger transport activities are referred to as $sh_P(sub, carr, yr)$, where the variable $sub = \{LDV, 2W, Bus\}$ is associated with LDV, 2W/3W, and Bus , $carr = \{elec, fos, H2\}$ with direct electricity, fossil fuel, and electrolytic hydrogen energy carriers, and $yr = \{2015, \ldots, 2100\}$ with the years.

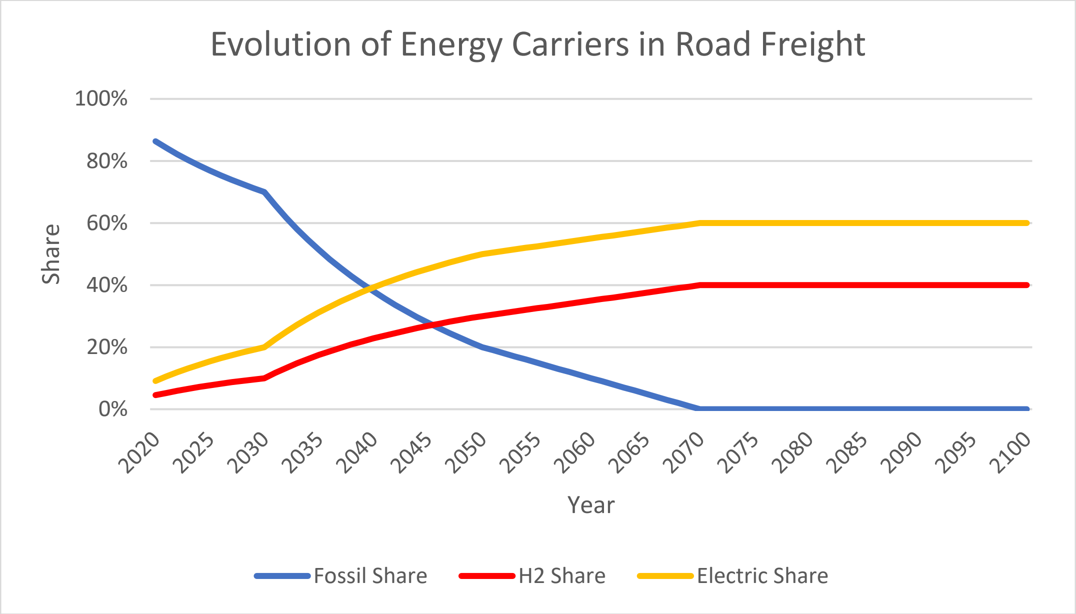

Figure 3-6 Evolution of Energy Carriers in Road Freight (HDV/MDV combined)

Share of energy carriers in road freight activities are referred to as $sh_F(HDV, carr, yr)$, where the variable $carr = \{elec, fos, H2\}$ is associated with direct electricity, fossil fuel, and electrolytic hydrogen energy carriers and $yr = \{2015, \dots, 2100\}$ with the years.

3.3.2. Proposed Evolution of Rail Transport

Current energy decomposition of rail mode is 45% electric, 55% diesel for passenger transport; 39% electric, 61% diesel for freight transport [74]. The strategy for rail seems rather straightforward: Full electrification. Only economic concerns can delay the electrification of rails, as its technology has already matured and considerable experience has already been accumulated. Governments may not only promote, but also even impose electrification, to reduce CO_2 emissions.

In this study, it has been targeted that full electrification will occur in 2050. Current [74] and targeted shares of energy carriers in rail transport are summarized in Table 3-3 and Table 3-4. The evolution of the road transport activities is also shown graphically in Figure 3-7 and Figure 3-8.

Table 3-3 Shares of Energy Carriers in Rail Passenger Transport (REALISTIC Scenario)

Year	Electric	Fossil
2015	45%	55%
2016-2029	Linear interpolation	
2030	80%	20%
2031-2049	Linear interpolation	
2050-2100	100%	0%

Table 3-4 Shares of Energy Carriers in Rail Freight (REALISTIC Scenario)

Year	Electric	Fossil
2015	39%	61%
2016-2029	Linear interpolation	
2030	80%	20%
2031-2049	Linear interpolation	
2050-2100	100%	0%

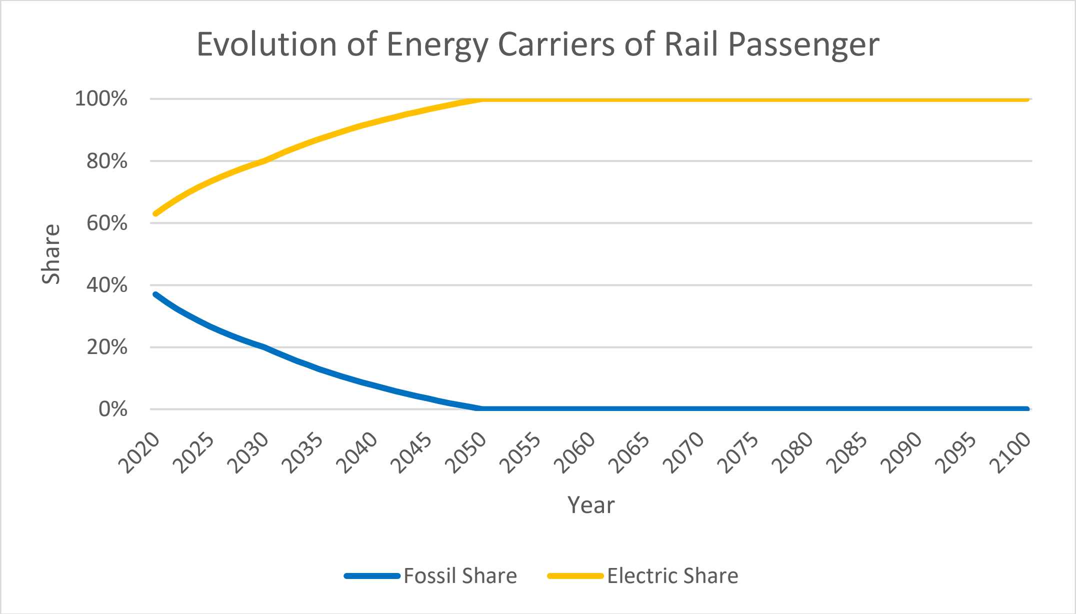

Figure 3-7 Evolution of Energy Carriers of Rail (Passenger Mode)

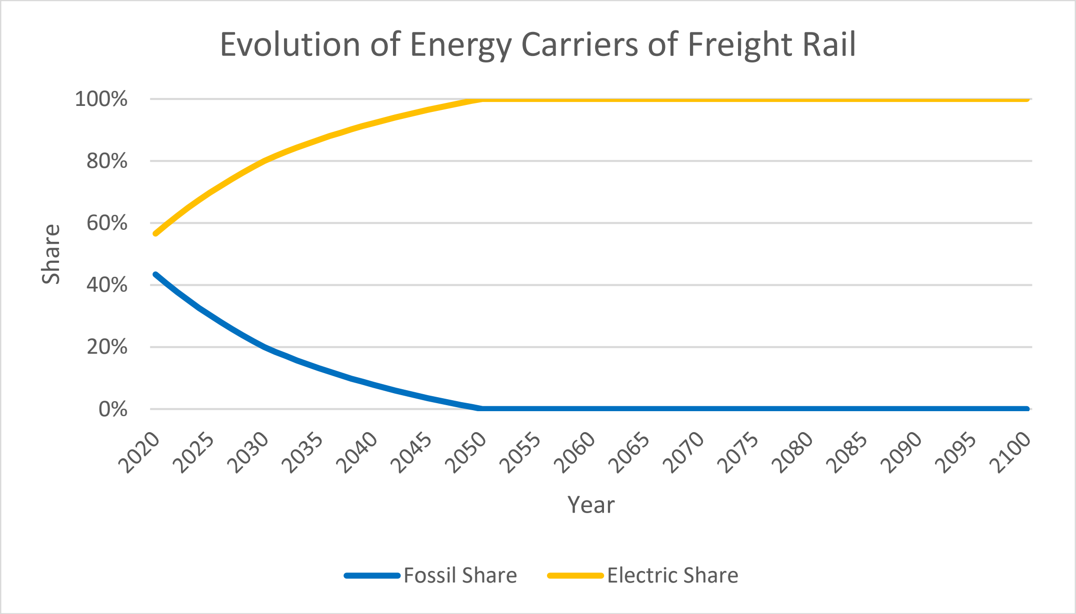

Figure 3-8 Evolution of Energy Carriers for Rail (Freight Mode)

Share of energy carriers in rail mode activities are referred to as $sh_X(rail, carr, yr)$, where the variable $carr = \{elec, fos\}$ is associated with direct electricity and fossil fuel, $X = \{P, F\}$ with passenger transport and freight, and $yr = \{2015, \dots, 2100\}$ with the years.

3.3.3. Proposed Evolution of Aviation Transport

Aviation currently is taking a significant share in passenger transport. Especially on long distant routes, it is without a competitor. Forecasts agree that this situation will remain intact in the future. On the other hand, aviation has little contribution to freight transport. Today, aviation relies purely on liquid hydrocarbons as energy carriers.

Scientific studies and promotional activities are currently ongoing for the use of alternative energy carriers in the future [91]. However, none of the proposed carriers has been demonstrated to be commercially successful. Owing to the high sensitivity to excess mass and volume, commercial aviation found an application of neither electricity nor hydrogen as an energy carrier. Storage difficulties, both in volume and mass, prohibit the potential use of both energy carriers. Nevertheless, search and development efforts are ongoing, yet, they seem far from mature to be considered in this study.

Currently, there exists no commercially viable solution for aviation, other than liquid hydrocarbons. Suggestions in the literature concentrate on the use of biofuels in an effort to reduce CO_2 emissions [92]. However, biofuels' carbon neutrality comes from the capture of CO_2 from the atmosphere during agriculture. There will be still emissions of CO_2 while transport activities occur. Hence, biofuels are not considered in the investigation of the transport sector, mainly because carbon capture technologies lie outside the scope of this study.

3.3.4. Proposed Evolution of Maritime Transport

The current situation is such that fossil fuels dominate the maritime mode [74]. Apart from some demonstration purposes, neither electric energy nor hydrogen has found any application in maritime mode: Examples of electric applications include *Zerocat 120* by Siemens and *Ar Vag Tredan* by STX France, and hydrogen fuel-cell powered ships *Viking Lady* and *FCS Altserwesser* [91]. It is important to remind that, in this study, maritime mode contributes solely to freight transport, in which it dominates all other modes. To this end, electric propulsion in maritime applications, even though is subject to many recent advertisements, because it is intended mostly for passenger transportation, will have no significant effect on CO_2 emission reductions. It may however serve in gaining public acceptance of alternate, greener energy carriers.

Maritime freight transport mostly consists of international trade, involving journeys with very long distances. Therefore, currently, electric energy does not prove an alternative, mainly because of the lack of storage technology on such large scales. Since no mature technology is available for the required storage, electricity as an energy carrier will have a very limited role in maritime transport mode. It may find a marginal application on short hauls, yet in terms of ton-km, its contribution is expected to remain very small.

Hydrogen, because of its storage difficulty cannot take a major share in maritime either. For long hauls, which constitute the majority of the maritime activities, a mature technology that will enable the use of hydrogen as an energy carrier in maritime transport has not been identified. The only acceptable use of hydrogen is limited to short hauls, such as river/canal transportation, where hydrogen supply can be maintained to ships. A demonstration for the use of a fuel cell running on hydrogen has already been performed on an inland waterway barge, named *Antonie* in the Netherlands [93]. Therefore, considering also the high efficiency potentials of fuel cells, some share has also been allocated to hydrogen in the future.

Another alternative, green energy carrier, which is widely discussed in the literature for maritime applications, is ammonia [94], [95]. The combustion properties of ammonia differ substantially from those of hydrocarbons. The lower flame propagation velocity requires changes in internal combustion engine designs. Nevertheless, there exist serious development projects for such engines, by large manufacturers including Wartsila, MAN, and MHI. By its very nature, the combustion of ammonia does not produce any CO_2. However, special care should be given to combustion chamber design to eliminate the potential generation of unwanted nitrous oxides [96].

Ammonia's low flame propagation implies an engine operation at a relatively constant speed. Quick changes in power levels cannot be achieved in contemporary internal combustion engines. Therefore, its use for road applications, where sudden changes in power are often required, needs further improvements. Furthermore, the energy intensity of ammonia is much lower than current hydrocarbons, hence, similar storage volume limitations that apply to hydrogen, are also valid to ammonia, although to a lesser extent. Therefore, the current maturity level of ammonia-burning internal combustion engines is acceptable only for maritime applications.

Even though the production of ammonia has a well-developed technology, its future use as an energy carrier seems very unlikely. The energy required for ammonia production, which has been discussed in detail in the industry sector, where its use is not related to its energy carrying capabilities, will be prohibitively large. Energy used during the electrolysis (let alone the energy used to combine hydrogen and nitrogen in Haber - Bosch process) to produce the needed hydrogen exceeds the Higher Heating Value (HHV) of ammonia. Because of the overall ineffectiveness of the process and the low maturity level of the technology, it has been presumed that ammonia combustion will not play an important role in the future of the maritime freight sector.

There are also studies in which Liquefied Natural Gas (LNG) is taking a significant share among marine transportation’s energy carriers [74]. There are several technical challenges to be overcome for this to realize. Yet, even if LNG becomes an important fuel in marine transport, it will still emit a comparable amount of CO_2. Therefore, in this study where minimizing CO_2 emissions is the fundamental goal, the possible use of LNG as an energy carrier has not been considered.

Wind power has been the fundamental source of propulsion for ships for millennia. However, in the late 19th century, with the steam revolution reaching the shipping industry, wind power has been wiped out. Efforts are ongoing in reestablishing the wind's dominance in the sector [91], however, so far no mature technology for wind can be identified that will replace the engine-powered ships. Similarly, there are also studies for photovoltaic ships, but this technology cannot compete with engines on commercial routes, where the majority of the maritime transportation activities occur.

The current and proposed shares of energy carriers used in this study are summarized in . The evolution of the shares of energy carriers are presented graphically in.

Table 3-5 Shares of Energy Carriers in Marine Freight (REALISTIC Scenario)

Year	Electric	H_2	Fossil
2015	0%	0%	100%
2016-2029	Linear interpolation		
2030	3%	5%	92%
2031-2049	Linear interpolation		
2050	5%	15%	80%
2051-2069	Linear interpolation		
2070-2100	10%	20%	70%

Figure 3-9 shows the evolution of the targeted shares of energy carriers in marine freight until 2100.

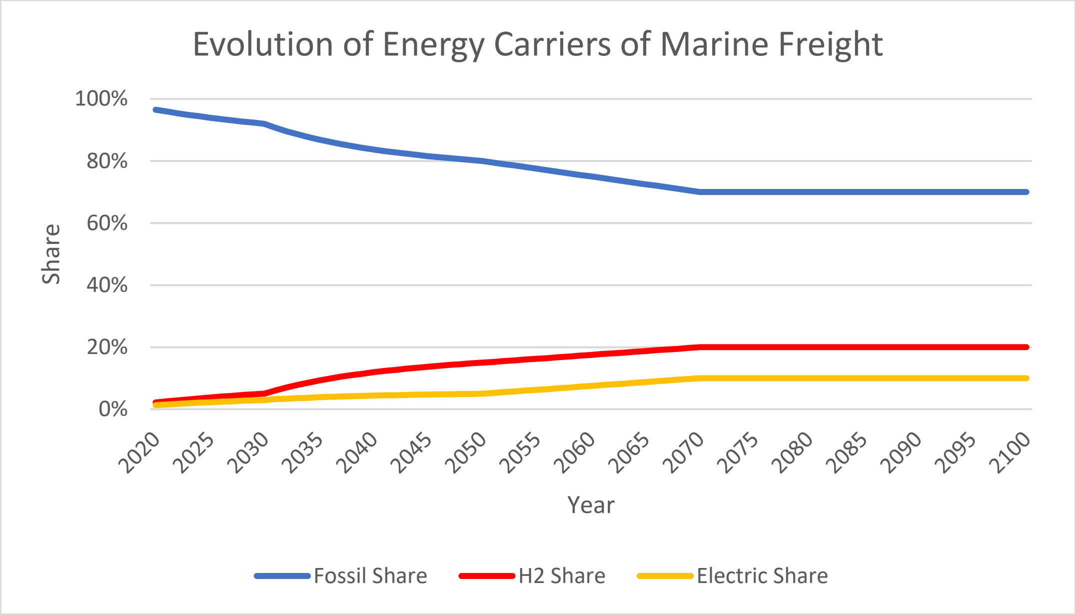

Figure 3-9 Evolution of Energy Carriers of Marine Freight

Share of energy carriers in marine freight activities are referred to as $sh_F(mar, carr, yr)$, where the variable $carr = \{elec, fos, H2\}$ is associated with direct electricity, fossil fuel, and electrolytic hydrogen energy carriers and $yr = \{2015, \ldots, 2100\}$ with the years.

3.4. Additional Installed Capacity Requirement and CO$_2$ Savings

Upon determining the evolution of shares of individual energy carriers in each mode, it remains to calculate the future electric energy demand in parallel to these changes. Forecasts by ITF (International Transport Forum) and OECD have been employed to identify the future magnitude of transport activities. When presenting each transport mode, its associated forecasted evolution has been given in detail. However, to have a better understanding of the overall transport sector, the comparative evolution of the transport modes have also been shown graphically in Figure 3-10 and Figure 3-11. It is worth emphasizing that road mode generates the largest CO$_2$ emissions, both in passenger transport and freight. Aviation plays a significant role in passenger transport, yet it is almost non-existent in freight. In revenge, the marine mode has almost nil contribution to passenger transport, yet it dominates the freight.

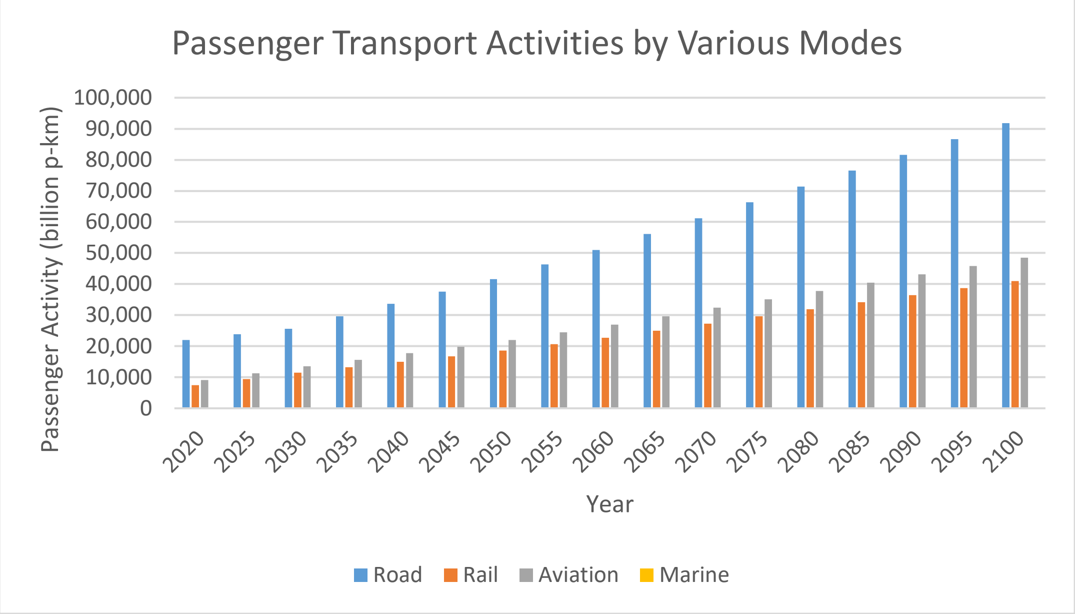

Figure 3-10 Passenger Transport Activity Forecast by Various Modes

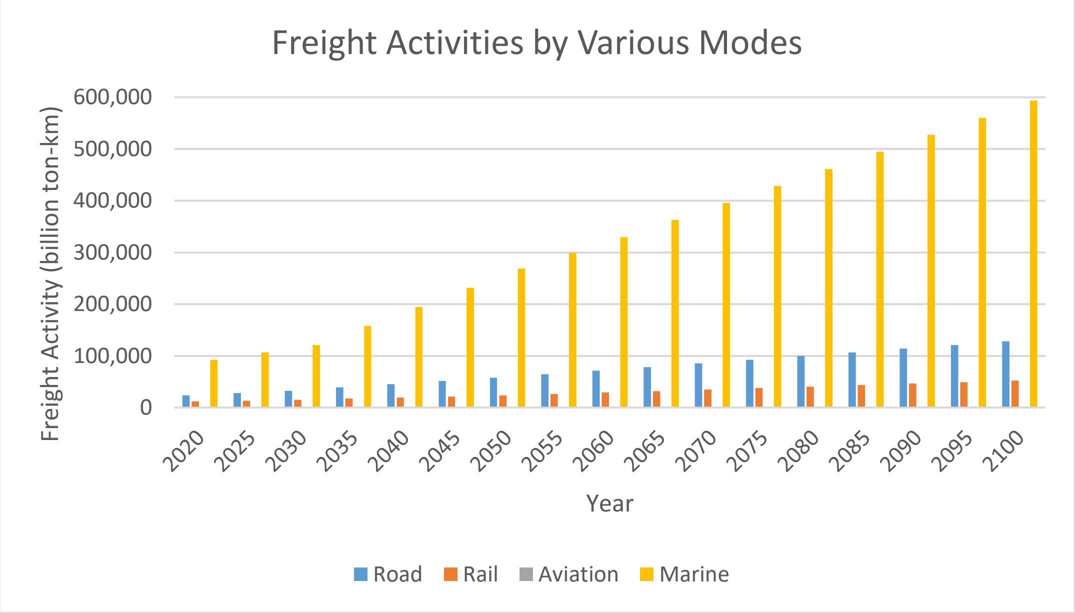

Figure 3-11 Freight Activity Forecast by Various Modes

Using the above described energy intensity in each mode; future electric energy demand to sustain the transport activities has also been predicted. Because fossil fuels will still play an important role in transportation, future CO_2 emissions originating from these activities have also been analyzed. Finally, savings that can be achieved in CO_2 releases, thanks to the proposed energy carrier transition in transportation have been calculated.

The findings are presented for each transport mode separately, so as the readers can have a better understanding of the origin of the future emissions.

3.4.1. Road Transport Mode

Road transport currently produces the most CO_2 emissions both in passenger and freight transport. It also represents the majority of the activity of the former. Road transport is highly inefficient when compared to both rail and marine modes. However, it is an inevitable transport as it typically represents the final stages of any journey, whether it involves passengers or freight. It is also the mode, in which, individual activities transport activities are mostly performed. Therefore, it will remain as a major mode; even policies are developed to replace it with other modes.

Road vehicles outnumber the vehicles in other modes and are predominantly owned by individuals. The transition to a new energy carrier, therefore, is expected to happen slower than in rail mode.

Data and forecasts provided by ITF on road passenger transport and freight activities [80] are tabulated in Table 3-6 and Table 3-7. To extend the activities beyond 2050, a linear increase has been adopted from 2050 to 2060 with 2.271% and 2060 to 2100 with 2% (in parallel to the GDP growth given by OECD [97], which are also reflected in the tables.

Table 3-6 Road Passenger Transport Activities (REALISTIC Scenario)

Year	LDV (Billion p-km)	2W/3W (Billion p-km)	Bus (Billion p-km)
2015	20,152.60	2,448.21	8,675.51
2030	25.652.12	3,839.41	16,304.21
2050	41.563.19	5,469.28	25,710.95
2060	51.002.19	6,711.35	31,549.90
2100	91.803.95	12,080.43	56,789.82

Table 3-7 Road Freight Activities (REALISTIC Scenario)

Year	HDV (Billion t-km)
2015	19,551.00
2030	32,656.00
2050	58,096.00
2060	71,289.60
2100	128,321.28

Passenger activities have been denoted by $A_P(sub, yr)$, where the variable $sub = \{LDV, 2W, Bus\}$ corresponds to LDV, 2W/3W, and bus activities, respectively. Linear interpolation is used to determine the activities corresponding to years not listed in Table 3-6. Total road passenger activity for a given year, denoted by $A_P(road, yr)$, is then given by the relation:

$$A_P(road, yr) = \sum_{sub} A_P(sub, yr) \tag{3-1}$$

Yearly road passenger transport activities corresponding to different energy carriers, which are denoted by $A_p(sub, carr, yr)$ (where the variable $carr = \{elec, fos\}$ corresponds to electric and fossil fuel energy carriers, respectively), are given by:

$$A_p(sub, carr, yr) = A_p(sub, yr) * sh_P(sub, carr, yr) \qquad (3\text{-}2)$$

These activities are evaluated for the years 2015, 2030, 2050, 2060, 2070, and 2100 (i.e., for the variable $yr = \{2015, 2030, 2050, 2060, 2070, 2100\}$). Linear interpolation is then performed for the years in between. The results are then presented graphically in Figure 3-12 through Figure 3-15.

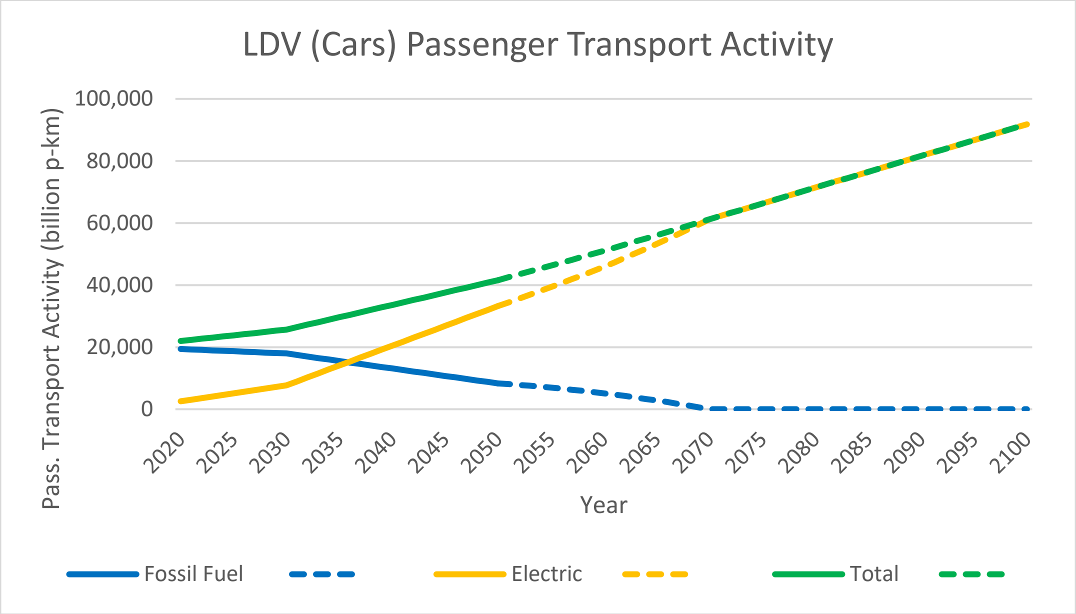

Figure 3-12 LDV (Cars) Passenger Transport Activity

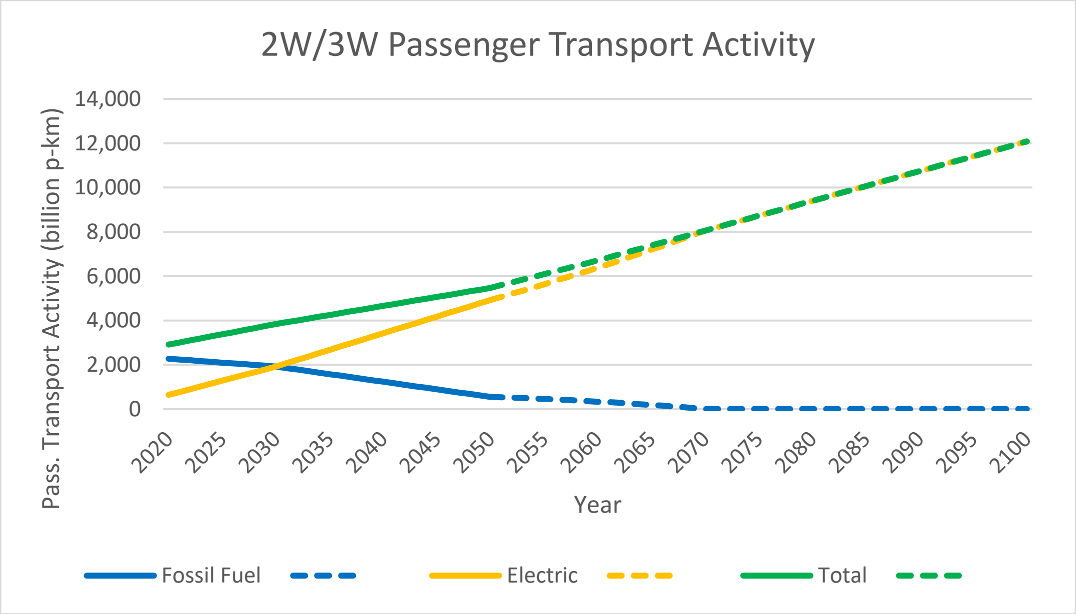

Figure 3-13 2W/3W Passenger Transport Activity

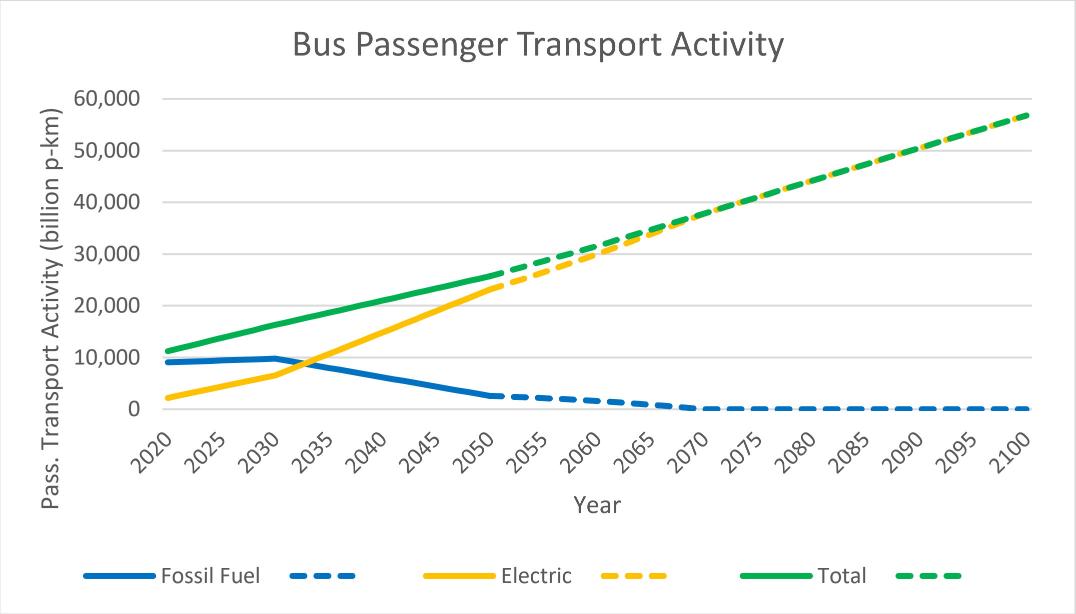

Figure 3-14 Buses Passenger Transport Activity

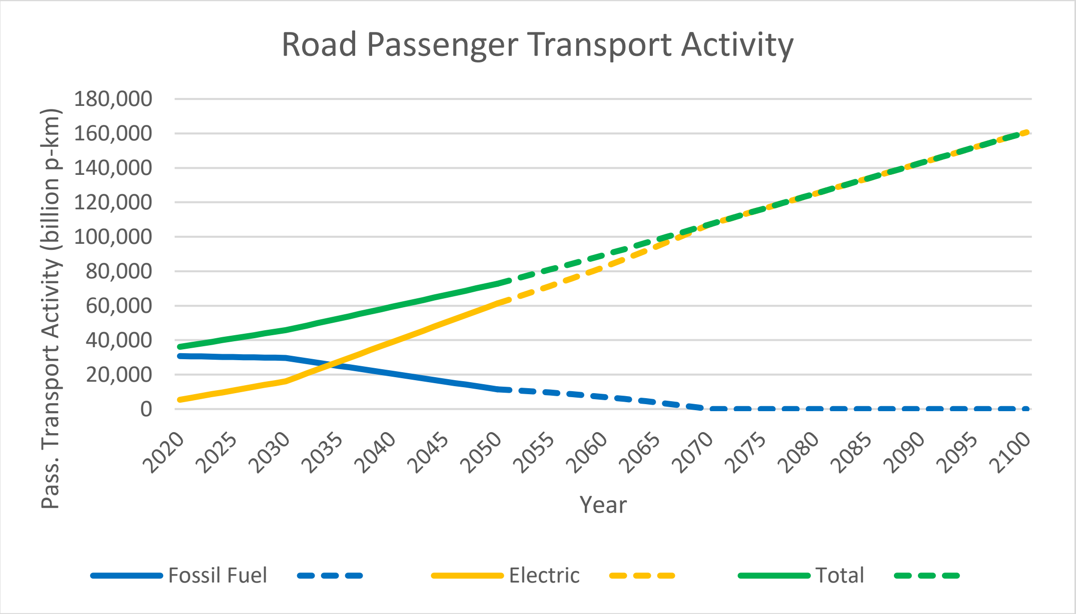

Figure 3-15 Road Passenger Transport Activity

In parallel to passenger transport, yearly road freight activity has been denoted by $A_F(road, yr)$. Again, linear interpolation has been used to determine the appropriate activity corresponding to a year not listed in Table 3-7. Yearly road freight activities corresponding to different energy carriers, which are denoted by $A_F(HDV, carr, yr)$

(where the variable $carr = \{elec, fos, H2\}$ corresponds to direct electricity, fossil fuel, and electrolytic hydrogen energy carriers, respectively), are given by:

$$A_F(HDV, carr, yr) = A_F(road, yr) * sh_F(HDV, carr, yr) \tag{3-3}$$

These activities are evaluated for the years 2015, 2030, 2050, 2060, 2070, and 2100. Upon performing linear interpolation for the years in between, they are presented graphically for years 2020 through 2100 in Figure 3-16.

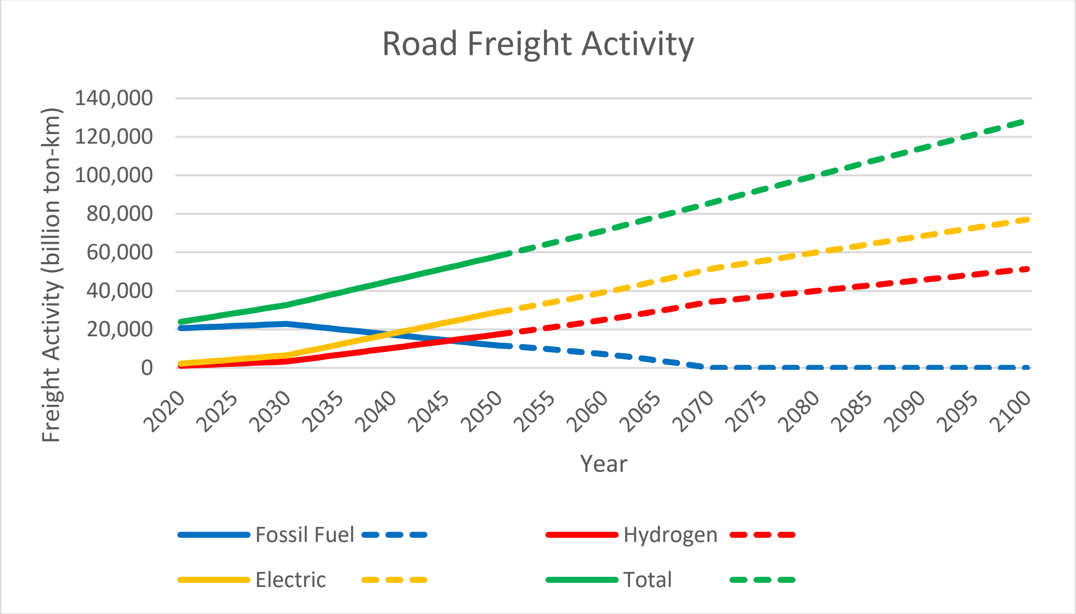

Figure 3-16 Road Freight Activity

To evaluate the additional electric energy required to sustain the proposed evolution, (both current and future) energy intensities in each vehicle category ($Eint_P(sub, carr, yr)$) have been identified. To this end, the author needed to use her own judgment to modify the evolutions proposed in the literature [74] and [89]. Energy intensities that have been adopted in this study are presented in Table 3-8.

Table 3-8 Energy Intensity of Vehicles in Road Passenger Transport

Year	LDV (MJ/p-km) Electric	LDV (MJ/p-km) Fossil	2W/3W (MJ/p-km) Electric	2W/3W (MJ/p-km) Fossil	Bus (MJ/p-km) Electric	Bus (MJ/p-km) Fossil
2015		2.0		0.5		0.7
2030	0.6	2.0	0.1584	0.5	0.25	0.7
2050-2100	0.5	2.0	0.1584	0.5	0.21	0.7

Additional electric energy requirement for each vehicle category ($Elec_P(sub, yr)$) resulting from the use of direct electricity in road passenger transport activities can be calculated using the relation:

$$\begin{cases} Elec_P(sub, yr) = A_P(sub, elec, yr) * Eint_P(sub, elec, yr) \\ sub = \{LDV, 2W, Bus\} \\ yr = \{2015, 2030, 2050, 2060, 2070, 2100\} \end{cases} \quad (3\text{-}4)$$

Linear interpolation is then performed to determine yearly additional electricity demand for years, which are in the set. The total additional electric energy requirement ($Elec_P(road, yr)$) is given by:

$$Elec_P(road, yr) = \sum_{sub} Elec_P(sub, yr) \quad (3\text{-}5)$$

Thus obtained results for passenger transport are presented in Figure 3-17 through Figure 3-19 for each mode and the overall road mode in Figure 3-20, until 2100.

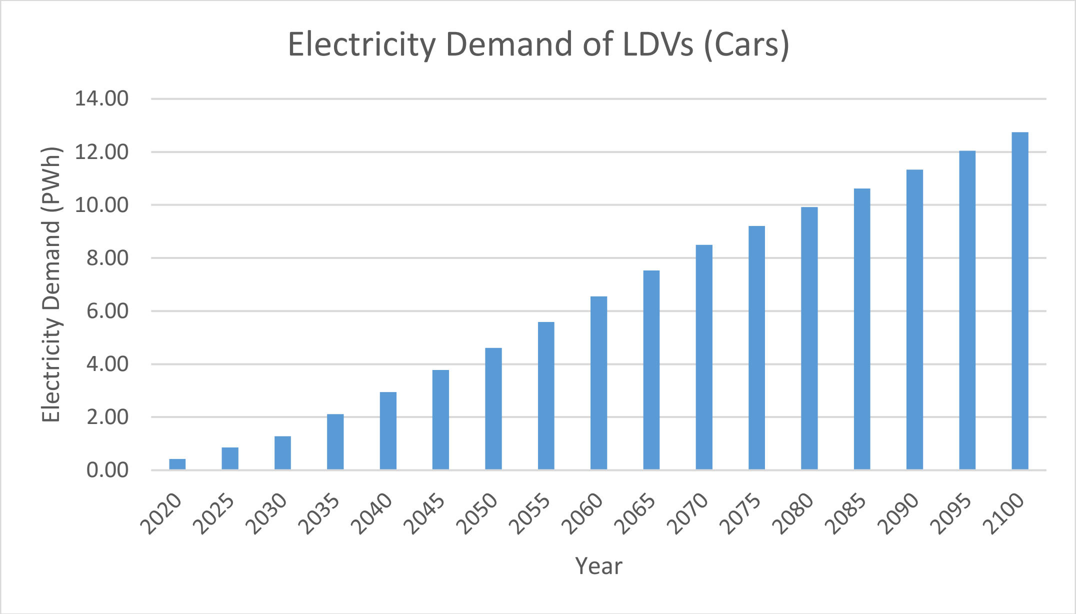

Figure 3-17 Electricity Demand of LDVs

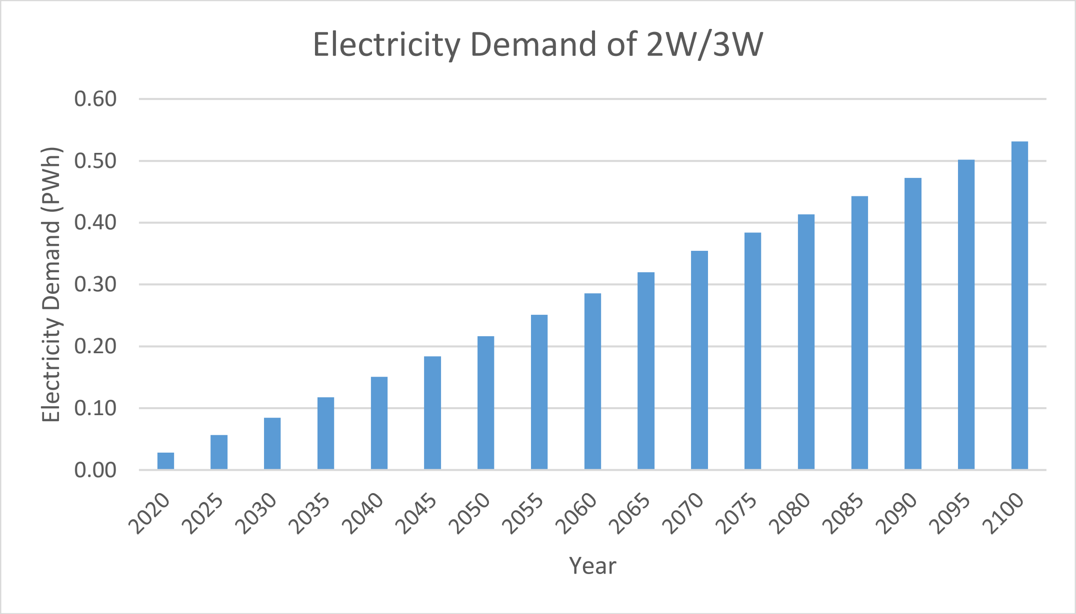

Figure 3-18 Electricity Demand of 2W/3W

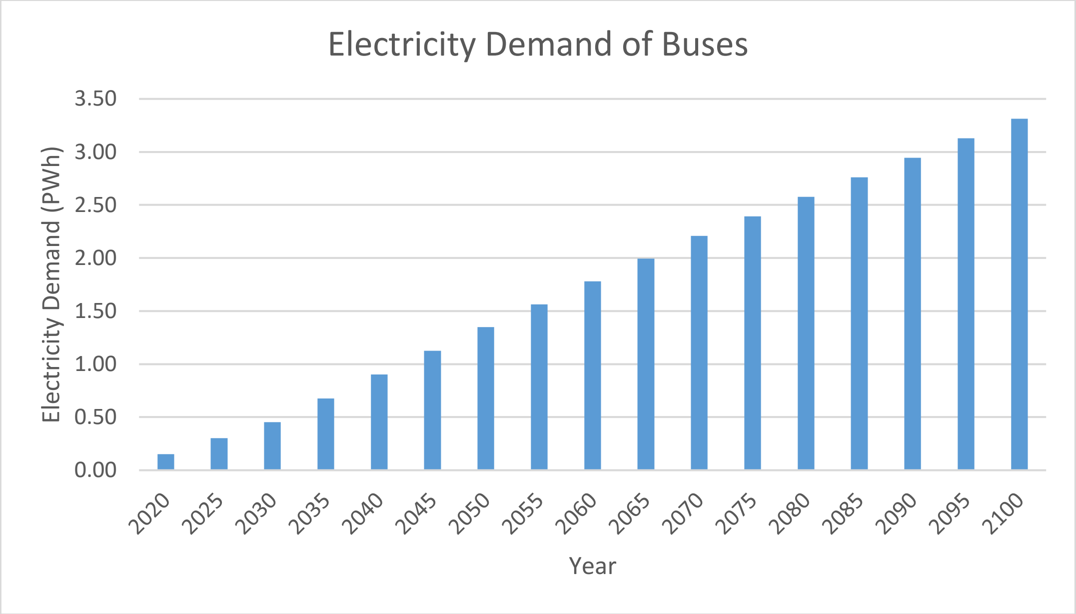

Figure 3-19 Electricity Demand of Buses

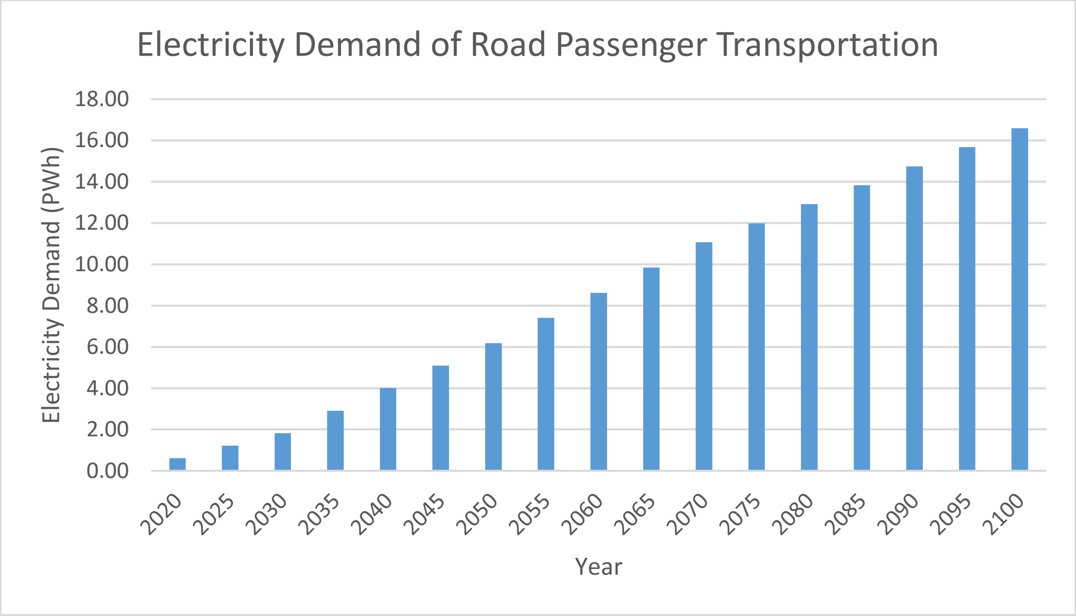

Figure 3-20 Electricity Demand of Road Passenger Transportation

Calculations reveal that an additional electricity generation of 1.82 PWh, 6.18 PWh, 11.06 PWh, and 16.59 PWh are required to achieve the proposed transition to new energy carriers in the years 2030, 2050, 2070, and 2100, respectively.

For the road freight, only one vehicle category has been considered, which is referred to as HDV. This vehicle category incorporates both HDV and MDV type vehicles, and energy intensities have been associated accordingly, using data from various sources [88], [78], and [74], together with the personal assessment of the author. Energy intensity values ($Eint_F(HDV, carr, yr)$) that have been adopted in this study are tabulated in Table 3-9.

Table 3-9 Energy Intensity of Vehicles in Road Freight

Year	Electric	HDV (MJ/t-km) H_2	Fossil
2015			1.6
2030	0.7	0.8	1.6
2050-2100	0.5	0.6	1.6

To determine the additional electricity generation required achieving the proposed mitigation strategy, both direct electricity and electrolytic hydrogen demands for road freight, (denoted by ($E_F(elec, yr)$ and $E_F(H2, yr)$, respectively) have been evaluated using the relations:

$$\begin{cases} E_F(elec, yr) = A_F(HDV, elec, yr) * Eint_F(HDV, elec, yr) \\ E_F(H2, yr) = A_F(HDV, H2, yr) * Eint_F(HDV, H2, yr) \\ yr = \{2015, 2030, 2050, 2060, 2070, 2100\} \end{cases} \tag{3-6}$$

Linear interpolation is then performed to determine yearly additional electricity demand for years, which are in the set. Taking into account the inherent inefficiency of the electrolytic hydrogen use, the total additional electricity demand resulting from the mitigation efforts ($Elec_F(road, yr)$) has been evaluated using the relation:

$$Elec_F(road, yr) = E_F(elec, yr) + 1.5 * E_F(H2, yr) \tag{3-7}$$

Results, with 5 years intervals, are shown graphically in Figure 3-21.

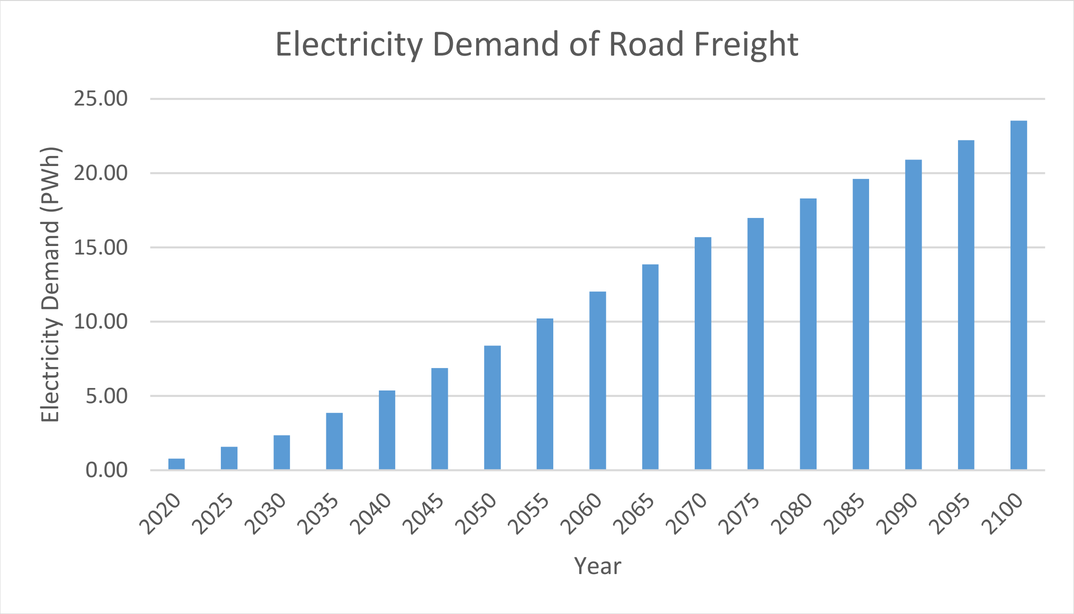

Figure 3-21 Electricity Demand of Road Freight

It has been found that an additional electricity generation of 2.36 PWh, 8.39 PWh, 15.68 PWh, and 23.53 PWh are required to achieve the proposed transition to new energy carriers in the years 2030, 2050, 2070, and 2100, respectively.

The main target of this study being to mitigate CO_2 emissions, savings in these emissions have been evaluated. To this end, CO_2 emissions calculated in the REALISTIC Scenario have been compared with emissions that will occur when equal transport activity is carried out with the current shares of the energy carriers (namely, under BAU conditions).

Emissions in the REALISTIC Scenario result from the partial use of fossil fuels. To assess the amount of CO_2 emissions, energy consumption in fossil-fueled transport activities ($E_X(fos, yr)$) has been determined. Using the road passenger transport activity performed by using fossil fuel ($A_P(sub, fos, yr)$) and energy intensities ($Eint_P(sub, fos, yr)$), fossil fuel energy consumption in the REALISTIC Scenario has been evaluated:

$$\begin{cases} E_P(fos,yr) = \sum_{sub} A_P(sub,fos,yr) * Eint_P(sub,fos,yr) \\ \quad sub = \{LDV, 2W, Bus\} \end{cases} \tag{3-8}$$

The corresponding fossil fuel energy requirement under BAU conditions ($E_{P,BAU}(fos,yr)$) is calculated under the assumption that all transport activities would be performed with the current of fossil fuels in the relevant category. For road passenger activity, this corresponds to almost 100% fossil fuel dependence, hence can be expresses as:

$$\begin{cases} E_{P,BAU}(fos,yr) = \sum_{sub} A_P(sub,yr) * Eint_P(sub,fos,yr) \\ \quad sub = \{LDV, 2W, Bus\} \end{cases} \tag{3-9}$$

Once the energy to be supplied by fossil fuels is determined, prospective CO_2 emissions ($Q_P(road,yr)$) have been evaluated using the emission intensity of a typical hydrocarbon fossil fuel used in transportation: $q_{fos} = 266\,\frac{gCO_2}{kWh}$ [74]:

$$\begin{cases} Q_P(road,yr) = E_P(fos,yr) * q_{fos} \\ Q_{P,BAU}(road,yr) = E_{P,BAU}(fos,yr) * q_{fos} \end{cases} \tag{3-10}$$

Thus collected results for emissions and savings over BAU are shown graphically in Figure 3-22 through Figure 3-25, for road passenger transport.

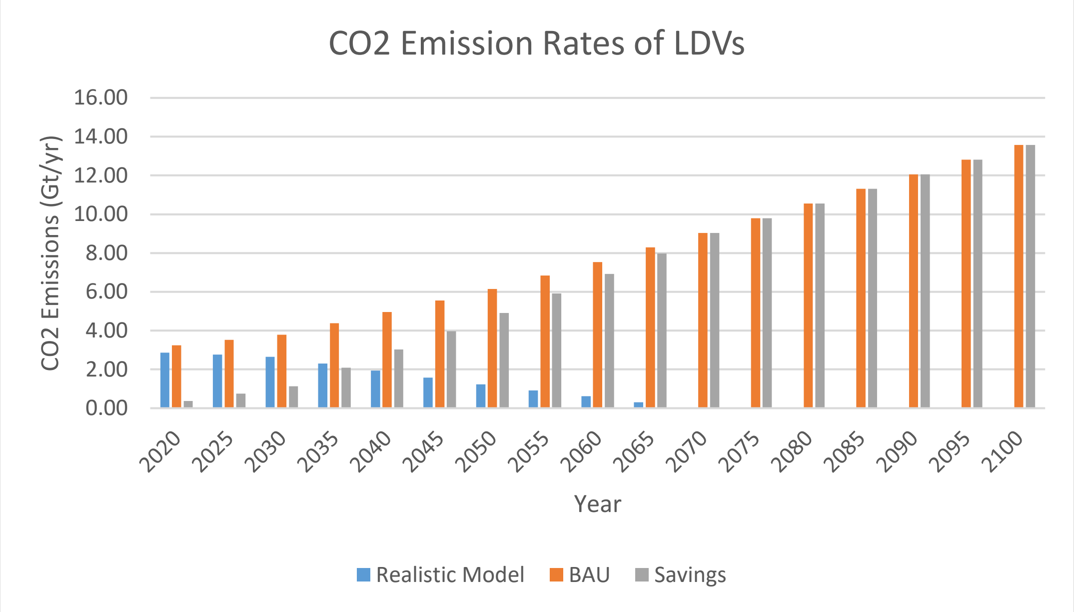

Figure 3-22 CO_2 Emission Rates of LDVs

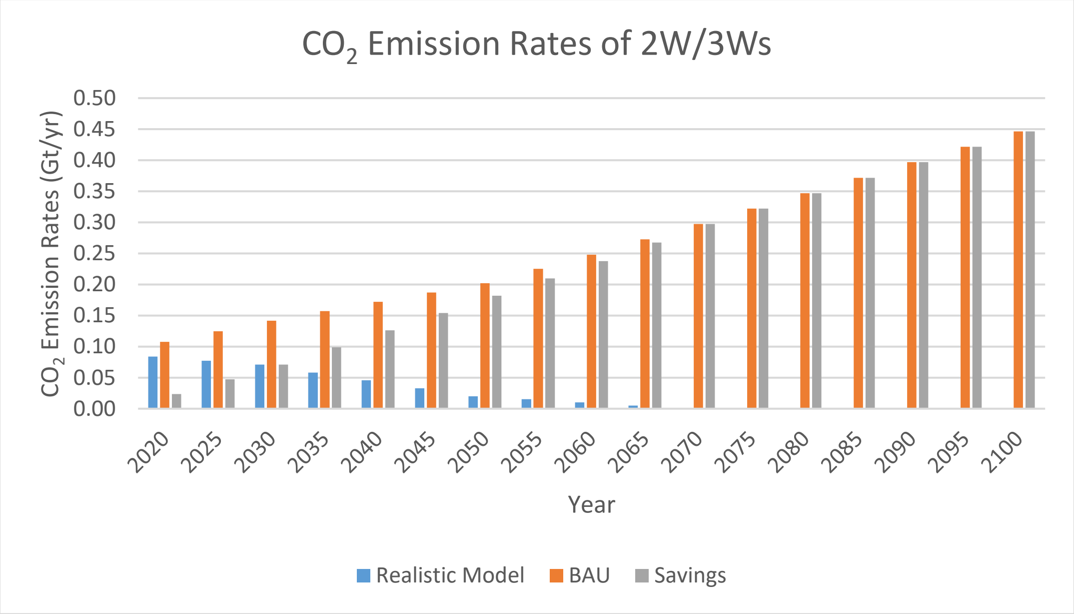

Figure 3-23 CO_2 Emission Rates of 2W/3W

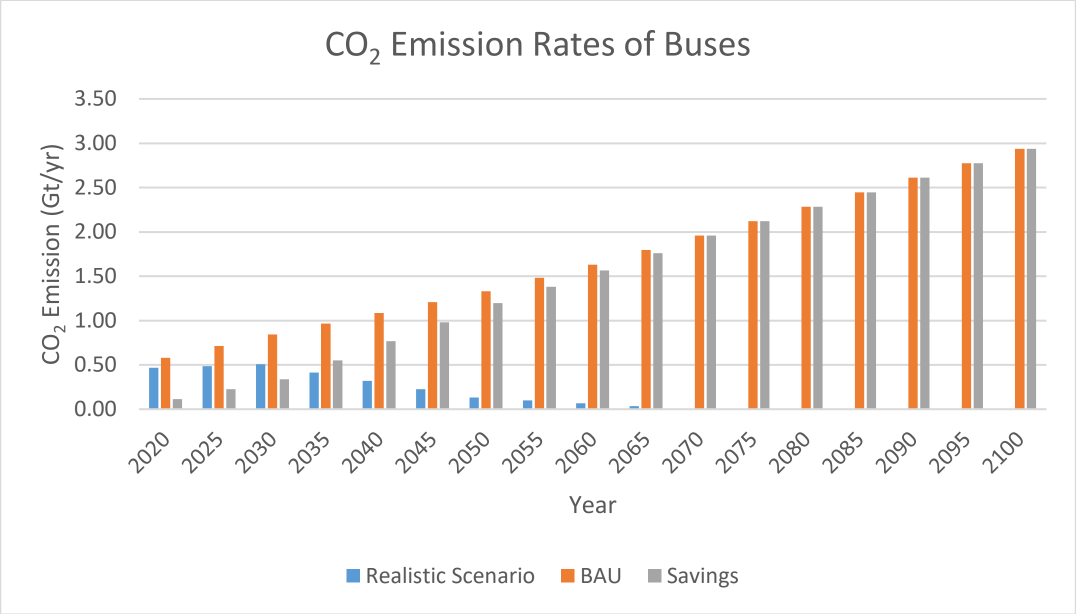

Figure 3-24 CO_2 Emission Rates of Buses

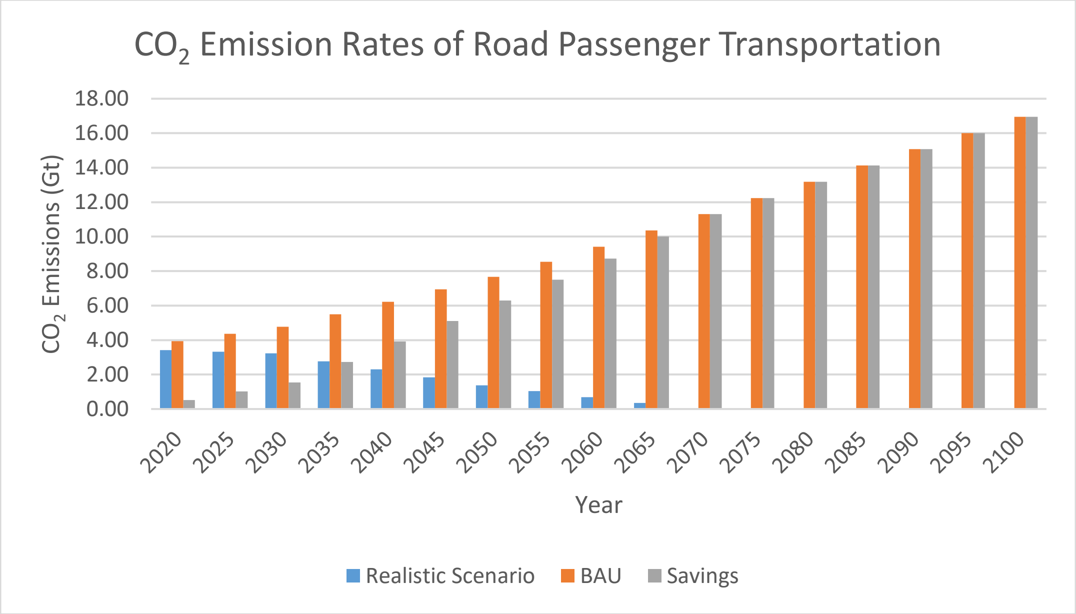

Figure 3-25 CO_2 Emission Rates of Road Passenger Transportation

It has been found that CO_2 emissions in road passenger transport are expected to be 3.23 Gt, 1.38 Gt, and 0.00 Gt in 2030, 2050, and 2070 & beyond, respectively. Under BAU conditions, however, the emission figures are 4.78 Gt, 7.67 Gt, 11.30 Gt, and 16.95 Gt, in 2030, 2050, 2070, and 2100, respectively.

In parallel to road passenger transport, emissions in the REALISTIC Scenario and under BAU conditions for road freight have also been determined. To evaluate the emissions under BAU conditions, as in the case previous case of passenger transport, it has been assumed that all transport activities would have been performed using fossil fuel. Fossil fuel energy demands have been calculated using the relations:

$$\begin{cases} E_F(fos, yr) = A_F(HDV, fos, yr) * Eint_F(HDV, fos, yr) \\ E_{F,BAU}(fos, yr) = A_F(HDV, yr) * Eint_F(HDV, fos, yr) \end{cases} \tag{3-11}$$

Using the same emission intensity for road passenger transport, $q_{fos} = 266 \frac{gCO_2}{kWh}$, emissions in road freight are evaluated. Hence, CO_2 emissions are given by:

$$\begin{cases} Q_F(road, yr) = E_F(fos, yr) * q_{fos} \\ Q_{F,BAU}(road, yr) = E_{F,BAU}(fos, yr) * q_{fos} \end{cases} \tag{3-12}$$

Results have been presented with 5 years period in Figure 3-26.

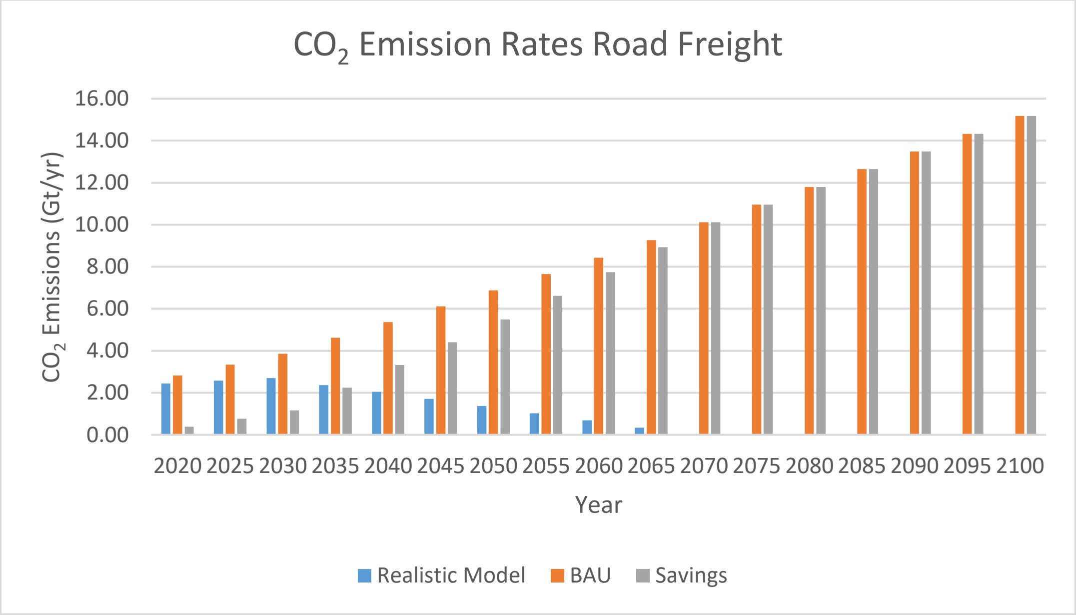

Figure 3-26 CO_2 Emission Rates of Road Freight

It has been found that CO_2 emissions in road freight are expected to be 2.70 Gt, 1.37 Gt, and 0.00 Gt in 2030, 2050, and 2070 & beyond, respectively. Under BAU conditions, however, the emission figures are 3.86 Gt, 6.87 Gt, 10.11 Gt, and 15.17 Gt, in 2030, 2050, 2070, and 2100, respectively.

3.4.2. Rail Transport Mode

Rail mode represents the most energy efficient mode for passenger transport. It competes successfully with marine transport in freight. The high level of electrification that has already been achieved also makes rail mode the greenest transport mode. However, the requirement for a developed infrastructure is its major drawback. The need for governments to promote rail mode is emphasized by IEA, as well [85]. In this study, data and forecasts provided by ITF on rail passenger transport and freight activities [80] have been adopted, until 2050. Beyond, the growth in GDP forecasted by its mother institution OECD has been employed to calculate the transport activities, as described in detail under road transportation. Data employed in this study are listed in Table 3-10.

Table 3-10 Rail Mode Activities (REALISTIC Scenario)

Year	Passenger (Billion p-km)	Freight (Billion t-km)
2015	5,421.76	10,127.00
2030	11,467.46	15,197.00
2050	18,541.48	23,654.00
2060	22,752.25	29,025.82
2100	40,954.06	52,246.48

Passenger activities have been denoted by $A_P(rail, yr)$ and freight activities by $A_F(rail, yr)$. Linear interpolation is used to determine the activities corresponding to years not listed in Table 3-10. Yearly rail activities corresponding to different energy carriers, which are denoted by $A_X(rail, carr, yr)$ (where the variable $carr = \{elec, fos\}$ corresponds to electric and fossil fuel energy carriers, respectively), are given by:

$$\begin{cases} A_X(rail, carr, yr) = A_X(rail, yr) * sh_X(rail, carr, yr) \\ X = \{P, F\} \end{cases} \qquad (\ 3\text{-}13)$$

These activities are evaluated for the years 2015, 2030, 2050, 2060, 2070, and 2100. Linear interpolation is then performed for the years in between. The results are shown graphically in Figure 3-27 and Figure 3-28.

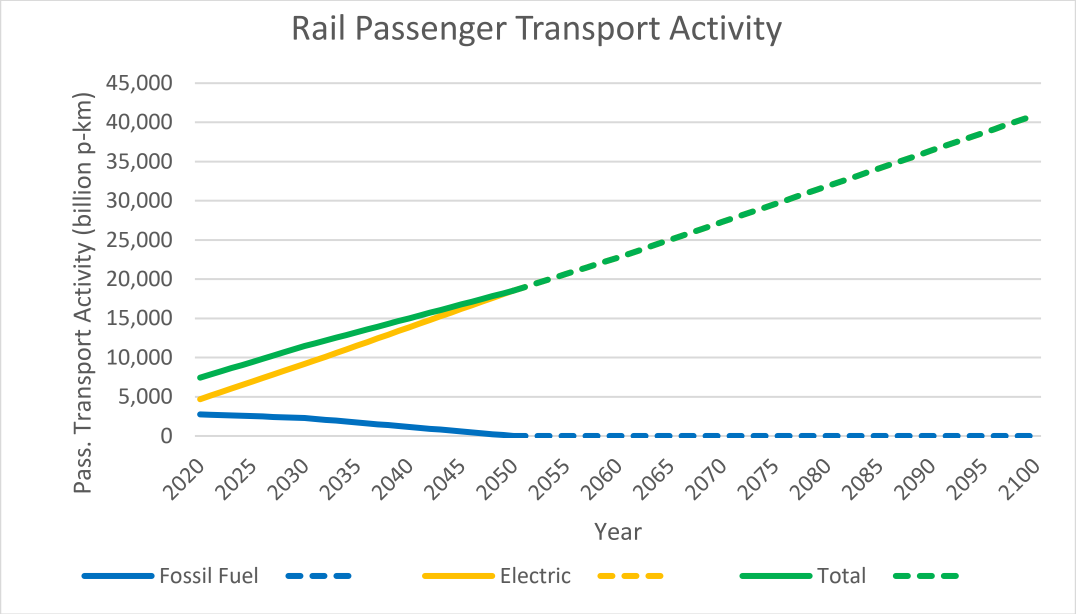

Figure 3-27 Rail Passenger Transport Activity

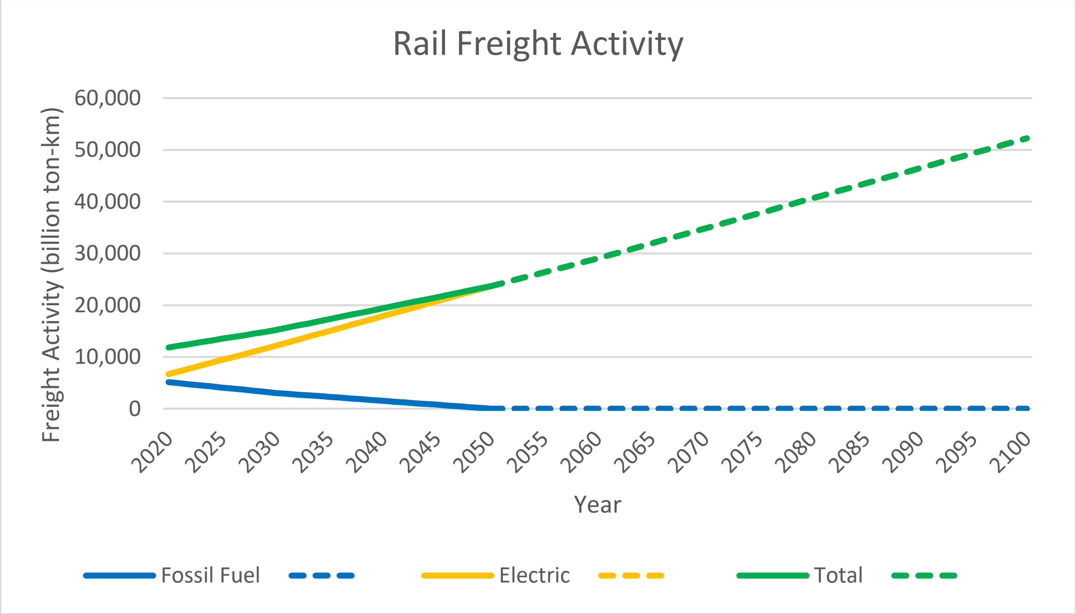

Figure 3-28 Rail Freight Activity

Energy intensity of rail passenger transport and freight activities were determined by using data from various sources [85], [78], and [74], together with the assessment of the author. Energy intensity values $(Eint_P(rail, carr, yr))$ and

$Eint_F(rail, carr, yr)$ that have been adopted in this study are tabulated in Table 3-11.

Table 3-11 Energy Intensities in Rail Mode

Year	Passenger (MJ/p-km)		Freight (MJ/t-km)	
	Electric	Fossil	Electric	Fossil
2015	0.13	0.38	0.117	0.234
2030	0.12	0.38	0.1	0.234
2050-2100	0.10	0.38	0.09	0.234

Future electricity requirement of rail passenger transport and freight activities (that are denoted by $(Elec_P(rail, yr)\ and\ Elec_F(rail, yr)$, respectively) are determined by using the relations:

$$\begin{cases} Elec_X(rail, yr) = A_X(rail, elec, yr) * Eint_X(rail, elec, yr) \\ X = \{P, F\} \\ yr = \{2015, 2030, 2050, 2060, 2070\} \end{cases} \tag{3-14}$$

Linear interpolation is then performed to determine yearly additional electricity demand for years, which are in the set. Forecasted electricity demands are presented with 5 years intervals in Figure 3-29 and Figure 3-30.

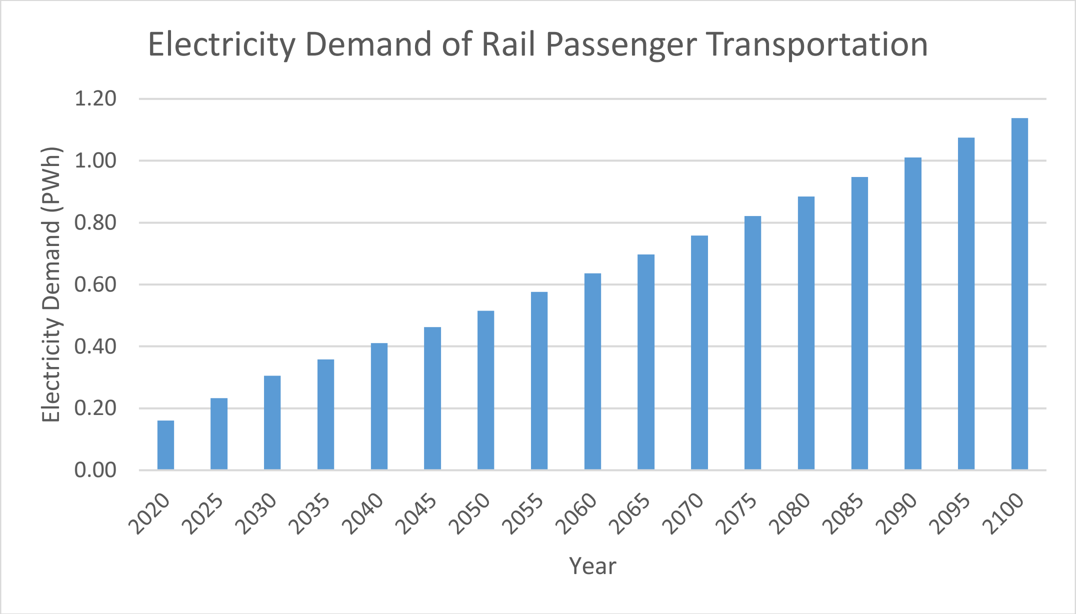

Figure 3-29 Electricity Demand of Rail Passenger

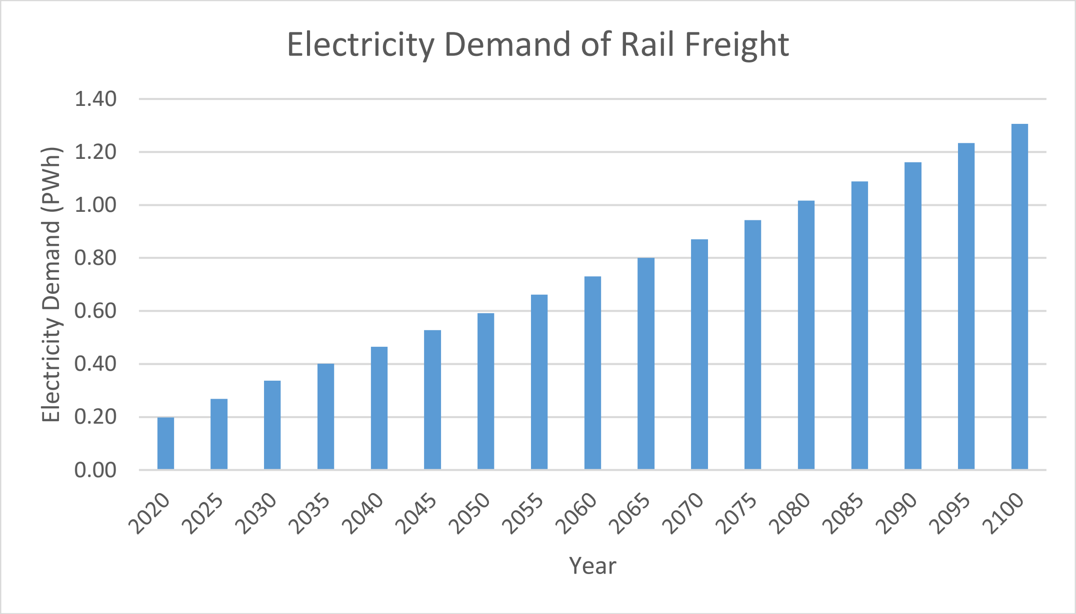

Figure 3-30 Electricity Demand of Rail Freight

It has been found that an electricity generation of 0.31 PWh, 0.52 PWh, 0.76 PWh, and 1.14 PWh are required for rail passenger transport in the REALISTIC Scenario, in the years 2030, 2050, 2070, and 2100, respectively. In the case of rail freight, the corresponding electricity requirements are 0.34 PWh, 0.59 PWh, 0.87 PWh, and 1.31 PWh, respectively.

In parallel to road mode, emissions in the REALISTIC Scenario and under BAU conditions for rail mode have also been determined. Evaluation of emissions in the former has been performed using the relations:

$$\begin{cases} E_X(fos, yr) = A_X(rail, fos, yr) * Eint_X(rail, fos, yr) \\ \qquad\qquad\qquad X = \{P, F\} \end{cases} \tag{ 3-15}$$

For the BAU conditions, it is assumed that the share of fossil fuels remain fixed in the future. Individual share figures given for the year 2015 have been employed, as they were provided in detail by ITF. Recalling that:

$$\begin{cases} sh_P(rail, fos, 2015) = 0.55 \\ sh_F(rail, fos, 2015) = 0.61 \end{cases} \tag{ 3-16}$$

Therefore, energy demands under the BAU conditions are given by the relations:

$$\begin{cases} E_{X,BAU}(fos, yr) = A_X(rail, yr) * sh_X(rail, fos, 2015) * Eint_X(rail, fos, yr) \\ \qquad\qquad\qquad X = \{P, F\} \end{cases} \tag{3-17}$$

Upon determining energy demand for fossil fuels, resulting CO emissions are evaluated by using the same emission intensity for road passenger transport, $q_{fos} = 266 \frac{gCO_2}{kWh}$. Hence, resulting emissions are given by:

$$\begin{cases} Q_X(rail, yr) = E_X(fos, yr) * q_{fos} \\ Q_{F,BAU}(rail, yr) = E_{X,BAU}(fos, yr) * q_{fos} \end{cases} \tag{ 3-18}$$

CO_2 emissions from rail mode, as well as the obtained savings over BAU conditions, are given in Figure 3-31 and Figure 3-32 for every 5 years.

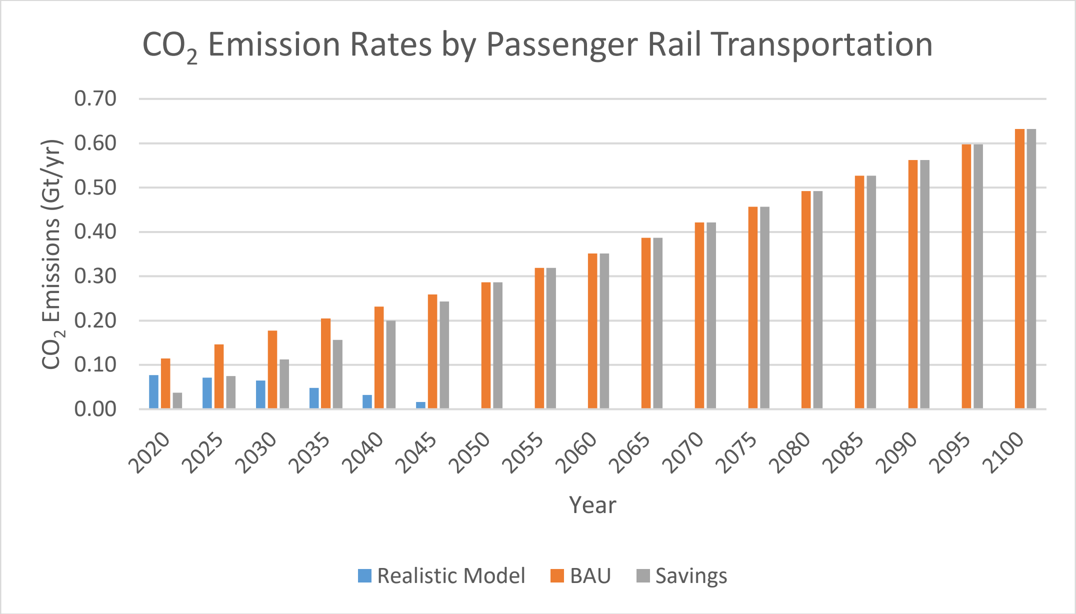

Figure 3-31 CO_2 Emission Rates of Rail Passenger Transportation

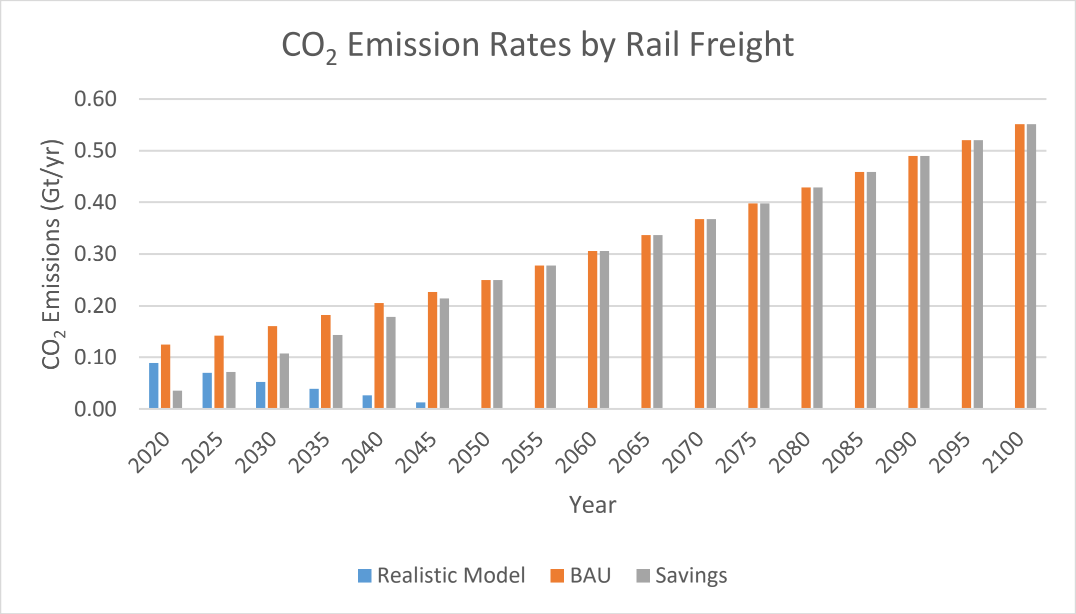

Figure 3-32 CO_2 Emission Rates of Rail Freight

It has been found that CO_2 emissions in rail passenger transport are expected to be 0.06 Gt, and 0.00 Gt in 2030 and 2050 & beyond, respectively. Under BAU conditions, however, the emission figures are 0.18 Gt, 0.29 Gt, 0.42 Gt, and 0.63 Gt, in 2030, 2050, 2070, and 2100, respectively. Whereas, in freight CO_2 emissions are expected to be 0.05 Gt, and 0.00 Gt in 2030 and 2050 & beyond, respectively. Under BAU conditions, they are 0.16 Gt, 0.25 Gt, 0.37 Gt, and 0.55 Gt, in 2030, 2050, 2070, and 2100, respectively.

3.4.3. Aviation Transport Mode

Aviation will remain a significant mode for passenger transport, as it is without a competitor, especially on long hauls. When it comes to speedy delivery of goods, again it will be choice of customers. Forecasts that are adopted in this study are taken from ITF [80] and OECD [97]. Data employed in this study are tabulated in Table 3-12.

Table 3-12 Aviation Mode Activities (REALISTIC Scenario)

Year	Passenger (Billion p-km)	Freight (Billion t-km)
2015	6,827.60	228.00
2030	13,532.73	511.00
2050	21,976.71	1,055.00
2060	26,967.62	1,294.59
2100	48,541.72	2,330.26

Upon performing linear interpolation for years not listed in the tables, evolution of the activities (which are denoted by $A_X(avia, yr)$, where $X = \{P, F\}$ designates passenger transport and freight categories) have been shown graphically in Figure 3-33 and Figure 3-34.

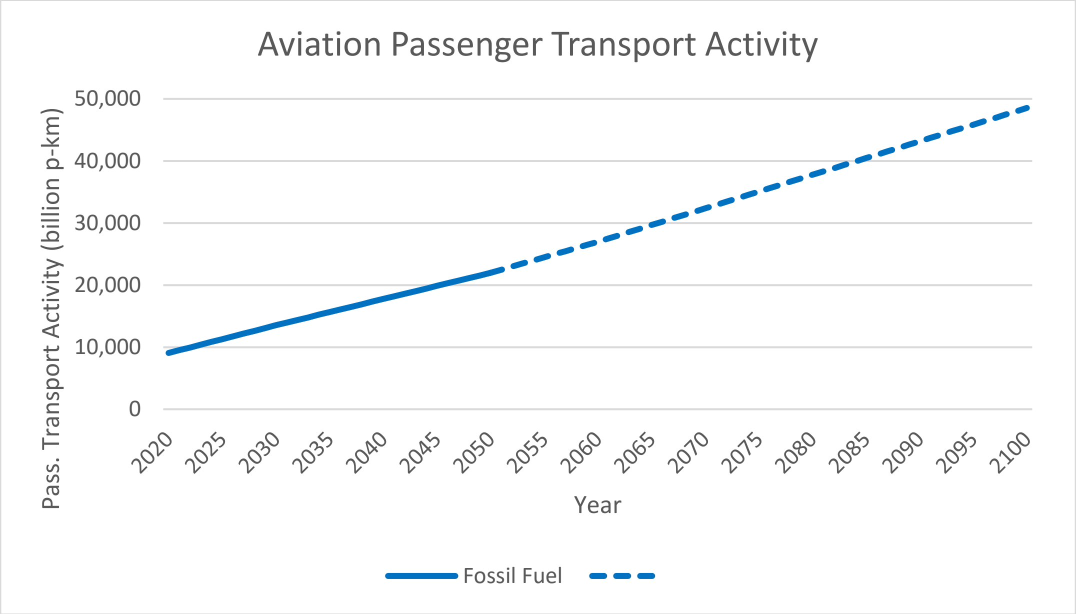

Figure 3-33 Aviation Passenger Transport Activity

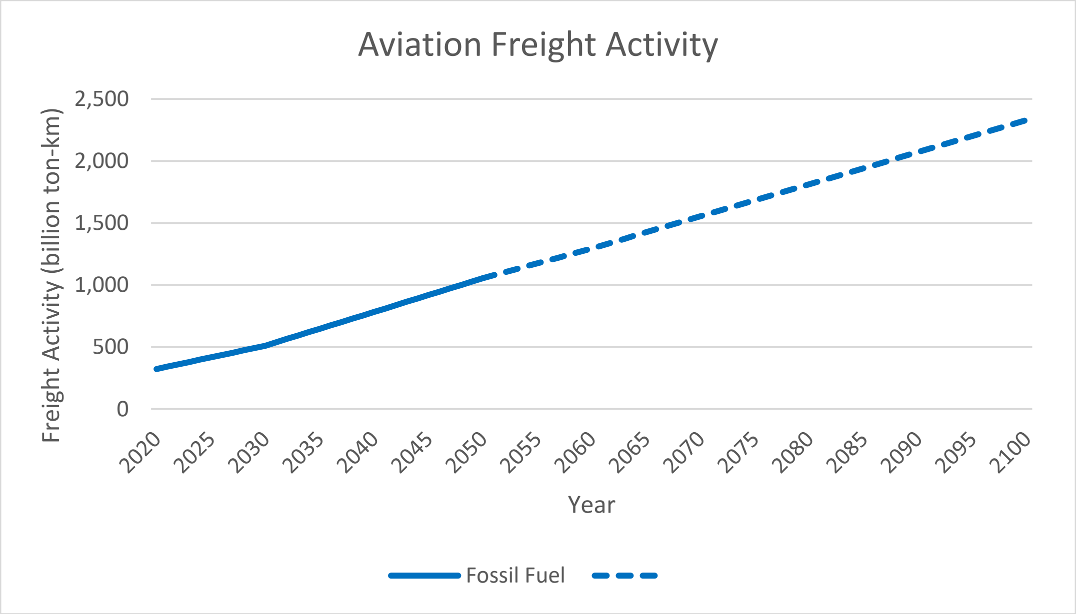

Figure 3-34 Aviation Freight Activity

No mature technology exists for even a partial replacement of the fossil fuels, on which the mode solely depends. Therefore, no additional electricity requirement arises either in the REALISTIC Scenario or under BAU conditions. This study's fundamental target is to assess future CO_2 emissions. Hence, they have been evaluated in parallel to the previous modes.

Energy intensities of vehicles in aviation mode are taken from Khalili et al. [74] and [77]. The values that have been adopted are presented in Table 3-13.

Table 3-13 Energy Intensities in Aviation Mode

Year	Fossil Passenger (MJ/p-km)	Fossil Freight (MJ/t-km)
2015-2100	1.80	0.50

Fossil fuel energy demands ($E_X(fos, yr)$) are given by:

$$\begin{cases} E_X(fos, yr) = A_X(avia, yr) * Eint_X(avia, fos, yr) \\ X = \{P, F\} \end{cases} \tag{3-19}$$

Emissions resulting from the consumption of fossil fuels are evaluated by using the emission intensity of a typical hydrocarbon fuel of $q_{fos} = 266 \frac{gCO_2}{kWh}$. Future CO_2 emission forecasts are given in Figure 3-35 and Figure 3-36, until 2100, for every 5 years.

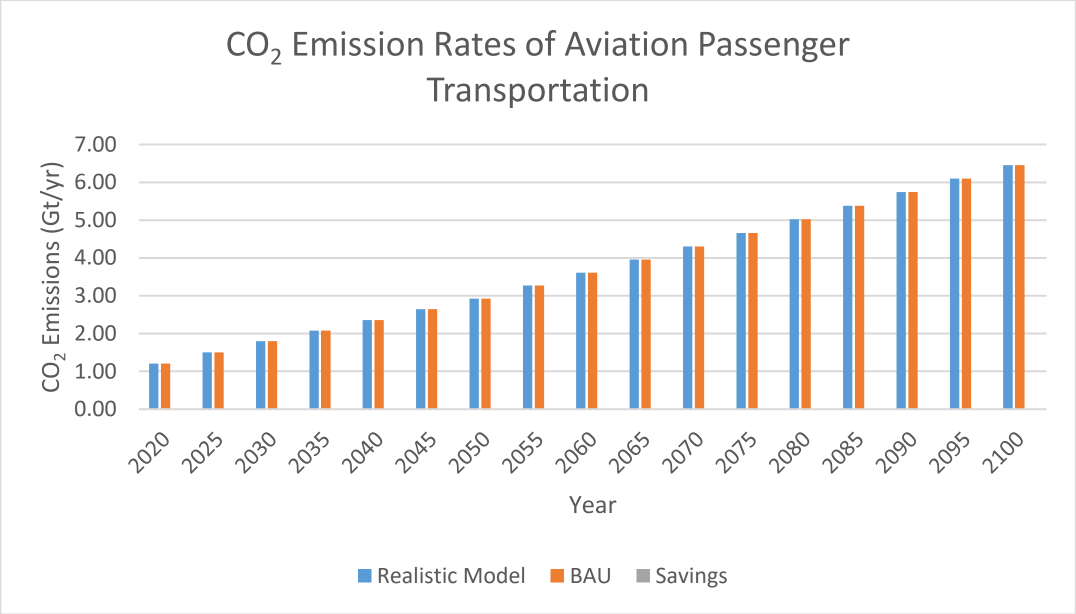

Figure 3-35 CO_2 Emission Rates of Aviation Passenger Transportation

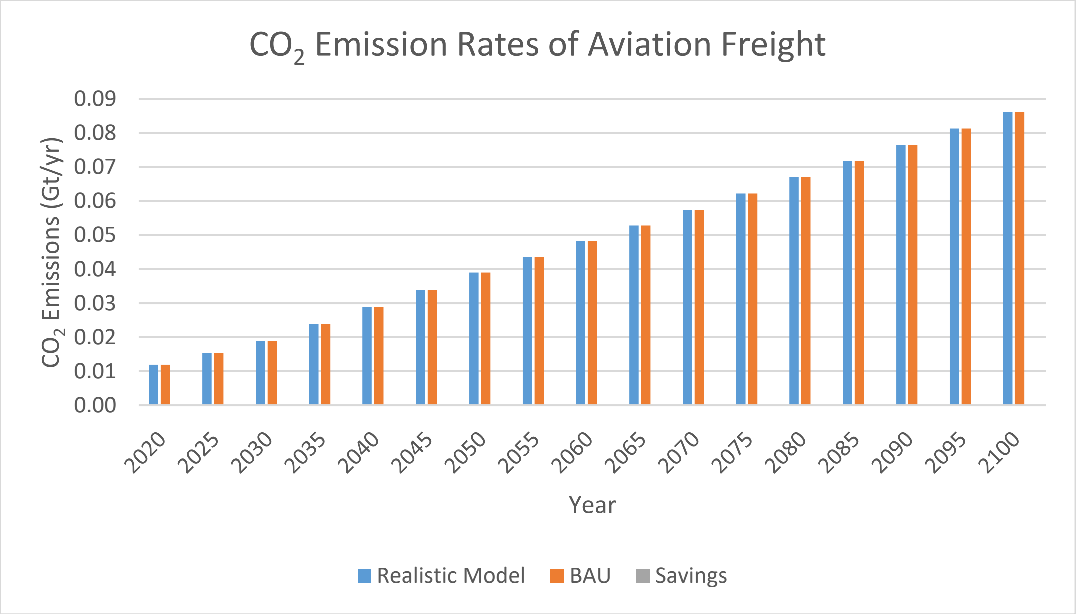

Figure 3-36 CO_2 Emission Rates of Aviation Freight

It has been found that CO_2 emissions in aviation passenger transport are expected to be 1.80 Gt, 2.92 Gt, 4.30 Gt, and 6.46 Gt, in 2030, 2050, 2070, and 2100, respectively. Whereas, in freight CO_2 emissions are expected to be 0.02 Gt, 0.04 Gt, 0.06 Gt, and 0.09 Gt, in 2030, 2050, 2070, and 2100, respectively.

3.4.4. Marine Transport Mode

The contribution of marine mode to passenger transport is negligible and is not expected to increase significantly. Marine mode however dominates the freight activities and in the long term, the situation will remain unchanged. Activity forecasts, which are taken from ITF [80] and OECD [97] studies, are tabulated in Table 3-14.

Table 3-14 Marine Freight Activities (REALISTIC Scenario)

Year	Freight (Billion t-km)
2015	77,862.00
2030	120,983.00
2050	268,667.00
2060	329,681.28
2100	593,426.30

Marine freight activities are denoted by $A_F(mar, yr)$. Yearly marine freight activities corresponding to different energy carriers, which are denoted by $A_F(mar, carr, yr)$ (where the variable $carr = \{elec, fos, H2\}$ corresponds to direct electricity, fossil fuel, and electrolytic hydrogen energy carriers, respectively), are given by:

$$A_F(mar, carr, yr) = A_F(mar, yr) * sh_F(mar, carr, yr) \qquad (3\text{-}20)$$

These activities are evaluated for the years 2015, 2030, 2050, 2060, 2070, and 2100. Upon performing linear interpolation for the years in between, they are presented graphically for years 2020 through 2100 in Figure 3-37

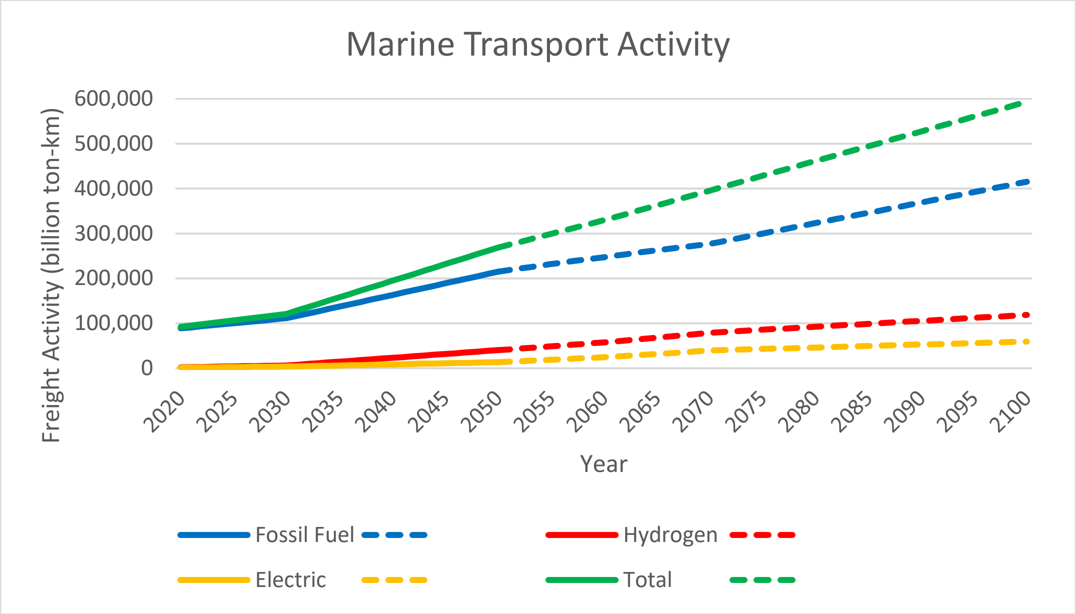

Figure 3-37 Marine Freight Activity

The transition to greener energy carriers will be limited in this study, mainly because long-haul activities prohibit the use of alternate energy sources. Energy intensities have been assigned accordingly, using data from various sources [78] and [74], together with the assessment of the author. Energy intensity values ($Eint_F(mar, carr, yr)$) that have been adopted in this study are tabulated in Table 3-15.

Table 3-15 Energy Intensity of Vehicles in Marine Freight

Year	Electric (MJ/t-km)	H_2 (MJ/t-km)	Fossil (MJ/t-km)
2015			0,15
2030- 2100	0.08	0.15	0.15

This limited transition requires a further supply of electric energy. To determine the additional electricity generation required to achieve the proposed mitigation strategy, both direct electricity and electrolytic hydrogen demands for marine freight, (denoted by ($E_F(elec, yr)$ and $E_F(H2, yr)$, respectively) have been evaluated using the relations:

$$\begin{cases} E_F(elec, yr) = A_F(mar, elec, yr) * Eint_F(mar, elec, yr) \\ E_F(H2, yr) = A_F(mar, H2, yr) * Eint_F(mar, H2, yr) \\ yr = \{2015, 2030, 2050, 2060, 2070, 2100\} \end{cases} \qquad (3\text{-}21)$$

Linear interpolation is then performed to determine yearly additional electricity demand for years, which are in the set. Taking into account the inherent inefficiency of the electrolytic hydrogen use, the total additional electricity demand resulting from the mitigation efforts ($Elec_F(mar, yr)$) have been calculated. They are given by the relation:

$$Elec_F(mar, yr) = E_F(elec, yr) + 1.5 * E_F(H2, yr) \qquad (3\text{-}22)$$

Results are shown graphically with 5 years intervals in Figure 3-38.

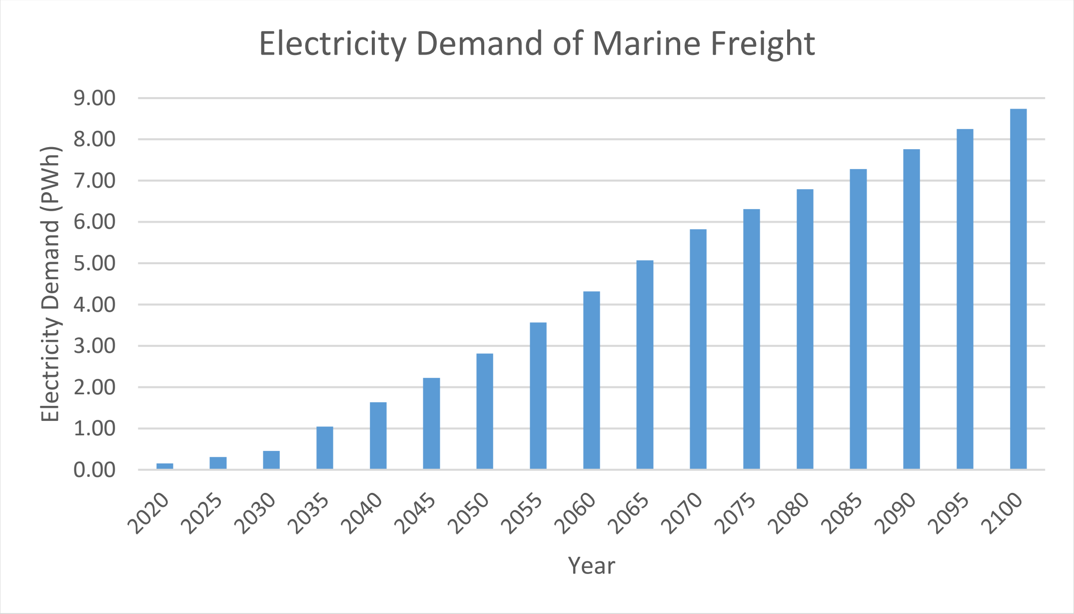

Figure 3-38 Electricity Demand of Marine Freight

It has been found that an additional electricity generation of 0.46 PWh, 2.82 PWh, 5.82 PWh, and 8.74 PWh are required to achieve the proposed transition to new energy carriers in the years 2030, 2050, 2070, and 2100, respectively.

In parallel with road freight, emissions in the REALISTIC Scenario and under BAU conditions have also been determined for the marine mode. To evaluate the emissions under BAU conditions, it has been assumed that all transport activities would have been performed using fossil fuel (which is almost the current situation). Fossil fuel energy demands have been calculated using the relations:

$$\begin{cases} E_F(fos, yr) = A_F(mar, fos, yr) * Eint_F(mar, fos, yr) \\ E_{F,BAU}(fos, yr) = A_F(mar, yr) * Eint_F(mar, fos, yr) \end{cases} \quad (3\text{-}23)$$

Using the emission intensity of a typical hydrocarbon fuel, $q_{fos} = 266 \frac{gCO_2}{kWh}$, emissions in marine freight have been evaluated. Hence, CO_2 emissions are given by:

$$\begin{cases} Q_F(mar, yr) = E_F(fos, yr) * q_{fos} \\ Q_{F,BAU}(mar, yr) = E_{F,BAU}(fos, yr) * q_{fos} \end{cases} \quad (3\text{-}24)$$

The results are presented graphically for every 5 years in Figure 3-39.

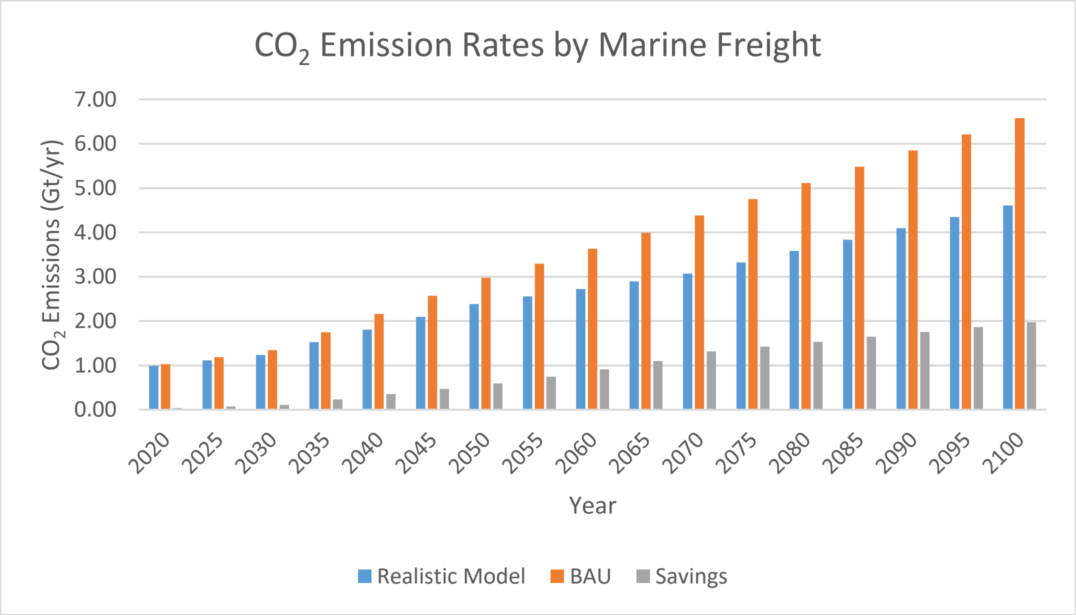

Figure 3-39 CO_2 Emission Rates of Marine Freight

It has been found that CO_2 emissions in road freight are expected to be 1.23 Gt, 2.38 Gt, 3.07 Gt, and 4.60 Gt in 2030, 2050, 2070, and 2100, respectively. Under BAU conditions, however, the emission figures are 1.34 Gt, 2.98 Gt, 4.38 Gt, and 6.58 Gt, in 2030, 2050, 2070, and 2100, respectively.

3.4.5. Overall Transport Mode

Combining all four transport modes (road, rail, aviation, and marine), the future need for additional electric energy supply has been determined. The more intensive use of electric energy and electrolytic hydrogen as an energy carrier in transportation lead to a significant increase in electric supply as presented in Figure 3-40. Electric energy demand for the transport sector alone gradually increases in the model to reach 51.3 PWh in 2100.

However, given that actions are taken on time as described in this study, a significant decrease in CO_2 emissions can be achieved until 2100, as shown in Figure 3-41. It is worth noting that, even with these serious measures, a considerable amount of CO_2 (around 700 Gt) will be released into the atmosphere, because of transport activities as presented in Figure 3-42, mainly originating from aviation and marine modes. Yet, this cumulative CO_2 emissions figure represents extremely large savings: under BAU assumptions, it has been determined that 2.144 Gt CO_2 would have been released, hence savings achieved in the REALISTIC Scenario escalates to almost 1.440 Gt CO_2.

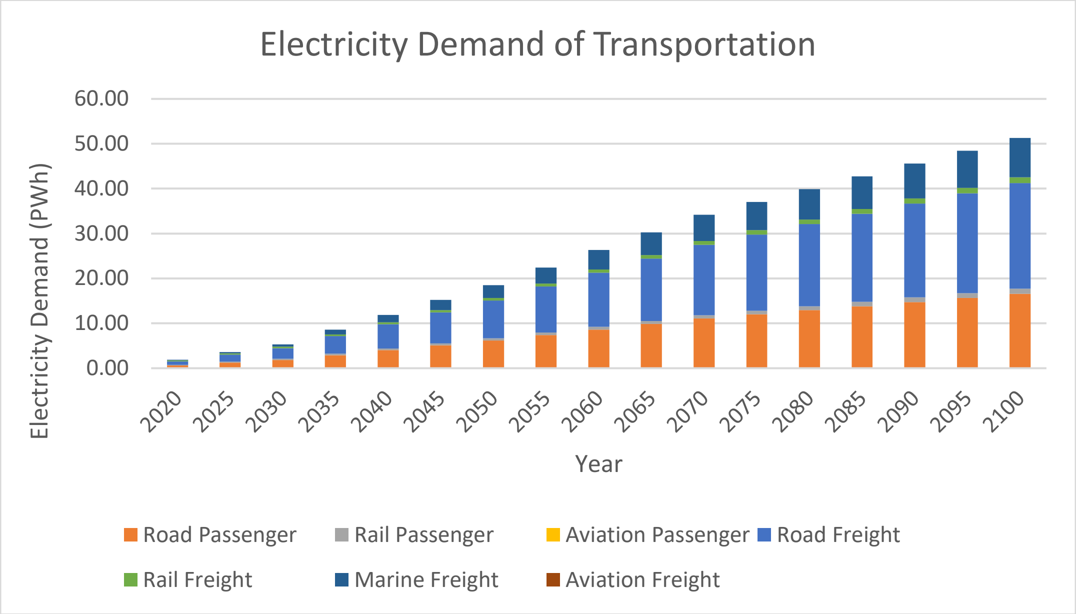

Figure 3-40 Electricity Demand of Transportation

It is worth underlining that, even with all proposed mitigation actions were taken in the REALISTIC Scenario that has been developed, in 2100 there will be still 6.46 Gt CO_2/yr emissions from aviation passenger transport, 4.60 Gt CO_2/yr from marine freight, and 0.09 Gt CO_2/yr from aviation freight activities.

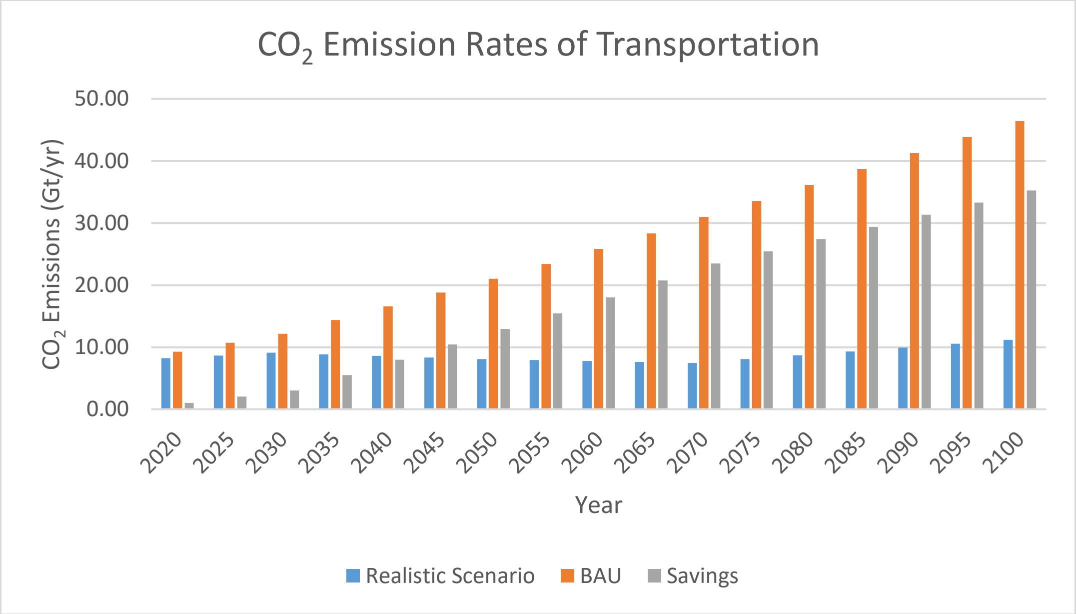

Figure 3-41 CO$_2$ Emission Rates of Transportation

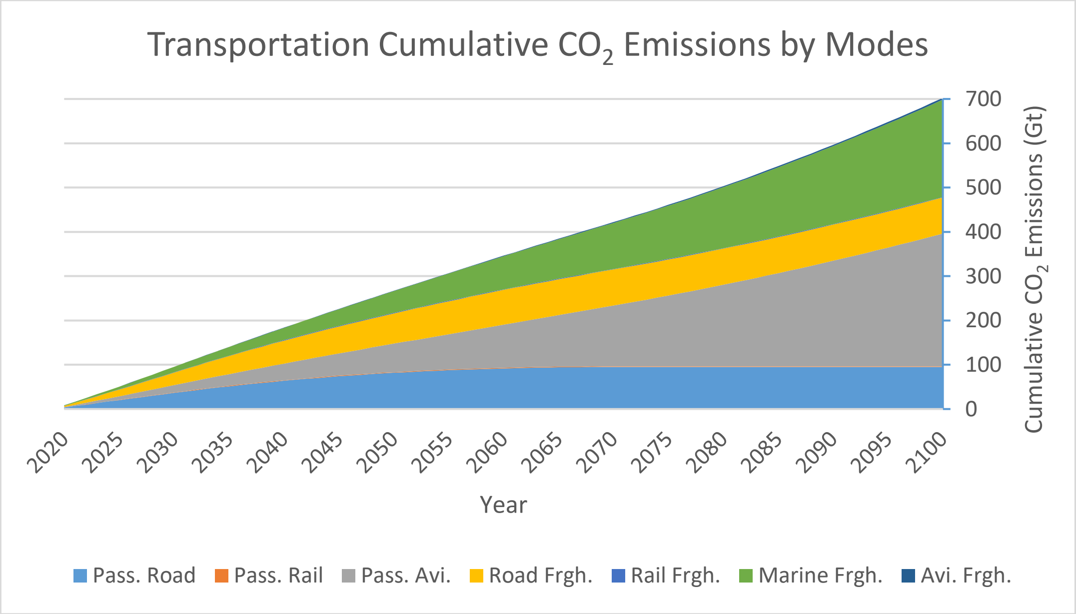

Figure 3-42 Cumulative CO$_2$ Emissions of Transportation

3.5. Possible Further Improvements

Cumulative CO_2 emissions until 2100 from the transportation sector remained exceptionally high in the developed model. The fundamental reason for the relatively lower savings achieved in the sector is the dominant fossil fuel dependence of aviation and marine modes. Both transport modes are expected to survive. Aviation is the fastest mode of transportation and it is practically the sole alternative today for overseas journeys. Marine transportation, because of its much lower operating cost per ton-km in comparison to other modes, will prevail the freight transport in the future.

Both aviation and marine modes depend on hydrocarbons. The uses of either hydrogen or electricity seem far from being practical, due to limited storage capabilities, as explained a priori. In the literature, a possible remedy for both modes is proposed: using biofuels. Biofuels are fundamentally artificial replicas of petroleum-based hydrocarbons. Upon their combustion, a comparable amount of CO_2 will be emitted. However, their production involves the absorption of CO_2 from the atmosphere; hence, they provide a good example of carbon capture, a methodology, which is left outside the present study. Effective use of biofuels can reduce substantially the long-term emissions from both modes, hence from the entire transport sector.

In this study, it has been presumed that transportation demand for each mode is predetermined. Transportation demands have not been altered, yet it is intended to reduce emissions under the specified conditions. It is beyond question that allocation of transport needs (demands) from one mode to the other is essential in reducing the energy demand of the sector. Energy efficient modes (e.g., modes with lower energy intensities) need to be preferred. This statement holds true within the modes as well: promoting public transportation, for instance, will reduce transport activities of LDVs, however, will increase those of buses, which are far less energy intensive when compared to LDVs. Similarly, promoting rail transportation mode over aviation and road transport will greatly reduce the energy demand for a given amount of transport activity; hence will help obtaining large savings in CO_2 emissions. Thus, it is essential to develop transportation policies and strategies to reduce the energy demand in the sector. This represents the policy aspect of the problem, which is beyond the scope of this study.

3.6. Sensitivity Analysis for Transportation

Our analysis is based on a set of assumptions, which constitute the REALISTIC scenario, as in the case of the industry sector. In parallel to the industry sector, the scenario for transportation represents a feasible, yet rather ambitious effort to reduce CO_2 emissions. To assess the effectiveness of the adopted assumptions involved in the REALISTIC Scenario, again two other scenarios have been proposed, in which the targeted transitional shares to electrolytic hydrogen in 2030, 2050, and 2070 have been altered.

There exists a minor distinction in the transport scenarios (when compared to industry): No target is set for the year 2100. Entities in the industry sector (especially factories) are few in number, yet far less expensive and have a very long service life, in comparison to the entities in the transport sector (vehicles). Therefore, transition to new technology may happen faster in transportation, where today's vehicles will be phased out in decades. In the case of the industry, however, industrial facilities either currently in operation or under construction will be in service for a much longer period, hence complete transition may not be completed by 2070, which is the last target year in transportation.

In parallel to the industry sector, resistance to transition to new technology (or new fuel) will exist mainly because of financial considerations. Therefore, the RELAXED Scenario, a version of REALISTIC but with a slower penetration rate for direct electric energy or electrolytic hydrogen use has been devised. To maintain the parallelism with other sectors, a third scenario, which omits financial considerations, hence limited only by technical difficulties has also been considered: AGGRESSIVE Scenario.

Differences among the three Scenarios that have been developed in this study are summarized in Table 3-16 through Table 3-21, where the share targets of direct electricity and electrolytic hydrogen in each analyzed mode are given for the years 2030, 2050, and 2070.

Table 3-16 REALISTIC Passenger Scenario

	Road					
	LDV		2W/3W		Bus	
Year	Electric	Fossil	Electric	Fossil	Electric	Fossil
2015	0%	100%	0%	100%	0%	100%
2030	30%	70%	50%	50%	40%	60%
2050	80%	20%	90%	10%	90%	10%
2070	100%	0%	100%	0%	100%	0%

	Rail		Aviation	
Year	Electric	Fossil	Electric	Fossil
2015	45%	55%	0%	100%
2030	80%	20%	0%	100%
2050	100%	0%	0%	100%
2070	100%	0%	0%	100%

Table 3-17 REALISTIC Freight Scenarios

	Road			Rail	
Year	Electric	H_2	Fossil	Electric	Fossil
2015	0%	0%	100%	39%	61%
2030	20%	10%	70%	80%	20%
2050	50%	30%	20%	100%	0%
2070	60%	40%	0%	100%	0%
	Marine			Aviation	
Year	Electric	H_2	Fossil	Electric	Fossil
2015	0%	0%	100%	0%	100%
2030	3%	5%	92%	0%	100%
2050	5%	15%	80%	0%	100%
2070	10%	20%	70%	0%	100%

Table 3-18 RELAXED Passenger Scenario

	Road					
	LDV		2W/3W		Bus	
Year	Electric	Fossil	Electric	Fossil	Electric	Fossil
2015	0%	100%	0%	100%	0%	100%
2030	20%	80%	40%	60%	25%	75%
2050	60%	40%	80%	20%	75%	25%
2070	100%	0%	100%	0%	100%	0%

	Rail		Aviation	
Year	Electric	Fossil	Electric	Fossil
2015	45%	55%	0%	100%
2030	60%	40%	0%	100%
2050	80%	20%	0%	100%
2070	100%	0%	0%	100%

Table 3-19 RELAXED Freight Scenario

		Road		Rail	
Year	Electric	H_2	Fossil	Electric	Fossil
2015	0%	0%	100%	39%	61%
2030	10%	5%	85%	60%	40%
2050	40%	20%	40%	80%	20%
2070	50%	50%	0%	100%	0%
		Marine		Aviation	
Year	Electric	H_2	Fossil	Electric	Fossil
2015	0%	0%	100%	0%	100%
2030	1%	2%	97%	0%	100%
2050	3%	5%	92%	0%	100%
2070	5%	15%	80%	0%	100%

Table 3-20 AGGRESSIVE Passenger Scenario

			Road			
	LDV		2W/3W		Bus	
Year	Electric	Fossil	Electric	Fossil	Electric	Fossil
2015	0%	100%	0%	100%	0%	100%
2030	40%	60%	60%	40%	50%	50%
2050	100%	0%	100%	0%	100%	0%
2070	100%	0%	100%	0%	100%	0%

	Rail		Aviation	
Year	Electric	Fossil	Electric	Fossil
2015	45%	55%	0%	100%
2030	90%	10%	5%	95%
2050	100%	0%	10%	90%
2070	100%	0%	20%	80%

Table 3-21 AGGRESSIVE Freight Scenario

	Road			Rail	
Year	Electric	H_2	Fossil	Electric	Fossil
2015	0%	0%	100%	39%	61%
2030	30%	10%	60%	90%	10%
2050	75%	25%	0%	100%	0%
2070	75%	25%	0%	100%	0%
	Marine			Aviation	
Year	Electric	H_2	Fossil	Electric	Fossil
2015	0%	0%	100%	0%	100%
2030	5%	10%	85%	5%	95%
2050	10%	25%	65%	10%	90%
2070	20%	30%	50%	20%	80%

The evolution of the electricity demand according to three comparative scenarios (REALISTIC, RELAXED, and AGGRESSIVE) is presented in Figure 3-43.

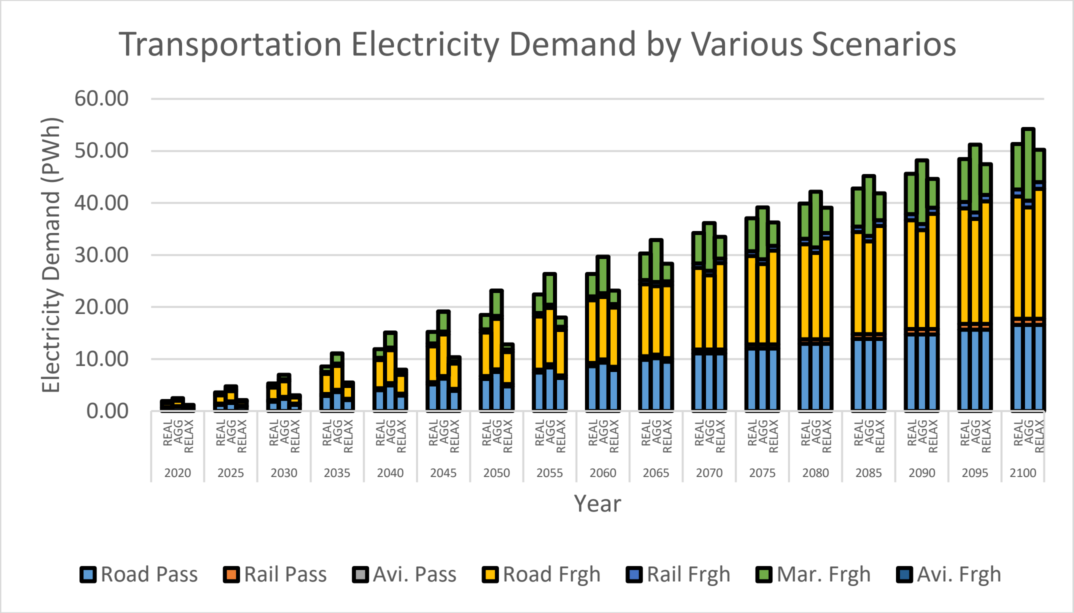

Figure 3-43 Transportation Electricity Demand by Various Scenarios

The faster transition to alternative energy carriers in the AGGRESSIVE Scenario implies a sharper increase in the electricity demand. However, this increase is not as pronounced as in the industry sector. In 2050, the electricity demand escalates to 23.1 PWh (AGGRESSIVE) from 18.5 PWh (REALISTIC). In case governments do not take timely actions to mitigate CO_2 emissions, the demand will only be 12.8 PWh in 2050 (RELAXED Scenario).

In all three scenarios, the electricity demands in 2100 converge to a range between 50 and 55 PWh, after all, humankind is expected to take emissions under control by then.

Reductions in CO_2 emissions that may be achieved under different scenarios are given in Figure 3-44. To better indicate the potential for savings in CO_2, BAU Scenario, which adopts equal activities in the future, but assumes that vehicles maintain today's energy carrier distribution (that is, the heavy dependence on fossil fuels).

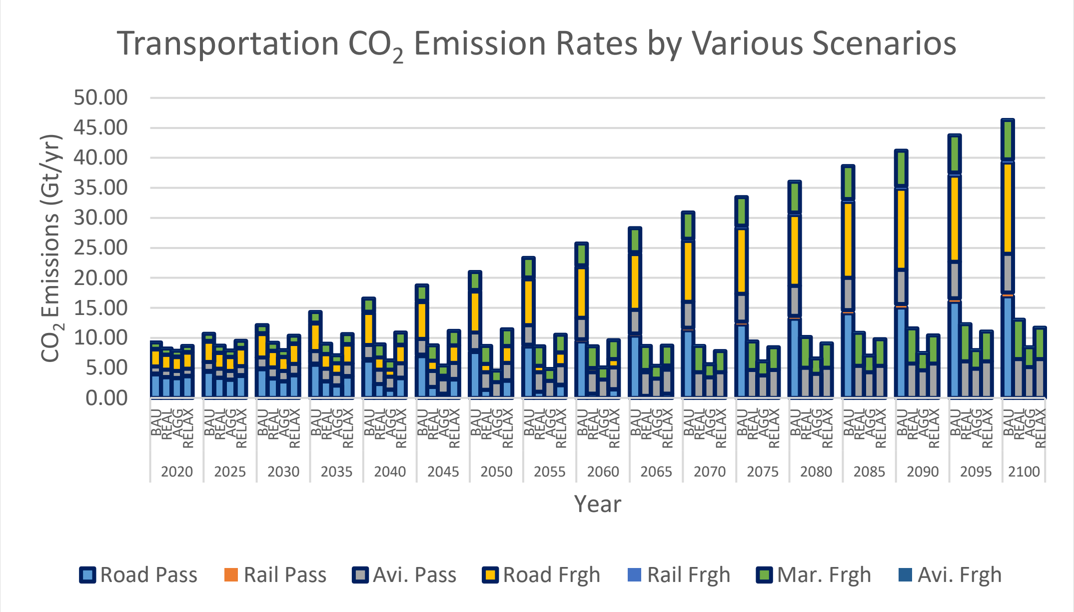

Figure 3-44 Transportation CO_2 Emissions by Various Scenarios

Upon determining CO_2 emission rates from each mode of transportation, potential savings in CO_2 emissions until 2100 have been evaluated. Findings will then be used to assess whether humankind can remain within the carbon budget until 2100, in a later chapter. The cumulative CO_2 emissions under each scenario are shown graphically in Figure 3-45. BAU Scenario results in CO_2 emissions of 2144 Gt from 2020 to 2100, whereas REALISTIC Scenario lowers them to 702 Gt. With a more dedicated approach (AGGRESSIVE Scenario) cumulative emissions may even be reduced down to 530 Gt. However, in case government involvements are slower (RELAXED Scenario) emissions during the same period can rise to 812 Gt.

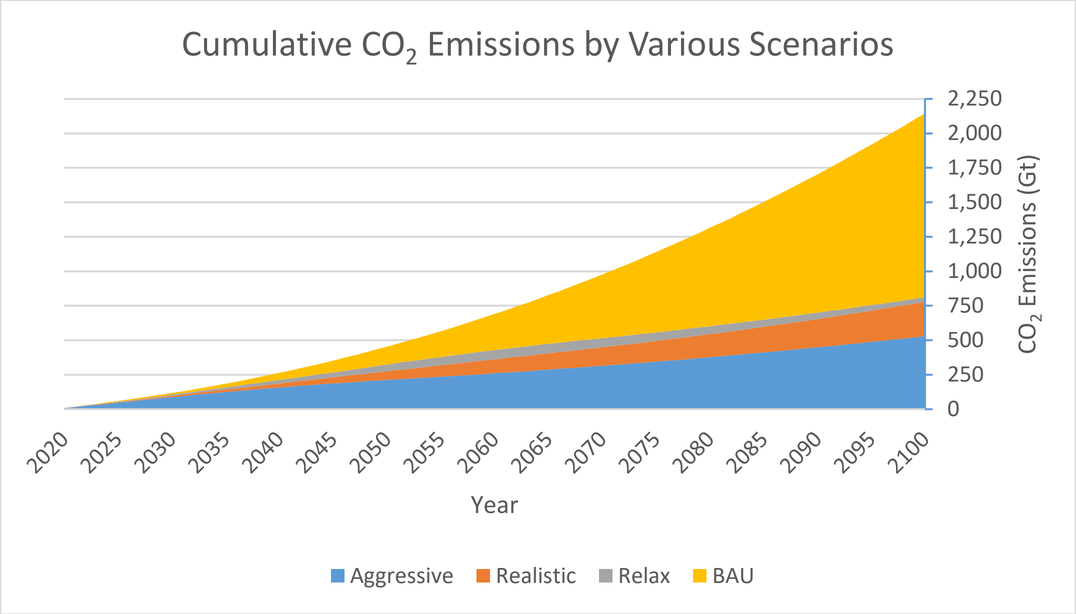

Figure 3-45 Cumulative CO_2 Emissions by Various Scenarios

While investigating the transportation sector, it has been assumed that both passenger and freight activities will increase with GDP, beyond 2050. The lack of a reliable forecast for this long-term demand forced the author to make such an assumption. Many speculations exist on how the transport demand will grow beyond 2050. To maintain the parallelism between other sectors, sensitivity of the assumptions adopted in this work (related to beyond 2050 demands) have been studied by altering the growth rate for the period.

GDP's growth rate surpasses the population growth rate, which have been employed in the sensitivity analysis of the industry. Calculations have been repeated in the basic scenario of REALISTIC, simply by modifying the beyond 2050 growth to be proportional to UN's population growth rates as explained in the industry sector chapter: From 2050 to 2060 0.43% yearly, 0.3% from 2060 to 2070, and 0.13% beyond 2070.

Recalling that the industry's material output (demand for industrial products, steel, cement, and chemicals) has been speculated to reach maturity by 2050, in the REALISTIC Scenario a flat demand has been forecasted in the industry for the long-term. Same conditions have been applied to the transportation sector, even though it is unlikely to have a flat transport activity beyond 2050. Results related to the altered growth rate beyond 2050 are presented in Figure 3-46 through Figure 3-48.

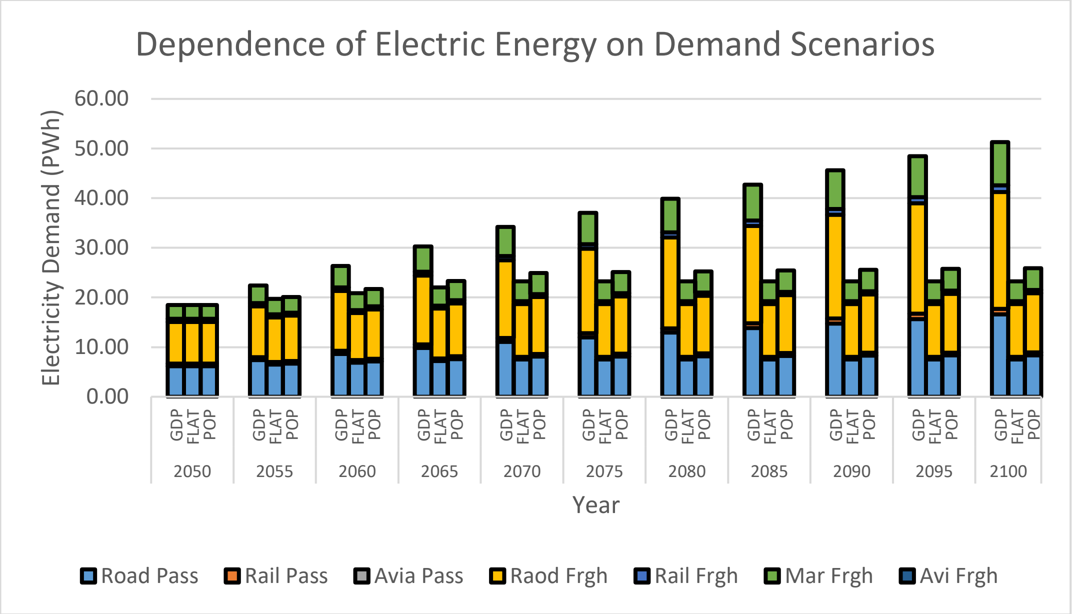

Figure 3-46 Dependence of Electricity on Demand Scenarios

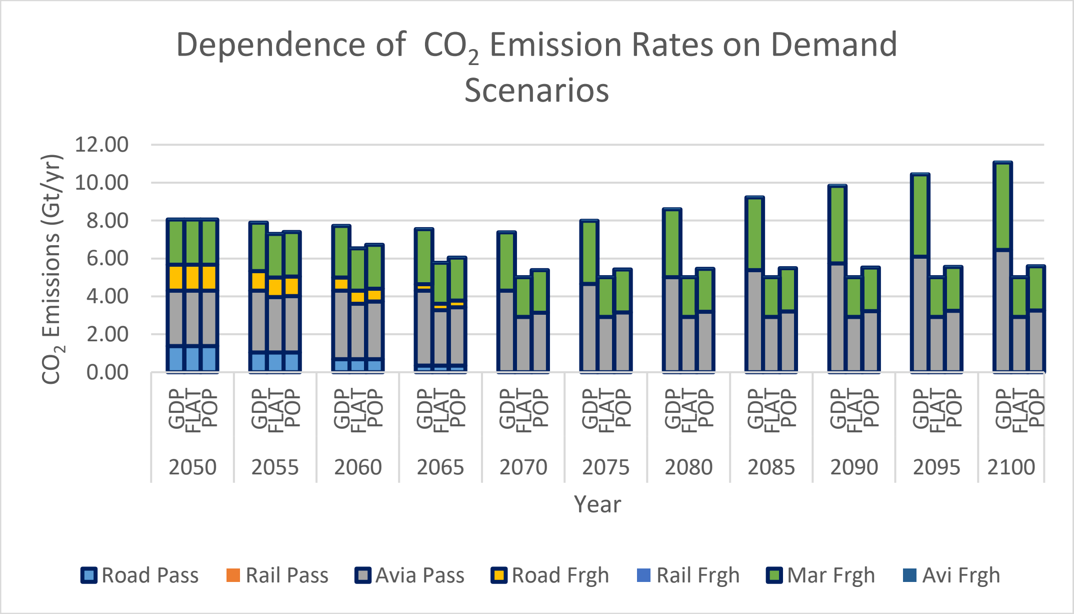

Figure 3-47 Dependence of CO_2 Emissions on Demand Scenarios

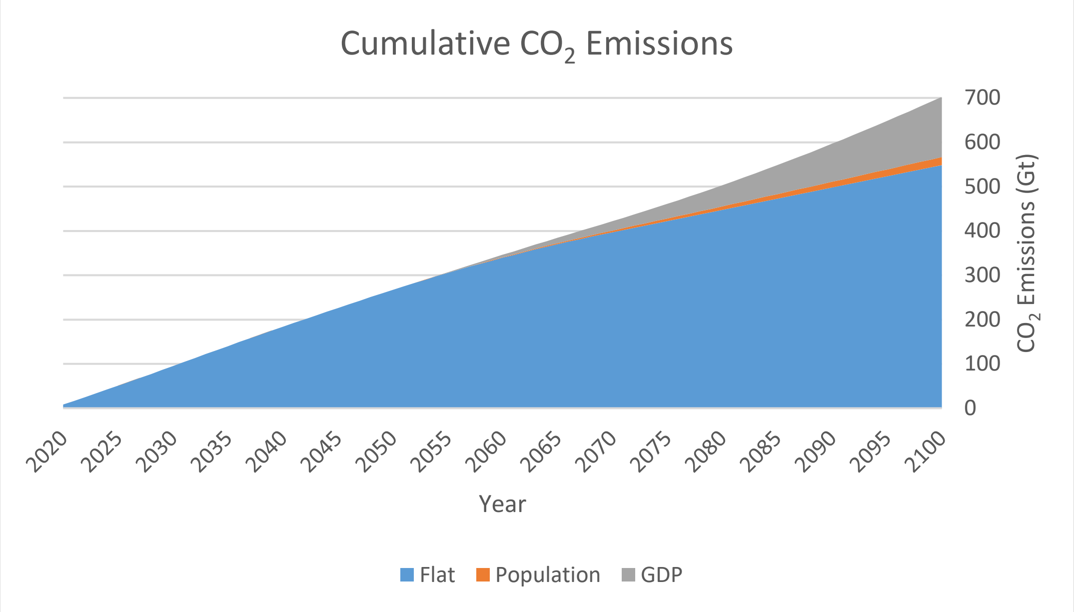

Figure 3-48 Cumulative CO_2 Emissions of Demand Scenarios

Assuming that transport activities will be either proportional to population growth or remain flat, results in serious savings in CO_2 emissions. If the transport activities were to remain fixed beyond 2050, the cumulative emissions are reduced from 702 Gt down 548 Gt in the REALISTIC Scenario. The growth in the transport activities which is proportional to population alters the predictions to 567 Gt.

It is important to note that, emissions will continue in transportation even after 2070, mainly because of the lack of a viable solution in aviation and marine modes. Therefore, reducing transport activities should be one of the targets in the effort to mitigate CO_2 emissions.

3.7. Summary and Novelty of the Approach

Forecasts for passenger and freight activities in four modes (road, rail, marine, and aviation) have been collected from the literature, which were available until 2050 or 2060. Upon comparing data from different sources, those provided by ITF have been selected to be used to identify the energy demand from today until 2050. The long-term material demand has been extrapolated until 2100. In the specific case of transportation, this evolution has been adopted to be parallel to the GDP growth. Current and future energy intensities in each mode have been identified, leading to the determination of the yearly energy demand of the transportation sector from 2020 to 2100. Thus evaluated energy demand values are specific to the present study.

Following the determination of the energy requirement of the sector, through intense use of direct electricity primarily, assisted by electrolytic hydrogen, a strategy has been developed to mitigate direct CO_2 emissions from the sector. Both selection of the two energy carriers (direct electricity and electrolytic hydrogen) and their adopted pace of penetration form the unique characteristics of the present study. Combined with yearly demand forecasts that are extended until 2100, they form part of the basic scenario developed in the study: REALISTIC.

Additional electricity requirement resulting from the proposed mitigation efforts has been evaluated, together with the savings that can be achieved in emissions. To assess the sensitivity of the results to the adopted assumptions, Calculations are performed not only in the basic REALISTIC Scenario but are also repeated under various alternative scenarios, which are also developed in the present study.

CHAPTER 4

BUILDINGS SECTOR

While performing energy consumption and thus related CO_2 emission calculations, it is almost universally agreed that the sector titled buildings sector, incorporates not only residential buildings but also public and commercial buildings, which are also referred to as the services sector.

Coming behind the power, industry, and transportation sectors, buildings sector ranks 4th in direct CO_2 emissions. IEA predicts that almost 10% of current CO_2 emissions arise from the sector. Although there are minor variations in the statistics, this figure remains almost constant in recent years. In their latest report on the subject, IEA indicates that the share of the buildings sector in CO_2 emissions in 2020 to be 9% [41], in 2019 to be 9% [40], again 9% in 2018 [98], and 10% in 2017 [52]. Currently, the emission rate from buildings corresponds to an annual release of 3 Gt CO_2 to the atmosphere.

It is important to emphasize that, the aforementioned 10% share includes direct emissions only. In many publications available in the literature, however, either indirect emissions or some allocations from the industry sector (to account for the cement and steel used in the construction of the buildings) are included the emission figures of the sector. This is especially the case in reports dedicated to the analysis of the sector. In its report on buildings [98], IEA allocates 39% share in energy related emissions to the buildings sector, of which 9% only is the direct emissions, whereas 19% corresponds to indirect emissions, and 11% to the construction industry (namely, resulting from the manufacturing of steel and cement used in the construction).

While analyzing the energy consumption in the sector, it is essential to identify clearly, where these energies are being consumed. Buildings sector is by a very large margin the leader in electricity consumption. IEA estimated that the sector's current share in electricity consumption has reached 55% [98]. This electricity consumption is responsible for indirect emissions, which will be discussed separately in another chapter. However, it is worth recalling that the indirect emissions from the sector raise the yearly emissions from around 3 Gt CO_2 to 10 Gt CO_2.

In this chapter, exclusively direct emissions from the sector have been investigated. To perform such an analysis, energy consumption characteristics within the sector need to be identified. It is a common practice to study energy consumption under 7 categories, characterized by the end-use of the energy [99]:

1) Space Heating
2) Water Heating
3) Cooking
4) Lighting
5) Space Cooling
6) Household and individually owned appliances
7) Miscellaneous equipment (common service equipment)

With negligible error, it can be assumed that end-uses in the latter 4 categories consume only electricity. For this reason, CO_2 emissions related to these categories will be the subject of indirect emissions that will be discussed later. Hence, direct emissions in the buildings sector may be assumed to emanate solely from space heating, water heating, and cooking.

Understanding the relative importance of the last three sub-sectors in CO_2 emissions requires further investigation. In a recent report, IEA states that space and water heating are responsible for 80% of direct CO_2 in the sector, whereas cooking for 16% [40]. An earlier report, for which detailed statistics are also available, indicates that 55% of direct CO_2 emissions in the sector originate from space heating, 20% from water heating, and 18% from cooking [39].

It is crucial to emphasize at this stage that the provided shares in direct CO_2 emissions of the sub-sectors, as well as the yearly direct emission rate of 3 Gt CO_2, take into account only the fossil fuels. Unlike power, industry, and transportation sectors, the buildings sector makes extensive use of biomass as an energy source. The biomass of consideration is primarily, wood and cattle dung, which provide a substantial contribution to cooking, water heating, and finally to space heating. The CO_2 emission rate attributed to the buildings sector represents therefore an underestimation. It may be argued that processes, which are employed to produce biomass, capture an amount of CO_2 equivalent to its release. However, this can only be justified, when the sustainability of the production methods can be demonstrated. In this study, as the effects of CO_2 capture technologies have excluded, CO_2 emissions from the use of biomass as a fuel has been taken into account in determining the overall release to the atmosphere.

To clarify the importance of the emissions from the use of biomass, it is worth analyzing the data provided by IEA. Using the report by IEA, for which detailed data are available [39] and the amount of direct CO_2 released from the sector has been estimated to be 2.9 Gt CO_2 in 2014, it is calculated that the employed biomass would have resulted in a release of 3.7 Gt CO_2. Hence, the majority of the CO_2 emissions in the sector are not accounted for. Only the emissions from fossil fuels are listed in many publications, representing an approach that is not adopted in this study.

In its investigation for developing a strategy for establishing a transition to sustainable buildings, IEA itself underlines the intense use of biomass in the sector. It has been reported that globally 25% of the space heating in residential buildings, 55% of the water heating in residential buildings [100], and 70% of cooking [100] have been supplied by biomass. India predominantly makes use of biomass for water heating applications. Similarly, densely populated southeastern Asia and also Africa heavily depend on this fuel. Therefore, in the mitigation of CO_2 emission rates, it is necessary to consider the effects of biomass use.

In parallel to the ongoing population growth, one can expect that energy consumptions in the buildings will increase. Furthermore, social development also promotes extensive use of energy. On the other hand, especially in the case of space heating, there exists a large room for improvement in efficiency. Building enveloping has proven to be very effective in reducing the energy requirement of space heating. Many countries have already adopted and are in the process of adopting building codes to reduce heating loads. Even when no further actions are taken to reduce CO_2 emissions, it is expected the energy demand for space heating will remain fairly constant in the short term and decrease in the long term. A similar pattern is also predicted for cooking, as cooking devices are currently very inefficient. In the case of water heating, however, expectations on efficiency improvements are low, hence a steady increase in demand is being forecasted, at least until 2050.

In the future, major energy consumption increase in buildings will be attributed to space cooling. So far, space cooling has been considered a luxury, whereas space heating is a necessity for humankind. With the advancements in technology and social development of societies, space cooling has become a daily routine operation. Today's technology for cooling relies on electric energy. Even though various alternatives are being proposed [101], the viable method of cooling still employs electric energy. The increase in the energy demand due to space cooling requirements will be discussed later, as it makes the subject of indirect emissions.

Further increase in indirect emissions is also expected with the ever-increasing use of lighting and appliances. However, recent developments in lighting, which revolutionized the sector, realized tremendous efficiency improvements. Thomas Edison's incandescent light bulb became obsolete and LED technology started to dominate the industry. Although not comparable in success with lighting, appliances are constantly being improved in performance. Therefore, the energy demand for lighting and appliances will increase in the future, but prospective efficiency improvements will cover part of these increases.

Finally, when studying the buildings sector it is important to assess the contribution of district heating, and related to it the use of geothermal energy. IEA estimated that in 2014, almost 13% of the space heating requirement has been supplied by district heating, whereas for water heating this ratio is only 5%. District heating is being effectively used in Eastern European countries (formerly under the influence of the USSR), in Russia, and in China. Countries like Denmark makes also extensive use of this energy carrier. However, it is important to emphasize that the majority of district heat plants rely on either fossil fuels or waste and biomass. It is argued that the use of waste and biomass makes part of a sustainable strategy. However, such an assumption is based on the carbon capture technology, which have been ignored in this study.

Geothermal energy on the other hand may be presented as a low CO_2 emitting technology. The distribution of geothermal energy via pipelines is a common practice. However, currently, the share of the high temperature steam/water extracted from the earth in supplying space heating turns out to be extremely small (less than 0.5%) [102] and [103]. Its use for water heating is more effective and has a larger share, but still of negligible importance. It is important to underline that, in the literature, much higher potential values are listed for geothermal energy. However, these high figures contain energy supplied from the earth via the operation of ground source heat pumps that are going to be investigated later. The majority of geothermal energy in the future will be related to the operation of these heat pumps. However, this operation has nothing to do with the conventional use of high temperature steam/water, hence orthodox geothermal energy.

4.1. Space Heating

Currently, space heating is the most energy demanding end-use in the buildings sector. It exhibits a large variation throughout the world, based on geographical location. In the northern hemisphere, the majority of the developed countries have been established in regions, where at least seasonal space heating is mandatory. A significant fraction of the world's population lives in southeastern Asia, where the space heating demand is not equally essential in pursuing life. Yet, overall space heating ranks number one among the end-uses.

From a historical perspective, humankind's energy need for space heating started long before today's extensive energy demanding industrial and transport activities. Because of its long history, sources employed in space heating exhibit a large variety. Every society, every culture has selected its favorite energy source for space, mostly based on its availability, achievability, and hence the cost.

Analysis of the distribution of energy sources has been performed on the detailed data provided by IEA [39]. Accordingly, in 2014 it has been estimated by IEA that natural gas ranks first with 39% among all sources by a large margin. This can be attributed to its wide use in developed countries, where space heating is a necessity. Natural gas has a good image for being the cleanest fossil fuel, especially in terms of particulate, NOx, and SOx emissions.

Oil, biomass, district (commercial) heating has each have a share of around 13%, where electricity and coal have a share of around 10%. The use of biomass is least pronounced in space heating when compared to other direct emission end-uses of water heating and cooking. An explanation for the relatively low contribution of biomass comes from the observation that highly populated, yet not well-developed countries lie in relatively moderate climate regions, where there is less need for space heating. However, it is interesting to note that in Scandinavian countries, wood is an essential fuel for heating, and its contribution can climb up to 40%. Nevertheless, these countries have a negligible population from a global perspective and they pay exemplary attention to the sustainability of wood supply. Energy sources’ share in space heating is given in Figure 4-1.

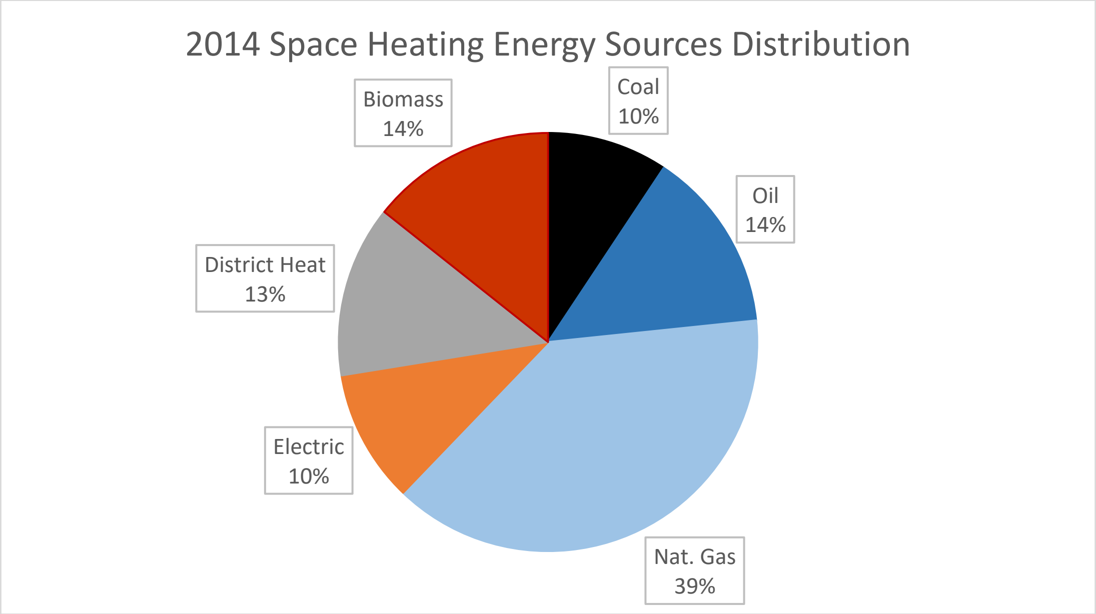

Figure 4-1 Space Heating Energy Sources Distribution, 2017 [39]

District (commercial) heating accounts for a considerable share in space heating. Emissions from district heating need to be included in the indirect emissions, in conformity with the definitions that have been adopted. Current practice involves the use of fossil fuels primarily for the production of district heat. In Denmark, where district heating is extensively used, biomass and wastes are used to generate the necessary heat. All these activities contribute to CO_2 emissions. Hence, district heating will be of limited use in emission mitigation. Geothermal energy may be considered as an exemption. It is noteworthy to mention that extraction of hot underground water is typically associated with a large release of CO_2. This is mainly due to limestone zones that contain the water reservoir and the dissolution of lime in the underground water results in the formation of CO_2. More importantly, geothermal energy, which relies on high temperature underground water, has a very limited potential, and currently provides only less than 0.5% of the space heating [102].

With the increasing population, it is clear that both residential and public buildings will grow both in numbers, but also in size. Therefore, it is expected to have continuous growth in space heating's energy requirement. Yet, awareness about the importance of heat insulation of buildings is rapidly growing. Measures to reduce heat losses, such as building envelops became simple, affordable, hence widely accepted practices. Many governments have implemented building codes; many others are in process of adapting them to their own needs. Construction practices have incorporated insulation applications, hence new buildings tend to be much more energy efficient than their predecessors. Remediation techniques of older buildings, especially through enveloping, are becoming more affordable.

The relatively long useful life of buildings, associated with the fact that they are predominantly owned by individuals is a major obstacle in the transition to newer energy efficient buildings. Nevertheless, authorities, including IEA, consider that prospective energy improvements have enough potential in compensating the future energy demand growth in space heating.

4.2. Water Heating

The level of civilization humankind has reached rendered hot water a necessity. Its use is not restricted to residential buildings but has already expanded to almost all social buildings.

In developed countries, centralized water heating facilities have already been incorporated into buildings. Still, individual water heating devices are also in use, depending on the selected residential building models. In developing countries, however, the situation is not quite similar. Water heating, which is still not accepted as a necessity that must be met through a centralized system, is being performed by using individually owned devices. This fact leads to extensive use of biomass (which primarily consists of wood and cattle dung, also referred to as conventional biomass, to distinguish from sustainable and renewable biofuel applications). India is a good example, where space heating need is minimal: almost 70% of water heating has been supplied by the combustion of biomass.

Throughout the world, the individual share of each energy source for producing hot water differs significantly from space heating. Biomass (mostly conventional) accounts for more than 40% of the energy demand. Natural gas ranks second with almost 23% share.

The best use of solar energy, an important renewable source, has been realized in water heating. Solar water heaters are affordable, readily available, and widely accepted by many societies. Yet, its contribution to water heating has been estimated to be inferior to 2% [104]. Breakdown of energy sources used in water heating is given in Figure 4-2.

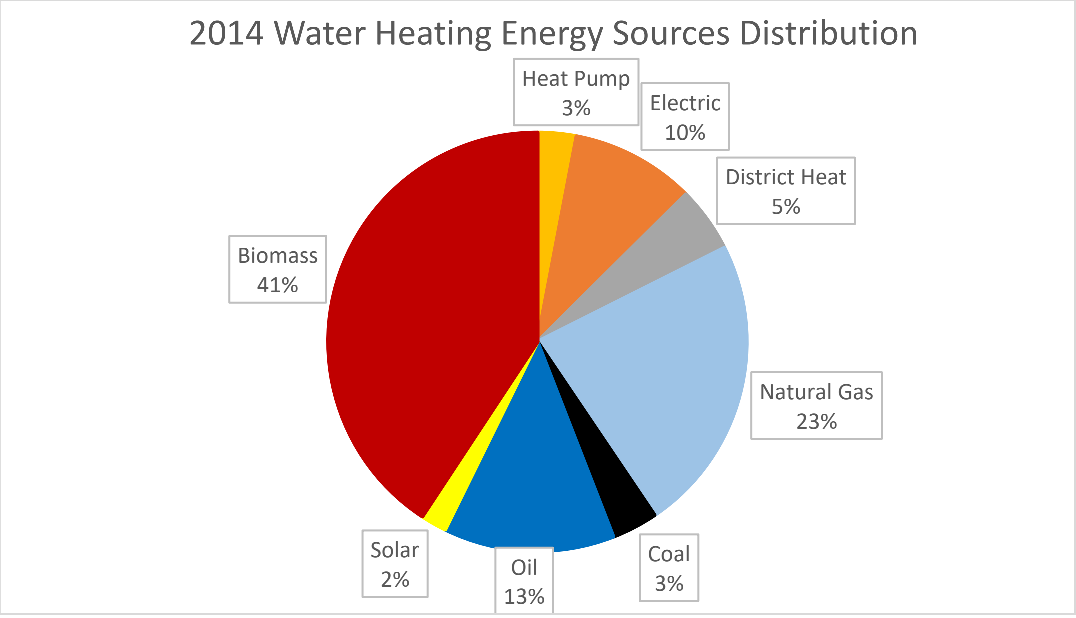

Figure 4-2 Water Heating Energy Sources Distribution, 2014 [39]

District heating has a much lower contribution in water heating than it has in space heating, around 5% in 2014 [39]. The use of geothermal energy is more abundant in water heating, yet it still is very limited and supplied only 1% of the demand in 2019 [102].

Growth in the population and further development of societies should implicate an increase in water heating. Yet, current technologies widely employed to generate hot water do not represent efficient ones. The reason for the extensive use of inefficient devices is primarily their low costs. The availability of solar water heating devices has increased only recently. Widespread use of solar devices, associated with the use of more efficient methods for hot water production, will reduce the energy demand. IEA predicts that energy demand for water heating will grow at a relatively slow pace reaching its maximum around 2050.

4.3. Cooking

It has been expressed that space heating represents a primary requirement for humankind to sustain its existence in relatively cold climates. Cooking on the other hand is mandatory regardless of the climatic conditions. Due to its long history, cooking has been performed using various devices. Even today, people employ different technologies, some of which are very inefficient.

A large fraction of the population is living in warm climates, mainly in southeastern Asia and Africa. Especially in under developed countries in these regions, cooking energy demand dominates the buildings sector. Because space heating, even water heating are not considered essential under such conditions, cooking methods rely on very inefficient devices. These low efficiency devices can be as simple as open fires. Globally, the use of biomass in cooking is predominant. IEA estimated that in 2014, the share of biomass in cooking was 65% [39]. In another study, again by IEA, this share is 70% for 2010 [100].

Cooking requires a treatment completely different from those for space or water heating. The use of open fires, millennia-old three-stone fires still play a significant role in the everyday life of human beings. Even today, the switch from open fire to stoves running on either biomass or LPG is being considered a major improvement. This reflects the relatively low development level in cooking.

Developed countries make extensive use of natural gas and electricity for cooking. However, in cooking, unlike industry or transport, energy demand is not proportional to the level of development but directly to the population. It is a fact that globally, developing countries' populations exceed that of developed countries by large margins. Cooking relies on relatively high temperatures, making the use of district heating impractical. Apart from electricity, all energy sources relate to the combustion of either biomass or fossil fuels. Solar cooking is being debated but did not find wide use. The breakdown of energy sources in cooking is presented in Figure 4-3.

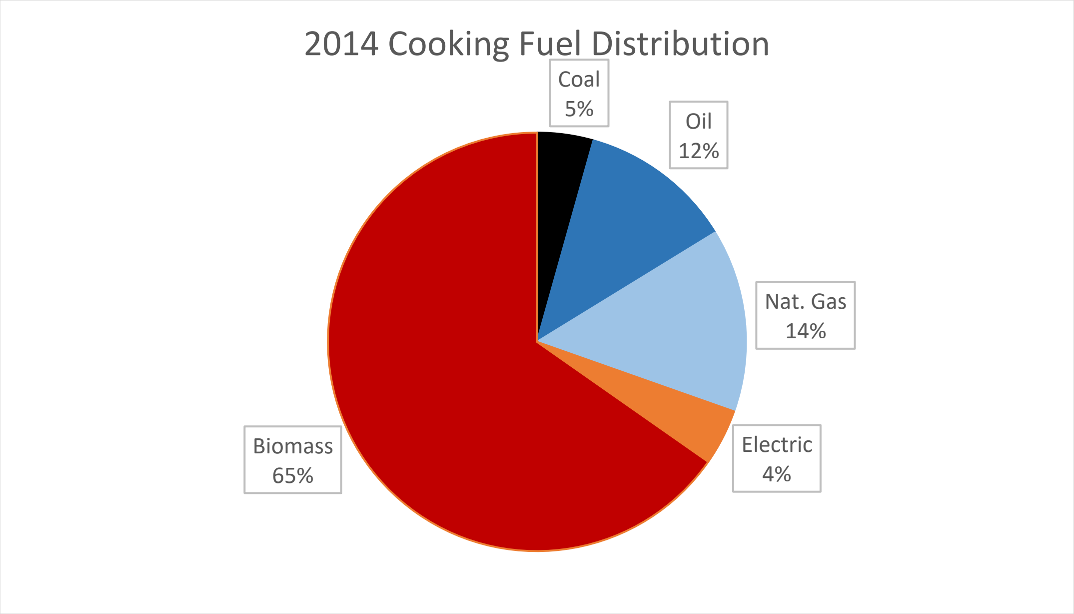

Figure 4-3 Cooking Energy Sources Distribution, 2014 [39]

4.4. Methodology in this study

Space heating, water heating, and cooking have been identified as the end-uses that contribute to direct emissions from buildings sector. Therefore, in order to estimate both future emissions and savings resulting from possible remediation efforts, the demand in each end-use needs to be forecasted. Future improvements in energy efficiency will have considerable effects on the sector. In the case of both industry and transport sectors, these improvements have relatively unimportant implications. The fundamental reason behind this assumption is that both industrial facilities and transportation vehicles have already undergone the necessary technological development. Whereas in the buildings sector, items are largely owned by individuals, have very long service lives, and hence they do not have satisfactory (by today's standards) energy saving characteristics.

In the literature, forecasts are available based on the floor area of buildings. Even further details are provided, such as the partition of these floor areas between residential and public (service) buildings. Yet, the energy intensity of buildings varies substantially not only from one county to another but even within each country. The evolution of energy intensity in each end-use carries even further ambiguities. Therefore, gathering reliable estimates is almost an impossible task. As the subject of the present work is not to provide suggestions on shaping the future of the buildings sector, but to analyze the possibility of reducing CO_2 emissions from the sector by proper choice of energy carriers and primary sources, a study performed by IEA has been selected. IEA has been chosen as a data provider, as it is a well-recognized and reputable authority in energy forecasts.

Detailed information is available in the 2017 Report of IEA [39]. One of the scenarios adopted by IEA is the Reference Technology Scenario (RTS), which might be considered as the Business As Usual (BAU). It incorporates several measures to be taken in the future (in reducing energy consumption and CO_2 emissions) because governments have declared that they will take the necessary precautions along the lines. These measures are far from being sufficient to meet the 2°C global warming limit, let alone the 1.5°C target. However, these future measures cannot be neglected, as they are expected to be implemented regardless of whether necessary actions that are recommended in this study will be considered in the future.

In RTS, forecasts for the World's energy demand for space heating, water heating, and cooking are available until 2060. Provided data is based on the statistics available for 2014, and starting from 2020 forecasts are listed every 5 years. Linear interpolation has been performed in between, until 2060.

Beyond 2060, it has been assumed that energy intensity in each mode has already reached maturity. However, energy demand in each end-use will continue to increase as the number of consumers (population) is growing. United Nations collects reliable projections on World's population growth. Many estimates have been compared by the UN and the median projection figures have been selected to be used in this study. Accordingly, the yearly linear growth rate is 0.3% from 2060 to 2070 and 0.13% beyond 2070 [105]. Hence, energy demand in each end-use has been extrapolated with the appropriate growth rate.

Once the energy demand on an end-use basis is determined, targets have been set on the use of energy carriers and primary energy sources to reduce future CO_2 emissions. Target years have been selected to be 2030, 2050, and finally 2070.

The proposed strategy for reducing future CO_2 emissions in the buildings sector is to make use of electric energy extensively, given that this electricity is produced from renewables or nuclear energy. Solar energy proves very useful in meeting the water heating requirements. There are applications of solar energy for space heating, yet its applicability is limited. Solar cooking is also proposed, yet such devices have not yet found public acceptance.

Electrolytic hydrogen is being investigated to reduce CO_2 emissions. In the case of the buildings sector, hydrogen distribution can be realized through the already installed (and to be installed) natural gas network. However, this approach faces important technical obstacles. Hydrogen has a higher heating value when compared to natural gas (almost by a factor of 3), as listed in many tables [106]. It is essential to understand that this comparison is on a per unit mass basis. The molecular weight of hydrogen is more than 8 times smaller than natural gas. Therefore, per unit volume of gas, the situation is the inverse: natural gas has a much larger heating value (per volume) when compared to hydrogen. Therefore, mixing hydrogen with natural gas significantly reduces the energy content of the supplied gas in the network.

In the case where hydrogen is added to the distribution network of natural gas, its share cannot exceed 15% on a volumetric basis. Even with 15% blending (on a volumetric basis), only 5% of the energy of the blended gas comes from hydrogen and the volumetric heating value of the gas reduces by 10% when compared to pure natural gas [107]. Boilers, furnaces, and similar devices used in the combustion of natural gas in buildings will require significant modifications to run on a gas with much lower energy intensity. The need for the fundamental renovation of boilers in buildings makes blending beyond 15% impractical. Even so, the reduction in natural gas consumption is marginal: 5%. Hence, in this study, it has been assumed that supplying hydrogen to buildings does not constitute a viable solution for reducing CO_2 emissions.

4.4.1. Proposed Evolution of Space Heating

Space heating is the end-use that is responsible for the highest energy consumption. In fact, even when end-uses that are generating indirect emissions are considered, still space heating has the highest energy intensity. The never-ending development of societies has a direct effect on the more intense use of electric energy. In the RTS scenario, IEA predicts that the leadership of space heating will continue until 2050, by the time household appliances are expected to exceed space heating in terms of energy consumption.

To maintain CO_2 emissions at a level as low as possible, the use of electricity has been proposed to the largest possible extent. At this point, it is essential to remind that the use of electricity for space heating applications, should depend on the use of heat pumps, especially ground (or water) source heat pumps. This approach represents the obvious choice given thermodynamic considerations. However, air source heat pumps will also find a vast area of application, especially in regions with moderate climate conditions, as they are more affordable and easy to install.

It has been assumed that electricity use is not restricted to heat pumps only, for space heating. Much less complicated, cheaper devices that operate on ohmic resistance will also play an important role. This is mostly of economic considerations (much lower Capex) but also validated by the use of electricity in temporary conditions, where installation time would be prohibitive. In calculations, an average COP

(Coefficient of Performance) of 3 has been taken for heat pumps, representing an achievable, yet conservative factor.

In this study, the recent (for the year of 2014) distribution of energy sources in space heating is taken from IEA, as explained in detail a priori. Targets have been set for years 2030, 2050, and finally for 2070, after which it has been assumed that distribution will assume an asymptotic shape identical to that in 2070. Targets primarily aim at promoting electric energy use. As full transition requires some time, immediate targets are to eliminate the most CO_2 emitting source, namely the coal. Next use of oil products should be completely prohibited; however, prediction has been made that this can be achieved in the longer term. The use of biomass, clearly a source of CO_2 will remain for even a longer period, mainly because it is the only energy source for rural areas in less developed countries. Transition to full electric use may prove difficult in the shorter periods, hence abandoning coal, oil, and even biomass use are projected to be temporarily compensated by the use of the cleaner natural gas. The assumptions are summarized in Table 4-1.

Table 4-1 Energy Carrier Distribution of Space Heating (REALISTIC Scenario)

Year	Heat Pump	Electric Device	District Heat	Natural Gas	Coal	Oil	Bio-mass
2014	10.26%		13.25%	38.83%	9.32%	14.03%	14.31%
2015-2029	Linear interpolation						
2030	25%	10%	10%	40%	0%	2.5%	12.5%
2031-2049	Linear interpolation						
2050	50%	20%	0%	20%	0%	0%	10%
2051-2069	Linear interpolation						
2070-2100	75%	25%	0%	0%	0%	0%	0%

Distribution of energy sources in years that fall between years listed in the table, a linear interpolation has been employed. Beyond 2070, it has been assumed that the energy distribution profile has reached its saturation, therefore remains invariant until 2100.

Yearly energy demand for space heating has been extracted from the detailed data supplied by IEA [39]. Using the evaluated shares of each energy source, the yearly energy consumptions have been determined. In the case of electric energy, a distinction between the use of heat pumps and ohmic heaters is performed, because per the adopted assumptions, their energy demands differ by a factor of 3. The proposed evolution of each space heating mode is presented graphically in Figure 4-4.

Shares of each mode in space heating are denoted by the variables:

$$\begin{cases} sh(space, mode, yr) \\ mode = \{hp, ohm, dist, NG, coal, oil, bio\} \end{cases} \tag{ 4-1}$$

The members of the set for $mode$ variable correspond to the heat pump, ohmic electric heaters, district heat, natural gas, coal, oil, and biomass, respectively.

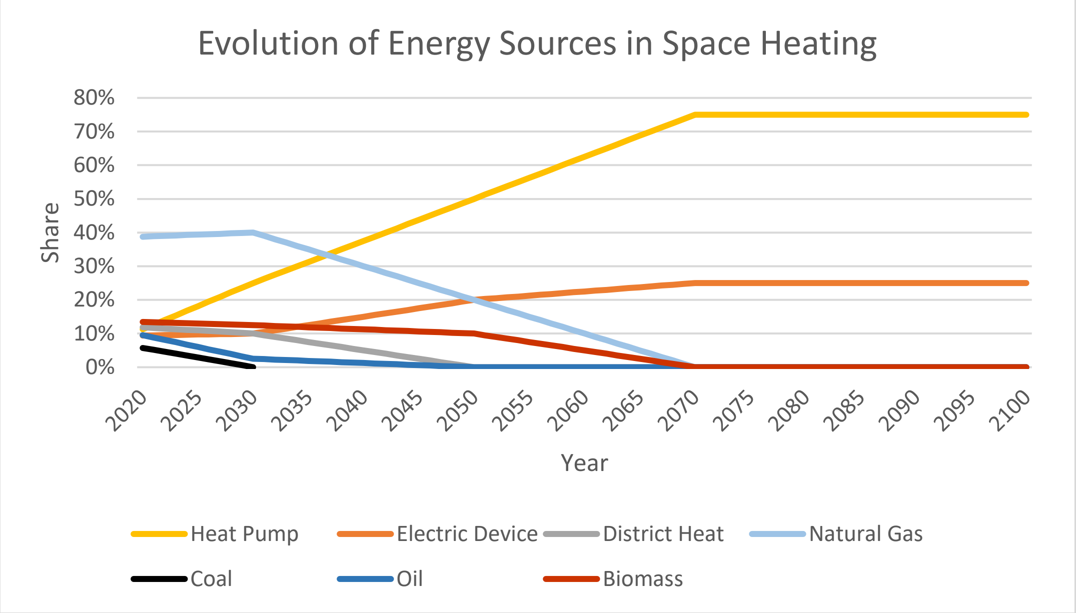

Figure 4-4 Evolution of Energy Sources in Space Heating

4.4.2. Proposed Evolution of Water Heating

Water heating ranks third (last) in energy consumption, among the end-uses that directly emit CO_2. Water heating has been analyzed in parallel with space heating, mainly because the technologies employed in both are similar, which is not the case for cooking. Even though there exist similarities between the two former end-uses, water heating has a large potential for the extensive use of solar energy. When space heating is considered, however, the potential for the use of solar energy is much limited and already incorporated in the design of buildings.

To maintain CO_2 emissions at a level as low as possible, the use of electricity has been proposed to the largest possible extent. Just like in the case of space heating, heat pumps, especially ground (or water) source heat pumps prove to be the ideal solution, given thermodynamic considerations. The combined operation of heat pumps for water and space heating is likely to become a common practice. Therefore, it has been assumed that a similar mixture of air, ground, and water source heat pumps will be used for water heating as well, thus an average COP value of 3 can be adopted in this study.

Solar energy has found its widest application in water heating. It has been demonstrated to be achievable and affordable, even cost-effective than other sources in many regions. There exists a consensus that solar will take a large share in water heating in the future. In one of its later reports, IEA predicts that solar will supply 1/3 of water heating demand in 2040, 1/2 by 2070 [40]. Accordingly, a significant future share has been allocated to the renewable energy source of solar in the study.

Targets have been set for years 2030, 2050, and finally for 2070, after which it has been assumed that distribution will assume an asymptotic shape identical to that in 2070. In parallel with space heating, targets aim at the extensive use of electric energy, while gaining strong support from solar energy, in the case of water heating. Early abandoning of coal and then oil, is essential. Similarly, the use of biomass should be reduced as earlier as possible. In the short term, where solar and electricity may not satisfy the demand, the use of cleaner natural gas is enhanced. The assumptions are summarized in Table 4-2.

Table 4-2 Energy Carrier Distribution of Water Heating (REALISTIC Scenario)

Year	Heat Pump	Electric Devices	District Heat	Natural Gas
2014	12.56%		5.04%	22.96%
2015-2029	Linear interpolation			
2030	25%	10%	5%	12.5%
2031-2049	Linear interpolation			
2050	40%	10%	0%	0%
2051-2069	Linear interpolation			
2070-2100	40%	10%	0%	0%
Year	Coal	Oil	Solar	Biomass
2014	3.55%	13.18%	2%	40.72%
2015-2029	Linear interpolation			
2030	0%	2.5%	20%	25%
2031-2049	Linear interpolation			
2050	0%	0%	40%	10%
2051-2069	Linear interpolation			
2070-2100	0%	0%	50%	0%

Distribution of energy sources in years that fall between years listed in the table, a linear interpolation has been employed. Beyond 2070, it has been assumed that the energy distribution profile has reached its saturation, therefore remains invariant until 2100.

Yearly energy demand for water heating has been extracted from the detailed data supplied by IEA [39]. Using the evaluated shares of each energy source, yearly energy consumptions have been determined. In the case of electric energy, a distinction between the use of heat pumps and ohmic heaters is performed, because per the adopted assumptions, their energy demands differ by a factor of 3. Here proposed evolution of each water heating mode is presented graphically in Figure 4-5.

Shares of each mode in water heating are denoted by the variables:

$$\begin{cases} sh(water, mode, yr) \\ mode = \{hp, ohm, dist, NG, coal, oil, solar, bio\} \end{cases} \quad (4\text{-}2)$$

The members of the set for $mode$ variable correspond to the heat pump, ohmic electric heaters, district heat, natural gas, coal, oil, solar, and biomass, respectively.

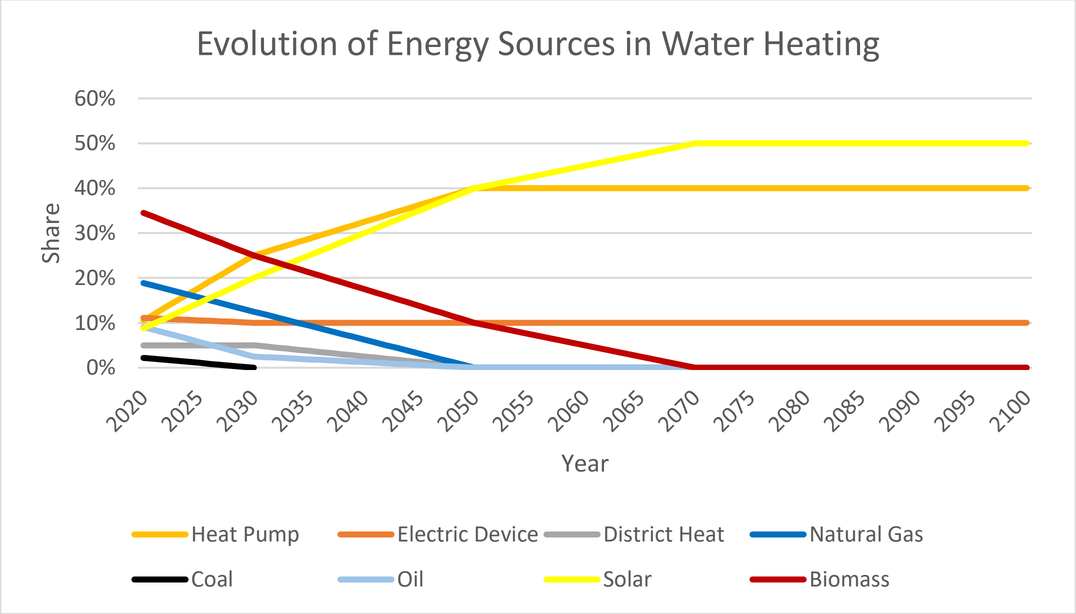

Figure 4-5 Evolution of Energy Sources in Water Heating

4.4.3. Proposed Evolution of Cooking

Cooking differs fundamentally from either space or water heating, mainly because the majority of emissions result from less developed countries, where the population is higher. Space heating is a regional requirement, whereas cooking is a strong function of population density. Therefore, cooking has a large share in energy consumption (over space and water heating) in less developed countries, where biomass is a dominant energy source. Authorities targeting better cooking techniques to reduce CO_2 consider primarily a transition from open fire and low efficiency fireplace technology to the use of stoves running on LPG. Hence, the concerns in cooking are substantially altered from those in heating.

To mitigate CO_2 emissions, extensive use of electric energy has also been proposed in cooking. However, the recommended technology cannot be heat pumps, because of the higher temperature requirement. Much-less efficient technologies, such as ohmic resistive heaters, microwave ovens, and induction cooktops will be used for cooking applications. Phasing out biomass will be more difficult in cooking, where it is the only source available in rural areas in less developed countries.

As done in space and water heating, targets have been set for years 2030, 2050, and finally for 2070, after which it has been assumed that distribution will assume an asymptotic shape identical to that in 2070. The effort in this study focuses on the elimination of most CO_2 emitting sources in the short term. However, LPG, hence oil products will remain valid for longer terms in the case of cooking. Again, the use of natural gas in the short term has positive effects, but its availability remains limited, especially in less developed regions. The proposed transition to cleaner energy sources is summarized in Table 4-3.

Table 4-3 Energy Carrier Distribution of Cooking (REALISTIC Scenario)

Year	Electric Devices	Natural Gas	Coal	Oil	Biomass
2014	4.32%	14.14%	4.36%	11.89%	65.29%
2015-2029	Linear interpolation				
2030	25%	20%	0%	10%	45%
2031-2049	Linear interpolation				
2050	60%	10%	0%	5%	25%
2051-2069	Linear interpolation				
2070-2100	85%	0%	0%	0%	15%

Distribution of energy sources in years that fall between the years listed in the table, a linear interpolation has been employed. Beyond 2070, it has been assumed that the energy distribution profile has reached its saturation, therefore remains invariant until 2100.

Yearly energy demand for cooking has been extracted from the detailed data supplied by IEA [39]. Using the evaluated shares of each energy source, the yearly energy consumptions have been determined. The proposed evolution of each cooking mode is presented graphically in Figure 4-6.

Shares of each mode in water heating are denoted by the variables:

$$\begin{cases} sh(cook, mode, yr) \\ mode = \{ohm, NG, coal, oil, bio\} \end{cases} \tag{4-3}$$

The members of the set for $mode$ variable correspond to ohmic electric heaters, natural gas, coal, oil, and biomass, respectively.

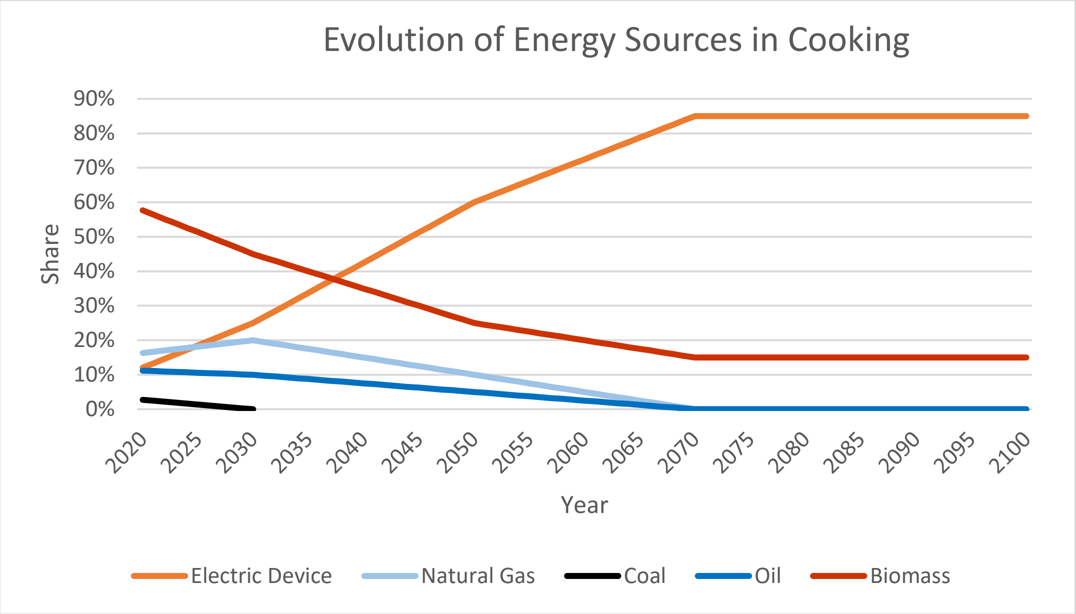

Figure 4-6 Evolution of Energy Sources in Cooking

4.5. Additional Installed Capacity Requirement and CO_2 Savings

In an effort to reduce substantially the CO_2 emissions from the buildings sector, the use of “cleaner” technologies has been proposed in meeting the energy demands of the three end-uses that contribute to direct emissions: space heating, water heating, and cooking. Intense use of electricity seems to be the correct strategy. In the case of space and water heating, the relatively low temperature requirements render heat pumps the ideal candidate. Because of their large COP, they take the most out of a given amount of electric energy [108], [109].

It is a common practice to categorize heat pumps based on their energy sources: air source, ground source, and water source. Air source heat pumps are the simplest version, which is essentially the everyday air-condition device operating in reverse mode. They are cheap and easy to install. However, when the outside air temperature drops, their COPs are adversely affected. Hence, they are suitable in relatively moderate climate regions, such as southeastern Asia, where their penetration is high [110].

In regions with colder climates, however, air source heat pumps become inefficient, requiring the need for using ground source heat pumps. Such heats pumps, extract heat from the ground (the depth can range from a fraction of a meter to several tens of meters) rather than the ambient air. The advantage lies in the low seasonal fluctuation in the temperature in deep soils. Installation of ground source heat pumps is more costly and complicated than air source ones, as piping performing as heat exchangers needs to be laid underground. However, important increases can be achieved in COPs (ranging from 3 to 6). Their use is also being referred to as geothermal energy in many sources, leading to a false impression that conventional geothermal, which relies on high temperature underground water (even steam) has a significantly dominant share in the future demand. In this study, it has been considered that majority of the heat pumps in the future will be of ground source type, so an average COP value of 3 can be achieved globally.

A water source heat pump is similar to a ground source heat pump. A large water reservoir (like sea, lake, or even river) is used to extract heat from, rather than the ground. Of course, this depends on the availability of such a source. However, technically, if such water reservoirs exist, enhanced heat transfer in aqueous environments makes water source heat pumps a good alternative to ground source heat pumps. In this study, no distinction has been considered between the two types, but rather assume that a good mixture of all three types will be maintained to achieve the target of COP=3.

In the literature, it is also emphasized that the use of either ground or water for energy extraction will also have a positive effect on the use of these sources for cooling purposes. Seasonal changes typically require the use of space cooling, which is becoming a new life standard for humans, in addition to space heating. Heat extraction during cold seasons will lower the temperature of the source (ground or water), which will be employed in warm seasons as a cooling reservoir to which heat is rejected. In the future, developed countries will employ combined heating/cooling devices that reverse their operation depending on the climatic conditions. It is worth reminding that space cooling will have the fastest energy demand growth in the future, but mitigation efforts for cooling will be discussed later when indirect emissions are analyzed.

In the case of cooking, however, heat pumps do not seem to be a viable solution, because of the higher temperature needs. Nevertheless, electricity use needs to be increased, as it is the least CO_2 emitting technology, assuming that the electricity has been generated by renewables or nuclear power. Conventional resistance based heaters, as well as, microwave and induction technologies offer affordable and simple alternatives to meet the energy demand for cooking.

Renewables can significantly contribute to the energy supply in the buildings. By a large margin, solar water heaters are the leaders in this race. In this study, a large fraction of water heating has been allocated to such devices, as they are mature, affordable, and readily available. The contribution of solar energy to either space heating or cooking is very limited, however.

Many studies consider biofuels as an alternative in CO_2 reduction efforts [111], [112], [113]. In the present study, all carbon capture strategies have been excluded; hence, the use of biofuels, even if they become available in the future, has not been included in the analysis.

Finally, (conventional) geothermal energy is an excellent source for meeting the heating needs in the buildings. Yet, its availability is so limited that no considerable contribution from geothermal power can occur, hence conventional geothermal is not considered as an option in this study.

The analysis of the three direct emitting end-uses begins with space heating, which consumes 44% of the energy of the total of three. It is followed by cooking with 30% and at last by water heating with 26% of the total. However, water heating has been discussed after space heating, as they rely on similar technologies. As will be discussed, cooking has entirely different characteristics and the level of technologies employed is much less developed when compared to the other two.

4.5.1. Contribution of Space Heating

Demand for space heating has been extracted from IEA's RTS Model [39]. The available data begins with the evaluations in 2014, contains forecasts for every 5 years from 2020 to 2060. For years not listed in the report by IEA, a linear interpolation has been performed. Yearly space heating energy demands $E(space, yr)$ are evaluated by increasing the values indicated in the RTS Scenario with 20% of the energy supplied by the electricity mode only. This increase has been performed to take into account the effect of heat pumps, which generate more space heating than their appropriate consumptions, the latter being the figure included in RTS.

Beyond 2060, average yearly population growth rates have estimated by United Nations have been adopted to evaluate the demands in 2070 and 2100, as described in Section 4.4. Summary of the employed data is provided in Table 4-4.

Table 4-4 Space Heating Energy Demand (REALISTIC Scenario)

Year	Energy Demand (PJ)
2014	40,184.58
2015-2024	Linear interpolation
2025	41,312.54
2026-2039	Linear interpolation
2030	41,122.29
2031-2034	Linear interpolation
2035	40,620.58
2036-2039	Linear interpolation
2040	40,015.47
2041-2044	Linear interpolation
2045	39,082.54
2046-2049	Linear interpolation
2050	37,848.58
2051-2054	Linear interpolation
2055	36,535.45
2056-2059	Linear interpolation
2060	34,994.87
2061-2069	Linear interpolation
2070	36,044.72
2071-2099	Linear interpolation
2100	37,450.46

Once the energy demand $E(space, yr)$ has been identified, individual demand for each source $E(space, mode, yr)$ has been evaluated using the appropriate shares, determined per the preset targets:

$$E(space, mode, yr) = E(space, yr) * sh(space, mode, yr) \tag{ 4-4}$$

The proposed evolution of yearly energy consumption rates for each source is shown in Figure 4-7.

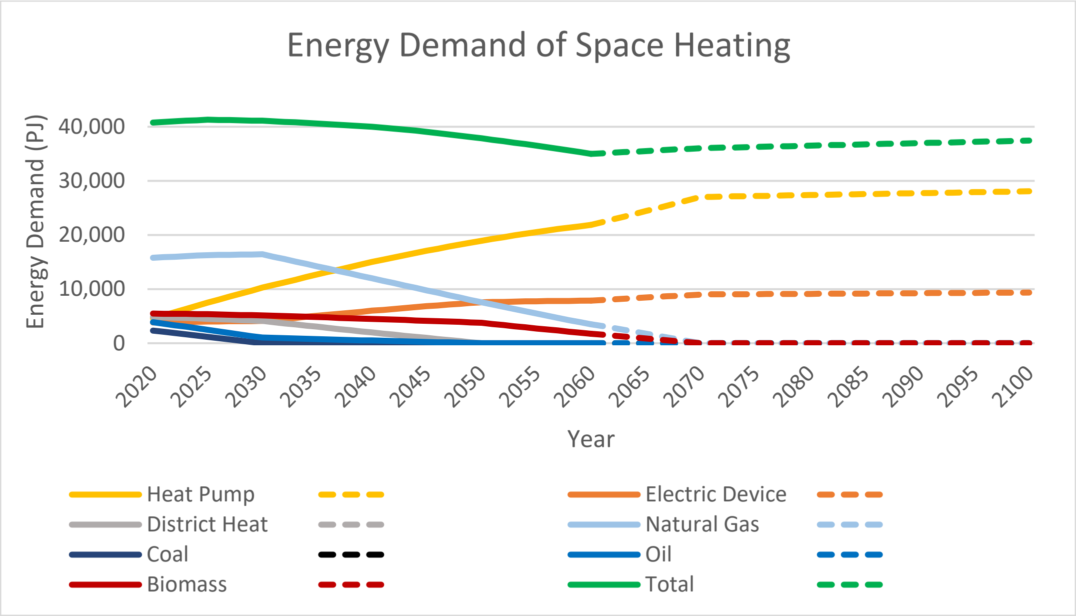

Figure 4-7 Space Heating Energy Demand by Energy Sources

Once the energy demand has been determined, the corresponding electricity demand has been evaluated. In the case of space heating, both ohmic heaters and heat pumps consume electricity. To determine the forecasted electricity requirement ($Elec(space, yr)$), the COP value for a typical heat pump is 3 has been taken; hence, it has been found that:

$$Elec(space, yr) = E(space, ohm, yr) + \frac{1}{3}E(space, hp, yr) \tag{4-5}$$

The proposal of more extensive use of electricity in this study implies a fast growth in electric energy demand, which are later included in the analysis of the power sector. The growth forecast in electricity requirement from 2020 to 2100 is presented in Figure 4-8.

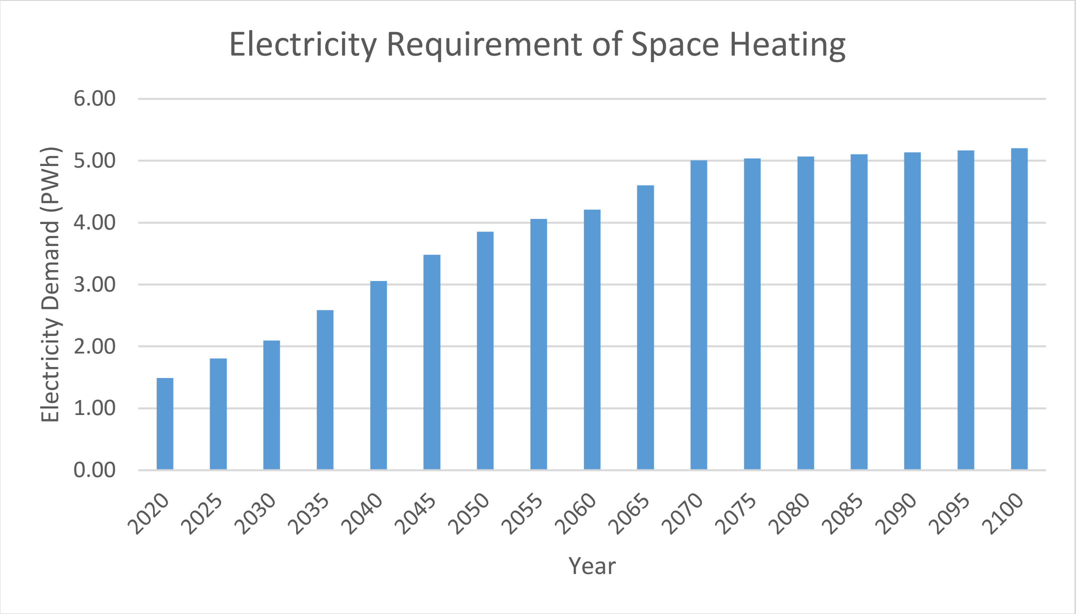

Figure 4-8 Electricity Requirement of Space Heating

It has been determined that the electricity demand reaches 2.09 PWh, 3.85 PWh, 5.01 PWh, and 5.20 PWh, in 2030, 2050, 2070, and 2100, respectively.

Knowing the distribution of energy sources to be employed for space heating, CO_2 emissions from each source have been evaluated. For the emission intensity of each fuel type, emission intensities that correspond to ones used in the RTS Model of IEA have been used. A list of the emission intensities of energy carriers (denoted by $q(mode)$) is given in Table 4-5.

Table 4-5 Emission Intensity of Energy Carriers

Emission Intensity (g CO_2/kWh)	
Natural Gas	201.96
Coal	340.56
Oil	244.80
Biomass	394.56

Yearly CO_2 emission rates from space heating ($Q(space, yr)$) are found by using the relation:

$$\begin{cases} Q(space, yr) = \sum_{mode} E(space, mode, yr) * q(mode) \\ \qquad\qquad mode = \{NG, coal, oil, bio\} \end{cases} \tag{4-6}$$

Evaluated future emission rates are then compared with the forecasted emissions used in the RTS Model of IEA, which can be regarded as the BAU conditions for the buildings sector. Results are presented graphically in Figure 4-9.

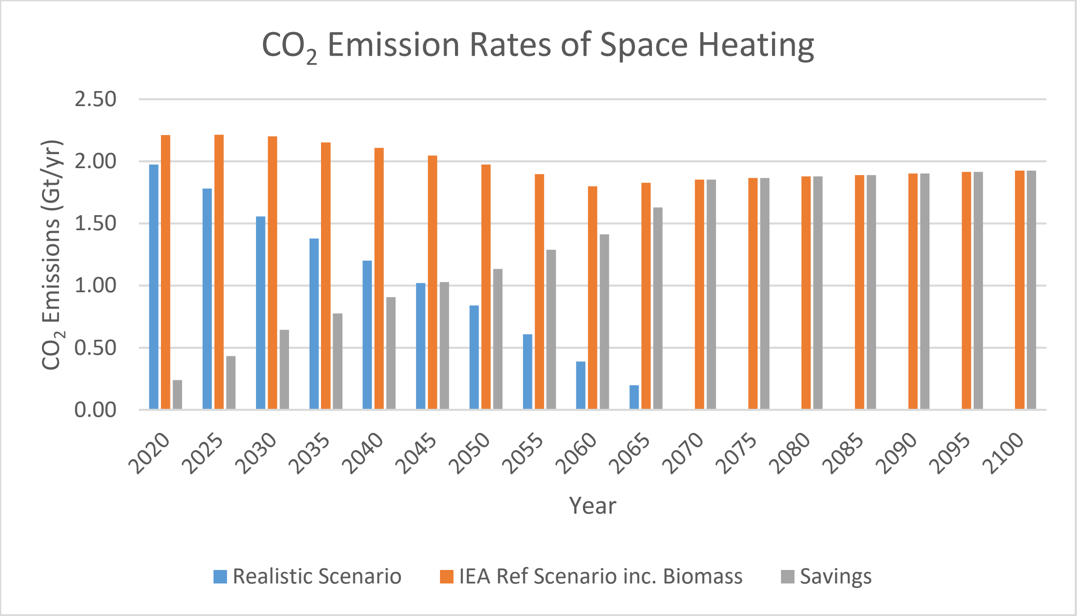

Figure 4-9 CO_2 Emission Rates of Space Heating

It has been calculated that CO_2 emissions, including the ones from biomass use, are 1.56 Gt, 0.84 Gt, 0.00 Gt, in the years 2030, 2050, and 2070 & beyond, respectively. Whereas under the BAU conditions (i.e., RTS Scenario by IEA), emissions are 2.20 Gt, 1.97 Gt, 1.85 Gt, and 1.93 Gt in the years 2030, 2050, 2070, and 2100, respectively.

4.5.2. Contribution of Water Heating

Forecast for the energy demand of water heating has been performed in parallel to space heating. IEA’s RTS Model has been used between 2020 and 2060, and UN’s population growth rates have been applied beyond 2060. Yearly water heating energy demands $E(water, yr)$ are evaluated by increasing the values indicated in the RTS Scenario with 10% of the energy supplied by the electricity mode only, to account for the supply to consumption ratio of heat pumps, which is larger than unity. The use of heat pumps for water heating is inferior to that in space heating, hence the coefficient has been reduced in comparison to space heating.

Beyond 2060, average yearly population growth rates estimated by United Nations have been adopted, to determine demands corresponding to years 2070 and 2100 as described in Section 4.4. Linear interpolation has been performed to determine the values corresponding to intermediate years. A summary of the employed data is provided in Table 4-6.

Table 4-6 Water Heating Energy Demand (REALISTIC Scenario)

Year	Energy Demand (PJ)
2014	23,662.77
2015-2024	Linear interpolation
2025	25,760.12
2026-2039	Linear interpolation
2030	26,464.54
2031-2034	Linear interpolation
2035	27,114.86
2036-2039	Linear interpolation
2040	27,617.49
2041-2044	Linear interpolation
2045	27,990.52
2046-2049	Linear interpolation
2050	28,308.14
2051-2054	Linear interpolation
2055	28,578.03
2056-2059	Linear interpolation
2060	28,639.63
2061-2069	Linear interpolation
2070	29,498.82
2071-2099	Linear interpolation
2100	30,649.27

Upon determining the energy demand $E(water, yr)$ has been identified, individual demand for each source $E(water, mode, yr)$ has been evaluated using the appropriate shares, determined per the preset targets:

$$E(water, mode, yr) = E(water, yr) * sh(water, mode, yr) \qquad (4\text{-}7)$$

The proposed evolution of yearly energy consumption rates for each source is shown in Figure 4-10.

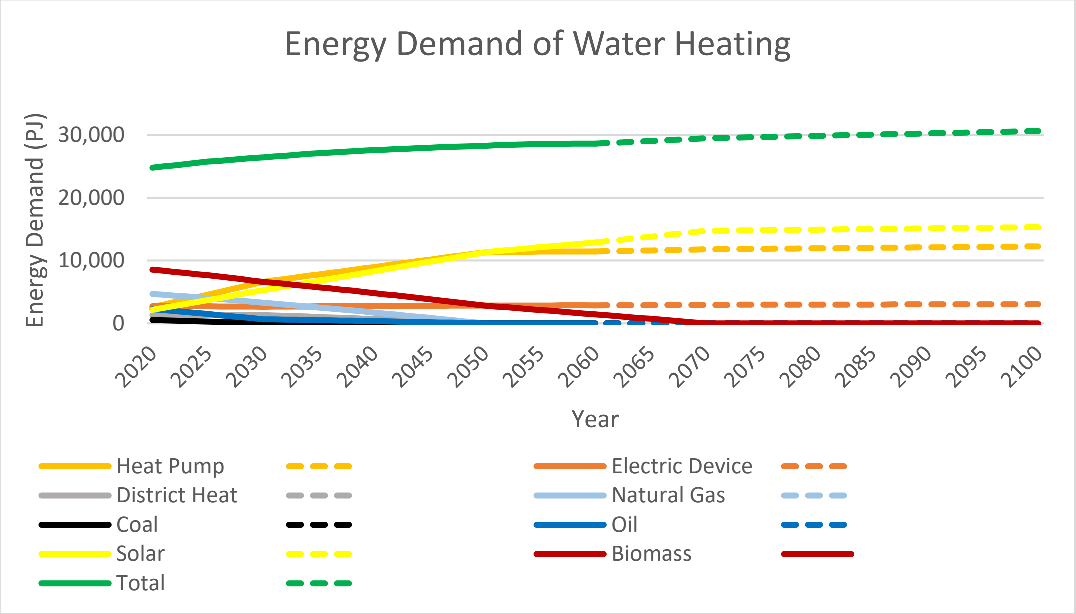

Figure 4-10 Energy Demand of Water Heating by Energy Sources

Using the evaluated energy demand, the corresponding electricity demand has been determined. In the case of water heating, both ohmic heaters and heat pumps contribute to electricity requirement, as in the case of space heating. Again, a COP value of 3 for the heat pump has been used. Then the forecasted electricity requirement ($Elec(water, yr)$) is given by:

$$Elec(water, yr) = E(water, ohm, yr) + \frac{1}{3}E(water, hp, yr) \qquad (4\text{-}8)$$

The forecasted electricity requirements from 2020 to 2100 are presented in Figure 4-11.

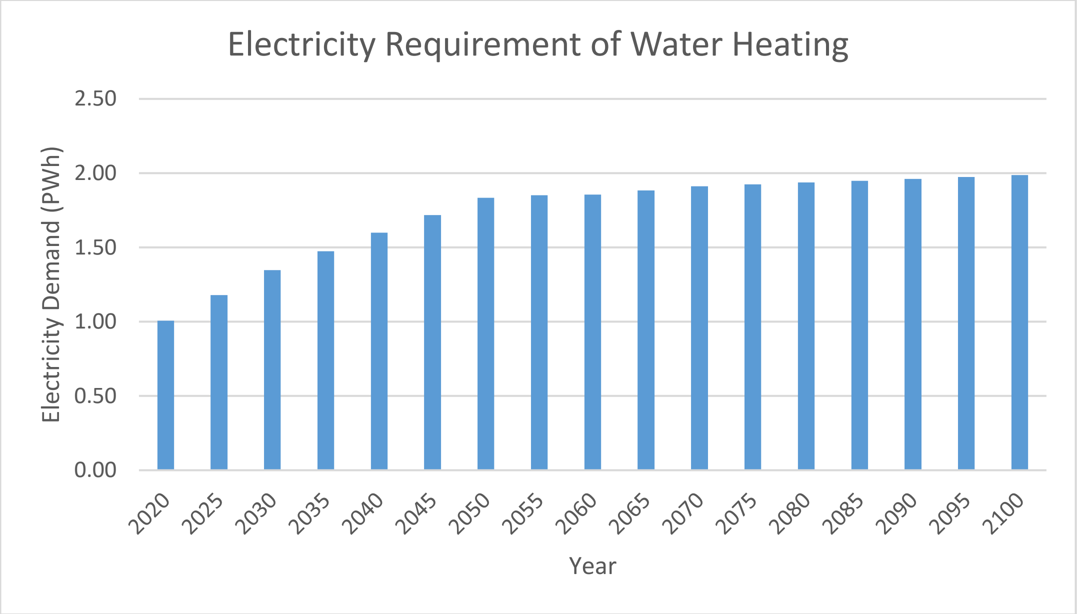

Figure 4-11 Electricity Requirement of Water Heating

Yearly CO_2 emission rates from water heating ($Q(water, yr)$) are evaluated using the emission intensity of energy carriers given in Table 4-5, according to the relation:

$$\begin{cases} Q(water, yr) = \sum_{mode} E(water, mode, yr) * q(mode) \\ \qquad\qquad mode = \{NG, coal, oil, bio\} \end{cases} \tag{4-9}$$

Evaluated future emission rates are then compared with the forecasted emissions used in the RTS Model of IEA, which can be regarded as the BAU conditions for the buildings sector. Results are presented graphically in Figure 4-12.

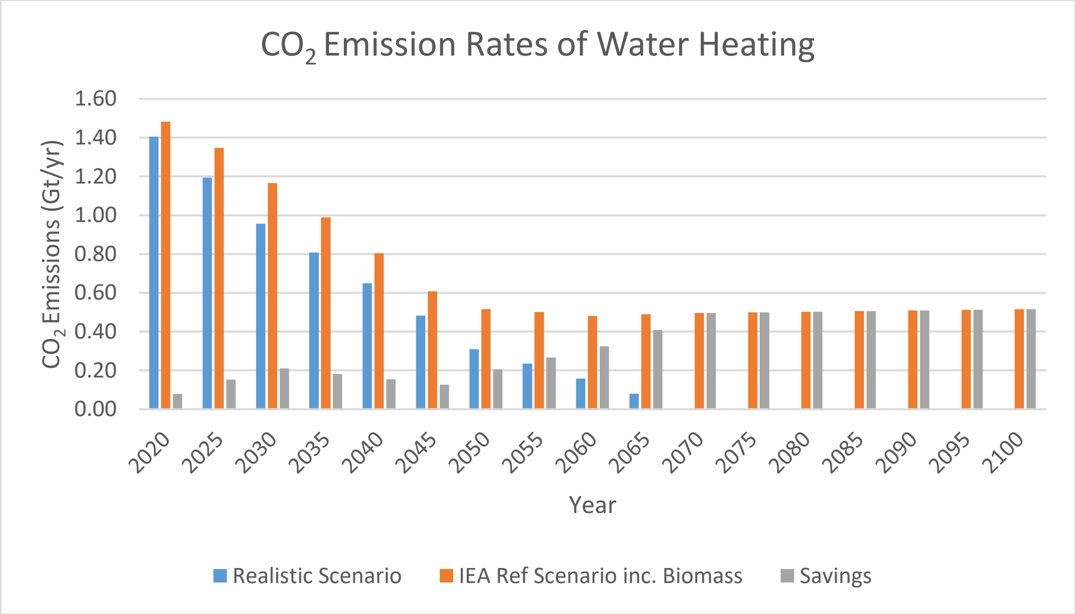

Figure 4-12 CO_2 Emission Rates of Water Heating

It has been calculated that CO_2 emissions, including the ones from biomass use, are 0.96 Gt, 0.31 Gt, 0.00 Gt, in the years 2030, 2050, and 2070 & beyond, respectively. Whereas under the BAU conditions (i.e., RTS Scenario by IEA), emissions are 1.17 Gt, 0.52 Gt, 0.50 Gt, and 0.52 Gt in the years 2030, 2050, 2070, and 2100, respectively.

4.5.3. Contribution of Cooking

Forecast for the energy demand of cooking has been performed in parallel to space heating. IEA's RTS Model has been used between 2020 and 2060, and UN's population growth rates have been applied beyond 2060. Beyond 2060, average yearly population growth rates estimated by United Nations have been adopted, as described in Section 4.4. Linear interpolation has been performed to determine the values corresponding to intermediate years. A summary of the employed data is provided in Table 4-7.

Table 4-7 Cooking Energy Demand (REALISTIC Scenario)

Year	Energy Demand (PJ)
2014	27,002.91
2015-2024	Linear interpolation
2025	28,716.43
2026-2039	Linear interpolation
2030	28,572.61
2031-2034	Linear interpolation
2035	28,071.52
2036-2039	Linear interpolation
2040	27,466.62
2041-2044	Linear interpolation
2045	26,650.64
2046-2049	Linear interpolation
2050	25,824.77
2051-2054	Linear interpolation
2055	24,989.12
2056-2059	Linear interpolation
2060	23,858.81
2061-2069	Linear interpolation
2070	24,574.58
2071-2099	Linear interpolation
2100	25,532.98

Upon determining the energy demand $E(cook, yr)$ has been identified, individual demand for each source $E(cook, mode, yr)$ has been evaluated using the appropriate shares, determined per the preset targets:

$$E(cook, mode, yr) = E(cook, yr) * sh(cook, mode, yr) \tag{4-10}$$

The proposed evolution of yearly energy consumption rates for each source is shown in Figure 4-13.

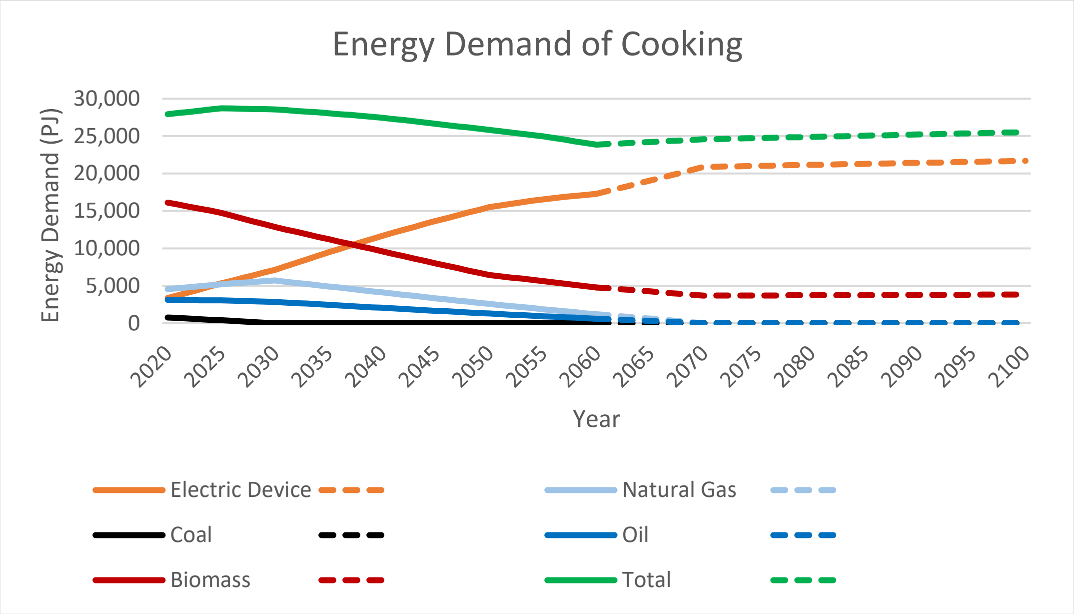

Figure 4-13 Energy Demand of Cooking by Energy Sources

Using the evaluated energy demand, the corresponding electricity demand for cooking ($Elec(cook, yr)$) has been determined. Unlike In the cases of space and water heating, heat pumps do not play a role in cooking, leading to the following relation:

$$Elec(cook, yr) = E(cook, ohm, yr) \tag{4-11}$$

The forecasted electricity requirements from 2020 to 2100 are presented in Figure 4-14.

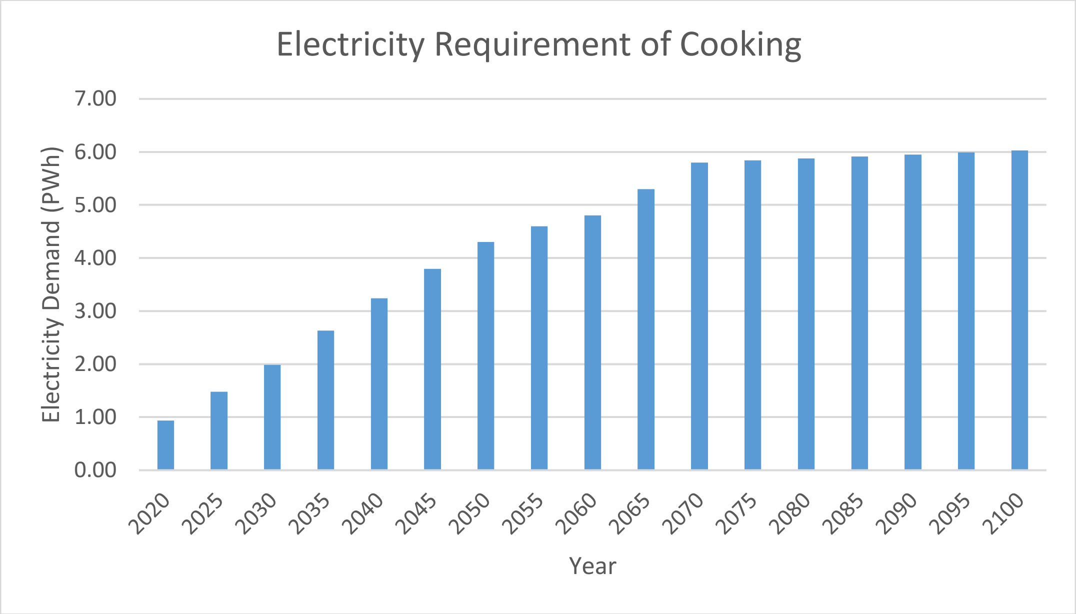

Figure 4-14 Electricity Requirement of Cooking

Yearly CO_2 emission rates from cooking ($Q(cook, yr)$) are evaluated using the emission intensity of energy carriers given in Table 4-5, according to the relation:

$$\begin{cases} Q(cook, yr) = \sum_{mode} E(cook, mode, yr) * q(mode) \\ \qquad mode = \{NG, coal, oil, bio\} \end{cases} \tag{4-12}$$

Evaluated future emission rates are then compared with the forecasted emissions used in the RTS Model of IEA, which can be regarded as the BAU conditions for the buildings sector. Results are presented graphically in Figure 4-15.

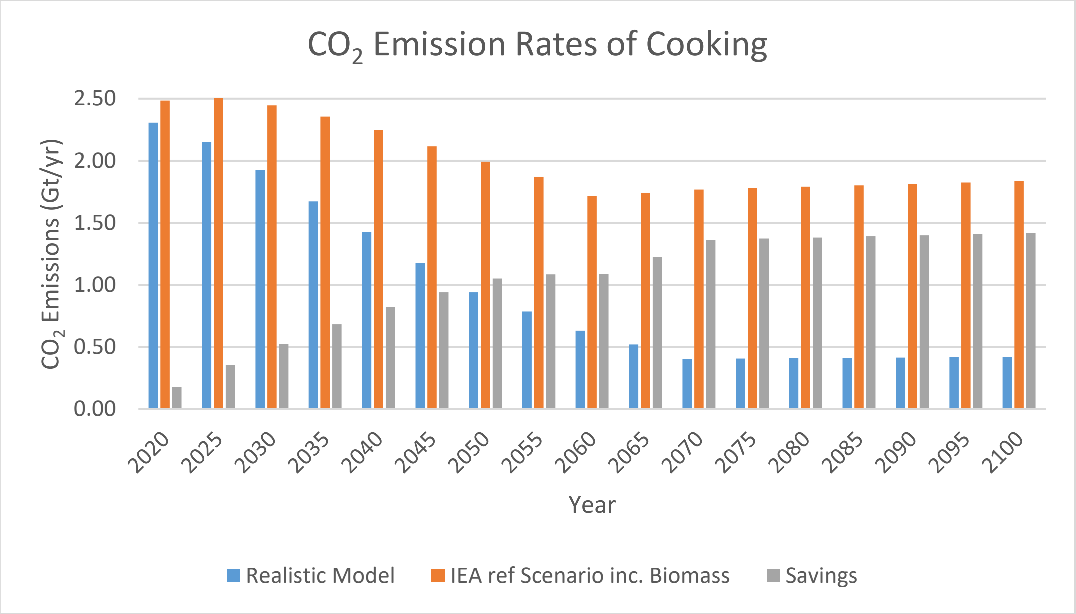

Figure 4-15 CO_2 Emission Rates of Cooking

It has been calculated that CO_2 emissions, including the ones from biomass use, are 1.92 Gt, 0.94 Gt, 0.40 Gt, and 0.42 Gt in the years 2030, 2050, 2070, and 2100, respectively. Whereas under the BAU conditions (i.e., RTS Scenario by IEA), emissions are 2.45 Gt, 1.99 Gt, 1.77 Gt, and 1.84 Gt in the years 2030, 2050, 2070, and 2100, respectively.

4.5.4. Overall Evaluation of the Buildings Sector

To analyze the overall impact of remediation actions in the buildings sector, individual contribution of the three end-uses, which are responsible for direct emissions are summarized: space heating, water heating, and cooking. The electricity requirement of the three end-uses are combined using the formula:

$$\begin{cases} Elec(swc, yr) = \sum\limits_{enduse} Elec(enduse, yr) \\ \quad enduse = \{space, water, cook\} \end{cases} \tag{4-13}$$

The results are shown graphically in Figure 4-16.

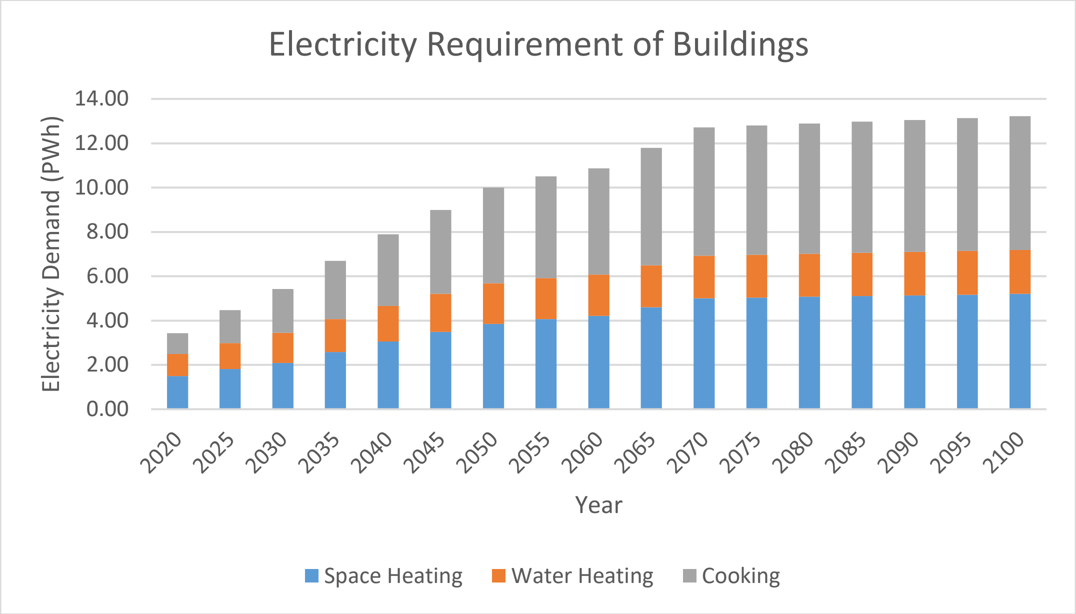

Figure 4-16 Electricity Requirement of Buildings

It is important to emphasize that the calculated electricity demands are from space heating, water heating, and cooking end-uses alone. The overall electricity requirement of the buildings sector will be determined by including the electricity demand from the other end-uses (lighting, space cooling, appliances, and miscellaneous equipment). The latter end-uses heavily depend on electricity, yet they contribute to indirect emissions only and have negligible direct emissions.

The electricity demand from the three end-uses rises from its current value of 3.44 PWh (in 2020) to 12.72 PWh in 2070, at an almost steady pace. Note that, in 2020 there exists electricity use for all three end-uses, therefore the extra capacity needed in the future according to the REALISTIC Scenario differs from the current value. From 2070 to 2100, the electricity demand's growth slows considerably and reaches 13.22 PWh in 2100. The decrease in the growth is dictated mainly by the already saturated use of electricity in the sector.

Given that actions are taken in a timely manner as described in this study, a significant decrease in CO_2 emissions can be achieved until 2100, as shown in

Figure 4-17. Nevertheless, 0.42 Gt CO_2/yr will still be emitted from the buildings sector, because of biomass use in cooking. Substantial savings in direct emission of CO_2 to the atmosphere can thus be achieved in the buildings sector, whose cumulative effect is presented in

Figure 4-18.

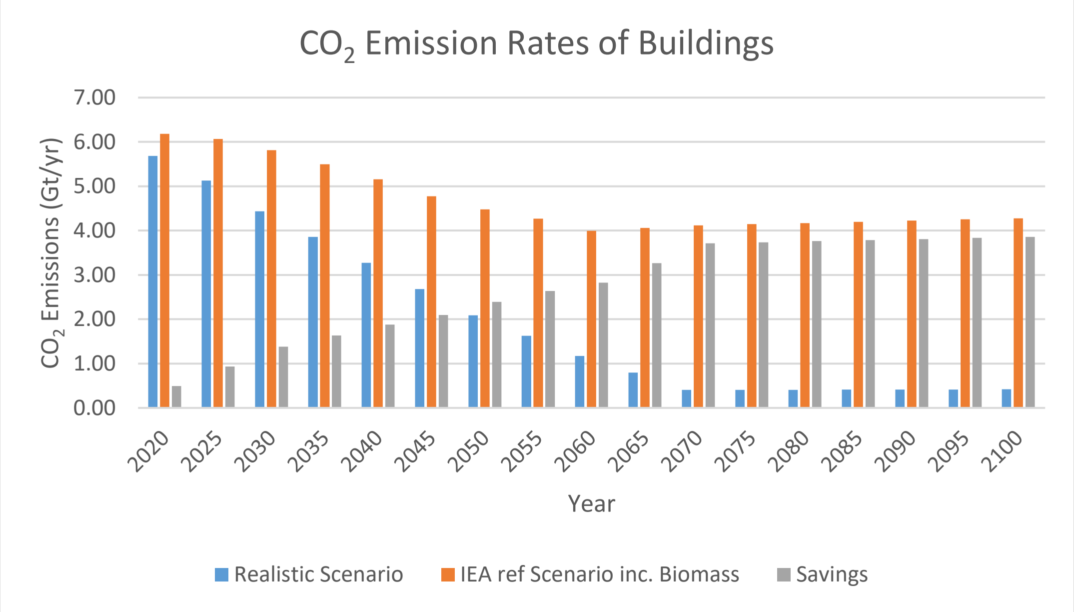

Figure 4-17 CO_2 Emission Rates of Buildings

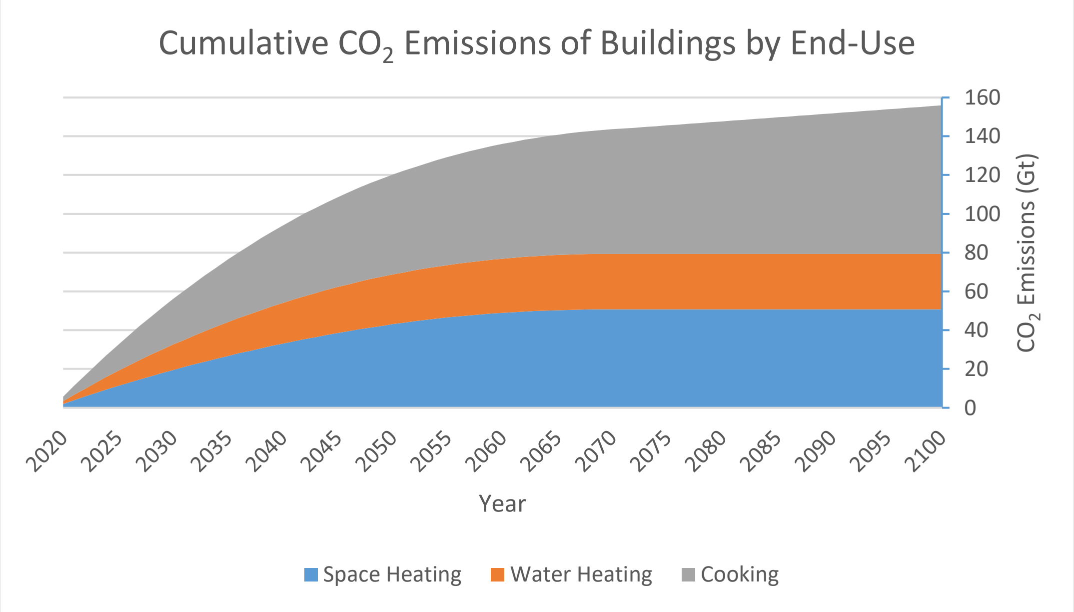

Figure 4-18 Cumulative CO_2 Emissions of Buildings by End-Use

Cumulative CO_2 emissions between 2020 and 2100 are 50.75 Gt from space heating, 28.61 Gt from water heating, and 76.61 Gt from cooking, summing up to 155.96 Gt collective emissions from the sector. These cumulative emissions represent a savings of 221.44 Gt over the BAU Scenario, in which the corresponding emissions were 377.4 Gt.

4.6. Sensitivity of the Proposed Model

In this study, a scenario has been proposed to reduce future CO_2 emissions. Fundamentally, the solution is based on the intense use of electricity generated from renewables and nuclear energy. To analyze the savings in CO_2 emissions that can be achieved by the model, certain targets have been specified. In the specific case of the buildings sector, the targets are the share of energy sources will reach in years 2030, 2050, and 2070.

The aforementioned calculations are based on a scenario, which is referred to as the REALISTIC Scenario. The adopted scenario represents the implementation of a relatively ambitious effort, to maximize the use of electricity. Reduction in future CO_2 emissions is then compared to the Reference Technologies Scenario (RTS) of IEA, in which governments are assumed to take the actions that they promised to date. However, it is also assumed that no further measures will be taken globally. It is clear that the already declared measures will suffice to meet neither the 1.5^{o}C nor the 2^{o}C global warming limit by 2100. Hence, RTS can be regarded as the Business As Usual estimate (even though certain precautions will be taken by officials), whereas the REALISTIC Scenario represents the path to be taken to meet the specified limits.

To better understand how the proposed Scenario can be affected by the preset targets; the sensitivity of the model on the defined goals has also been analyzed. To this end, two more scenarios have been studied, by altering the specified targets. One model, which is referred to as AGGRESSIVE, assumes stronger measures to be taken at earlier stages when compared to the REALISTIC Model. The former model may represent the ultimate earliest transition to combined electricity and solar energy, without taken cost considerations into account.

The second alternative scenario that is analyzed, is named the RELAXED Scenario, in which again similar energy carrier and primary source transition do occur, but on a time scale that can be realized with much less effort and cost, when compared to the REALISTIC Scenario.

In Table 4-8 through Table 4-10, targets that are adopted in all three scenarios are summarized. IEA’s RTS Scenario’s energy sources partitions are also listed for comparison purposes. However, in the case of RTS, data for the year 2070 is not available, instead, the last data, which are provided in 2060 are included.

Table 4-8 Scenario Summaries of Space Heating

Scenario / Year	Heat Pump (%)	Elec. Dev. (%)	Distr. Heat (%)	Nat. Gas (%)	Coal (%)	Oil (%)	Bio-mass (%)
REALISTIC							
2030	25	10	10	40	-	2.5	12.5
2050	50	20	-	20	-	-	10
2070	75	25	-	-	-	-	-
AGGRESSIVE							
2030	30	10	10	35	-	2.5	12.5
2050	50	50	-	-	-	-	-
2070	80	20	-	-	-	-	-
RELAXED							
2030	20	10	10	37.5	-	10	12.5
2050	40	15	-	30	-	5	10
2070	70	30	-	-	-	-	-
IEA-RTS							
2030	?	12.47	13.37	40.76	6.90	8.93	17.57
2050	?	14.04	14.70	41.32	3.23	4.58	22.13
2060	?	14.96	14.93	41.28	2.19	3.49	23.15

Table 4-9 Scenario Summaries of Water Heating

Scenario / Year	Heat pump (%)	Elec. Dev. (%)	Dist. Heat (%)	Nat. Gas (%)	Coal (%)	Oil (%)	Solar (%)	Bio-mass (%)
REALISTIC								
2030	25	10	5	12.5	-	2.5	20	25
2050	40	10	-	-	-	-	40	10
2070	40	10	-	-	-	-	50	-
AGGRESSIVE								
2030	30	10	5	7.5	-	2.5	20	25
2050	40	20	-	-	-	-	40	-
2070	45	5	-	-	-	-	50	-
RELAXED								
2030	20	10	5	5	-	10	20	30
2050	30	10	-	5	-	5	30	20
2070	35	15	-	-	-	-	45	5
IEA-RTS								
2030	?	18.75	4.28	24.78	0.60	8.96	?	42.63
2050	?	26.13	4.19	26.34	0.38	5.35	?	37.61
2060	?	30.39	4.22	25.61	0.32	4.00	?	35.45

Table 4-10 Scenario Summaries of Cooking

Scenario	Year	Elec. Dev. (%)	Nat. Gas (%)	Coal (%)	Oil (%)	Biomass (%)
REALISTIC						
	2030	25	20	-	10	45
	2050	60	10	-	5	25
	2070	85	-	-	-	15
AGGRESSIVE						
	2030	50	15	-	5	30
	2050	100	-	-	-	-
	2070	100	-	-	-	-
RELAXED						
	2030	15	20	-	10	55
	2050	40	15	-	5	40
	2070	75	-	-	-	25
IEA-RTS						
	2030	7.29	18.14	1.16	13.09	60.32
	2050	12.02	21.82	0.5	16.20	49.45
	2060	15.77	23.57	0.3	16.58	43.78

Electricity energy demand evaluated in each scenario (RELAXED, REALISTIC, AGGRESSIVE, and RTS) is presented graphically for ease of comparison in Figure 4-19.

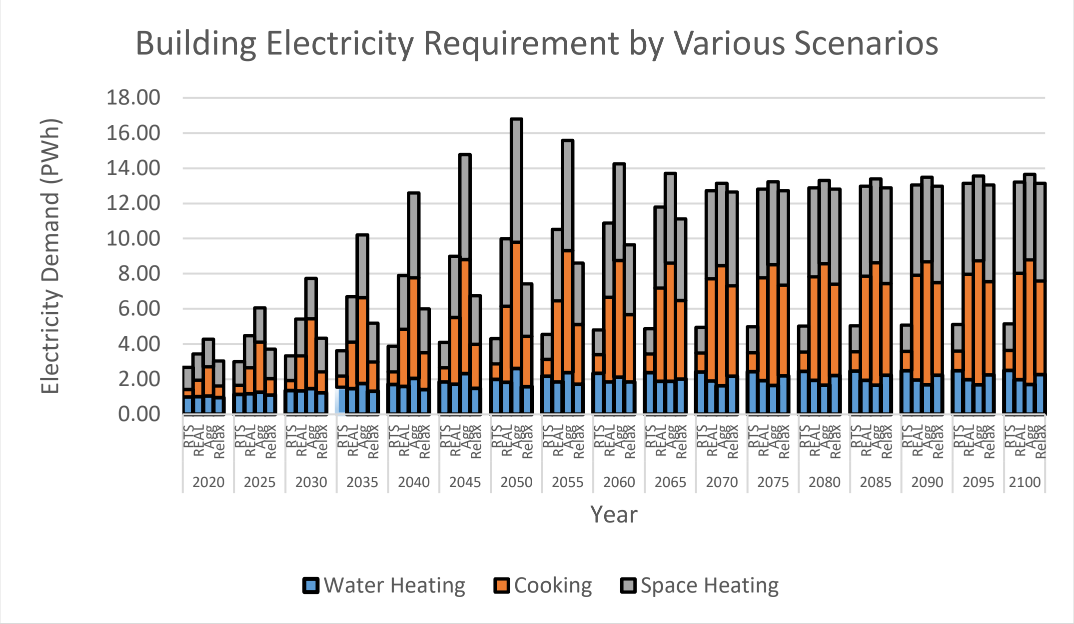

Figure 4-19 Electricity Requirement by Scenarios

A striking result is observed in the AGGRESSIVE Scenario: the electricity demand peaks in 2050 to 16.80 PWh. This high demand decreases down to 13.65 PWh in 2100, despite the increase in the population, hence the demand. This decrease results from the wider use of heat pump in the long term, over the ohmic heaters. In the AGGRESSIVE Scenario, to maximize the benefits of using electricity, more intense use of ohmic heaters have been favored until 2050. As can be seen in Figure 4-20, such a strategy cuts down the emissions drastically. Yet, a substantial amount of electricity generation capacity is needed.

In both RELAXED and REALISTIC Scenarios, steady increases in electricity demand have been observed until 2070. Electricity demand reaches 12.64 PWh in the RELAXED Scenario, whereas 12.72 PWh in the REALISTIC Scenario. The electricity demand growth rate in the former scenario is rather small until 2050, catching up with the latter afterward. Beyond 2070 growths in both scenarios are relatively small.

Finally, CO_2 emissions by all three scenarios until 2100, are shown in Figure 4-20. It is important to note that emission rates vanish completely in the AGGRESSIVE Scenario after 2050.

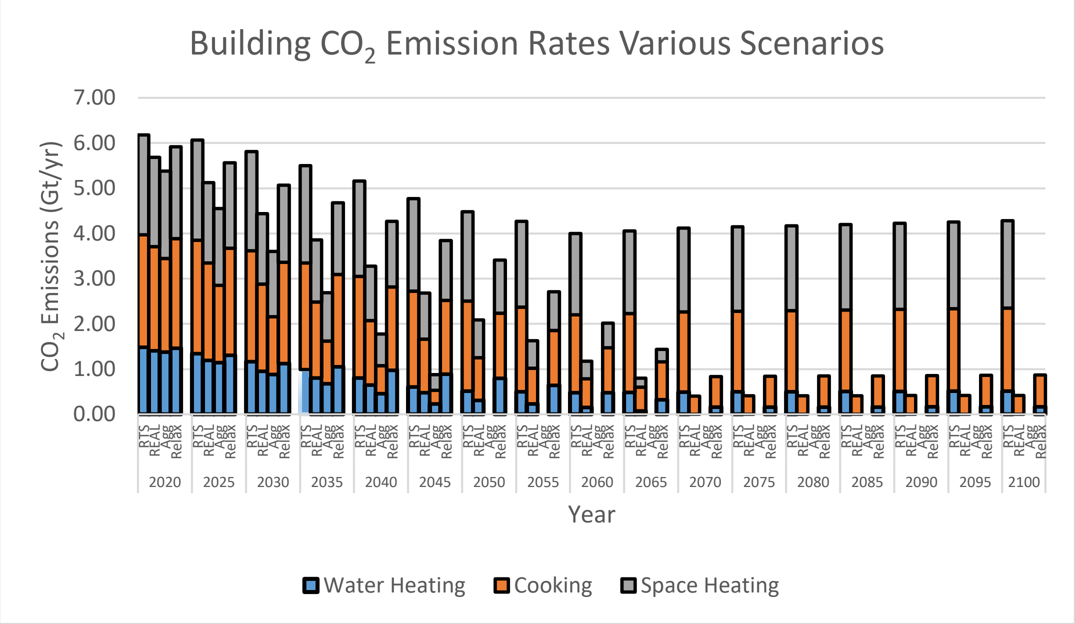

Figure 4-20 CO_2 Emissions by Different Scenario

The early extensive use of electricity (by employing more ohmic heaters) in the AGGRESSIVE Scenario considerably reduces cumulative emissions. The cumulative emissions from 2020 to 2100 can be lowered down to 83.55 Gt CO_2. The fundamental scenario (the REALISTIC) of this study on the other hand emits 155.96 Gt in the same period. With the less governmental contribution, in the RELAXED Scenario the emissions are 210.78 Gt, still much inferior to BAU (that is, with no precautions taken to reduce emissions) which will emit 379.30 Gt in the same period. Hence, with the REALISTIC Scenario, CO_2 emissions savings of more than 220 Gt can be achieved between 2020 and 2100. These results are presented graphically in Figure 4-21.

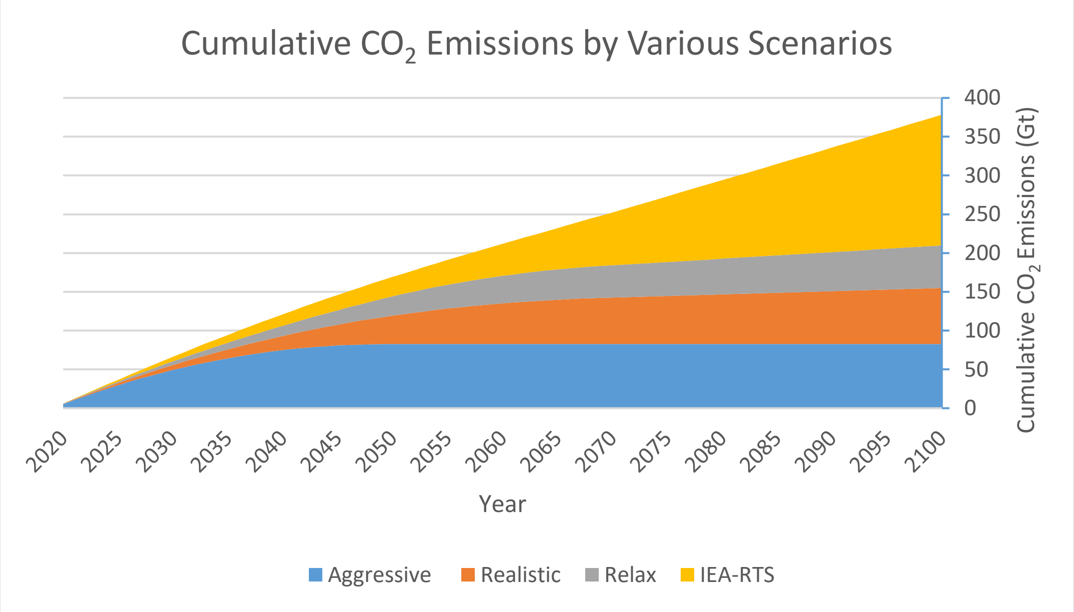

Figure 4-21 Cumulative CO_2 Emissions by Various Scenarios

While investigating the buildings sector, it has been assumed that the energy demand in each three end-use responsible for direct emissions (space heating, water heating, and cooking) will increase in parallel to population growth, beyond 2050. The lack of a reliable forecast for this long-term demand necessitated such an assumption. However, different scenarios can be adopted for the change in energy demand beyond 2050. To maintain the parallelism between other sectors, the sensitivity of the adopted assumptions (related to beyond 2050 demands) has also been studied by altering the growth rate for the period.

In the basic REALISTIC Scenario, it has been assumed that the energy demand is likely to grow either with GDP (it is the fastest growing model), as in the case of transportation, or with population growth as in the case of the buildings, or remain invariant, as in the case of industry. To maintain the parallelism with other sectors and be able to draw a conclusion at the end of this work, calculations performed in the basic scenario of REALISTIC have been repeated, simply by modifying the beyond 2050 energy demand. In one alternative, beyond 2050 the energy demand has been taken be proportional to GDP (as done in the transportation sector). The growth rates are taken from OECD: 2.2710% between 2050 - 2060, 2% between

2060 - 2070, and 1.6667% beyond 2070. In the second, the energy demand has been maintained flat (as in the industry sector case). Results related to the altered growth rate beyond 2050 are presented in

Figure 4-22 through Figure 4-24.

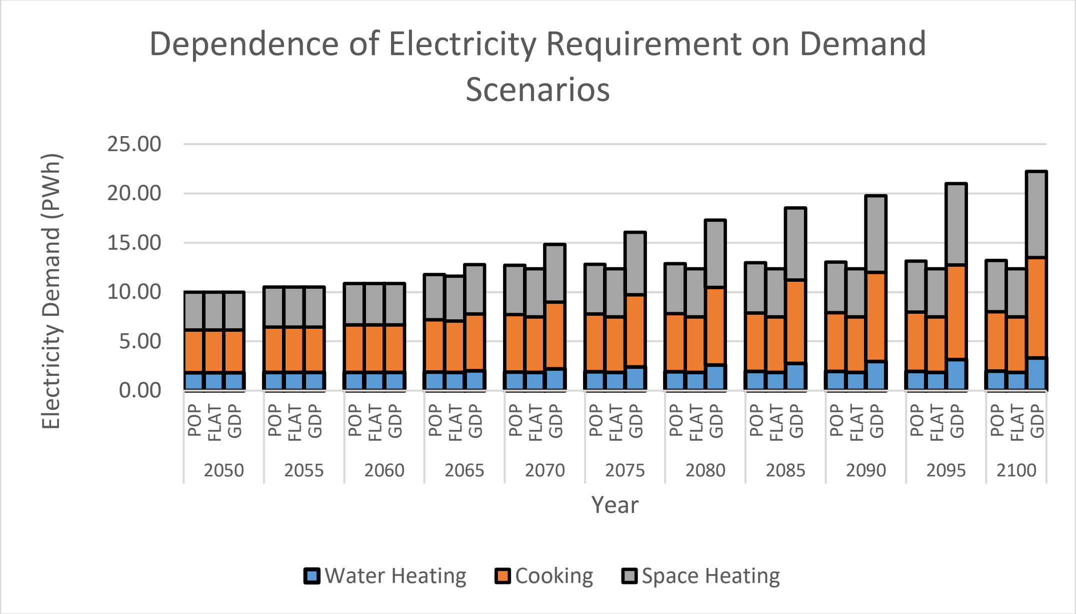

Figure 4-22 Dependence of Building Electricity by End-Use on the Demand

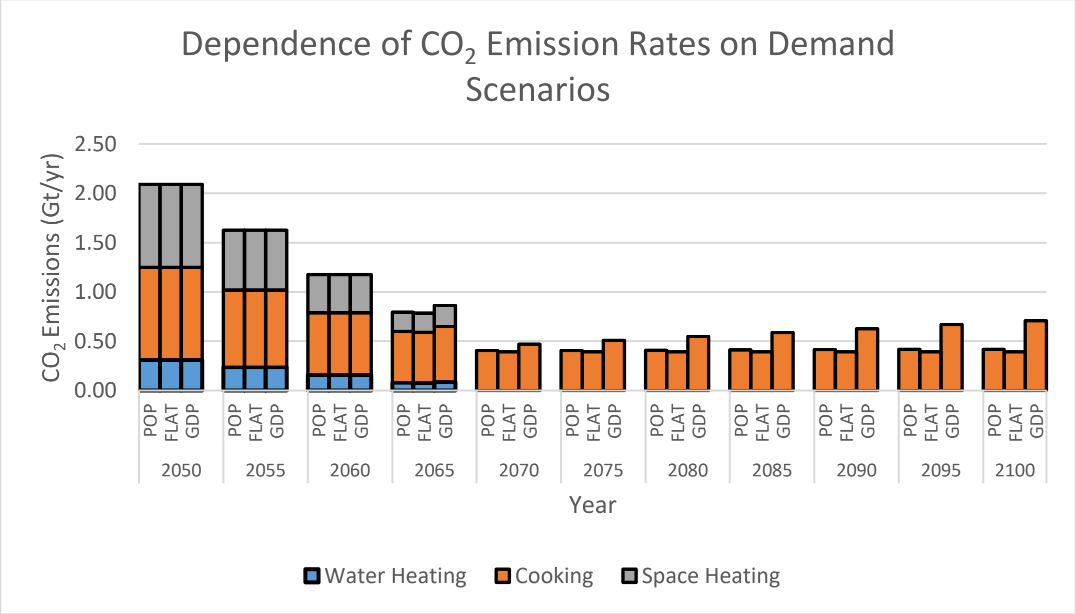

Figure 4-23 Dependence of CO_2 Emissions by End Users on Demand

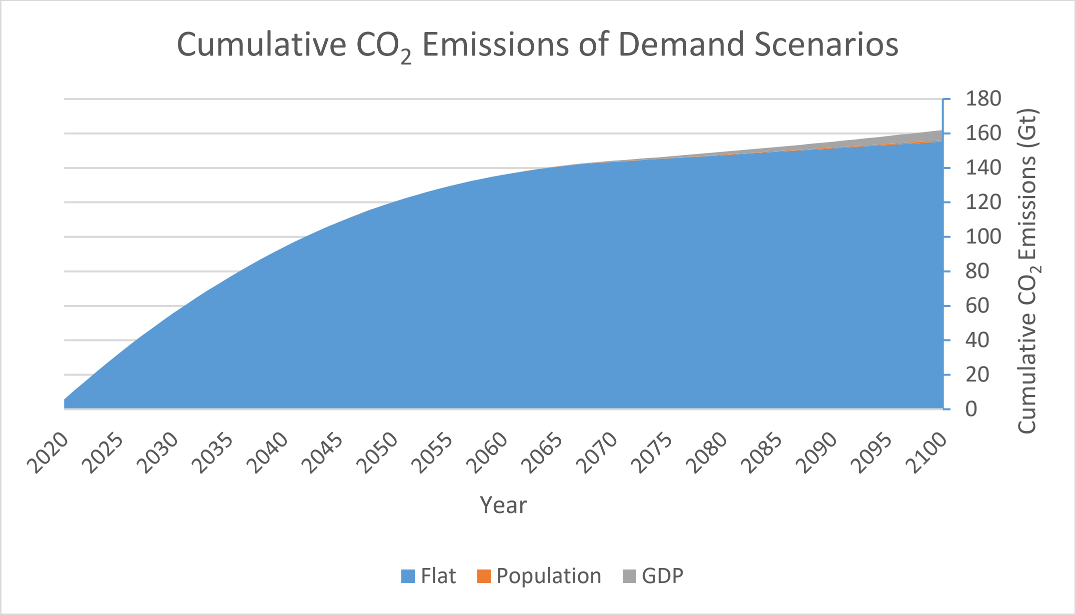

Figure 4-24 Cumulative CO_2 Emissions of Demand Scenarios

Altering the energy demand beyond 2050 has only minor effects on CO_2 emissions. The reason behind this insensitivity is related to the fact that almost all necessary actions have already been taken by 2050 to eliminate the emissions. The cumulative emissions in the REALISTIC Scenario (in which the demand growth is taken to be proportional to population growth) was 155.96 Gt. It changes to 161.95 Gt when the demand is taken proportional to GDP, 155.26 Gt when a flat demand is taken.

4.7. Summary and Novelty of the Approach

Forecasts for energy demands in the three end-uses (space heating, water heating, and cooking) have been collected from the literature, which were available until 2050 or 2060. Upon comparing data from different sources, those provided by IEA in their RTS Scenario have been selected to be used to identify the energy demand from today until 2050. The long-term energy demand has been extrapolated until 2100. In the specific case of buildings, this evolution has been adopted to be proportional to population growth. Energy demand values ranging from 2020 to 2100 are therefore specific to the present study.

Following the determination of the energy requirement of the sector, through intense use of direct electricity primarily, assisted by solar energy, a strategy has been developed to mitigate direct CO_2 emissions from the sector. Both selection of the two energy carriers (direct electricity and solar energy) and their adopted pace of penetration form the unique characteristics of the present study. Combined with yearly demand forecasts that are extended until 2100, they form part the basic scenario developed in the study: REALISTIC.

Additional electricity requirement resulting from the proposed mitigation efforts has been evaluated, together with the savings that can be achieved in emissions. To assess the sensitivity of the results to the adopted assumptions, Calculations are performed not only in the basic REALISTIC Scenario but are also repeated under various alternative scenarios, which are also developed in the present study.

CHAPTER 5

POWER SECTOR

The largest emitter of CO_2 among all sectors is the power sector. It is responsible for around 40% of all emissions. Indirect emissions from all other sectors are accounted for in this sector. In a broader definition, the sector includes both electricity and commercial heat. However, in this study, the analysis has been limited to electricity generation only, as it constitutes the majority of the sector, both thermodynamically and financially.

The current situation of electricity generation needs to be analyzed as the starting point of the study. Upon consulting various sources that provide details of the electricity generation in the world, data provided by the World Resources Institute (WRI) [114] have been selected as the input. This choice of data can be justified by its consistency in the yearly generation amount specified in other sources and the plant details it contains. The set of data (which includes almost 30,000 power plants worldwide) that have been downloaded from this open-source was for the year 2018. Commercial heat producing plants were not taken into consideration, as will be discussed later in the chapter.

The fundamental CO_2 emission mitigation efforts proposed in this study are related to the power sector. Zero CO_2 emitting power plants are proposed to supply the future electricity demand. However, a transition period is required for the implementation of new power plants, which are essentially renewables or nuclear. Therefore, production of both electricity and CO_2 emissions from the already operating power need to be analyzed and forecasted.

5.1. Assessment of the Current Power Plants

Data taken from WRI contained various inconsistencies that need to be treated to generate a set of reliable information. Original data were quite detailed, providing the following information for each plant: Country, name of the plant, installed capacity (in MW), primary and secondary fuels, commissioning year, generation in 2018.

There were some power plants, which were missing from the list by WRI. The first correction of the data involved the addition of these plants to the data set. Next, data missing in the list have been compensated:

- If no commissioning year is provided, the appropriate cell is filled with the year 2000 information.
- Load factors for some power plants were unreliable. Load factors greater than unity, are corrected by the average load factor determined for the corresponding primary fuel.
- Electricity generation information in 2018 was not available for some units. Using the average load factor, the appropriate generation information has been associated.
- For the cogeneration, petcoke, hydro-storage, and wave-tidal plants, electricity generation was not provided. Load factors for these plants were taken from the literature and appropriate electricity generation values are accordingly calculated for 2018.

Upon performing these corrections, the detailed data set coincides (with less than 1% error) with the electricity generation in 2018 documented by IEA, which is 26.73 PWh.

5.2. Proposed Evolution of Power Sector

To mitigate the CO_2 emissions from the power sector, it has been recommend in this study that future electricity generation should rely on renewables and nuclear only. Therefore, for the sake of this study, the use of wind, solar, and nuclear energy only has been proposed for the new power plants. Hydroelectric power plants undeniably play an essential role in electricity generation. However, an already high saturation level has been reached. Furthermore, large hydroelectric power plants also cause serious environmental changes, decreasing their popularity. For these reasons, it has been assumed that hydroelectric power plants will resume their operation for a long time to contribute to power generation, yet no new installed capacity will be added to the system.

To determine the installed capacity of the new (wind, solar, and nuclear) plants, the amount of electricity that can be produced by the current power plants needs to be assessed. The details of the latter calculations are presented in the next section. The determination of the new installed capacity requires further analyses, which are performed and explained in the next chapter.

5.3. Future Electricity Generation by the Current Power Plants

However, the transition to zero (or near zero) emitting sources will require a great deal of time. The current power plants will continue their operation, until their decommissioning. To determine the future structure of the power sector, the gap between the total electricity demand from the other sectors and the supply from the current power plants has been identified.

In the present study, assumptions were made about the future of the electricity generation potentials of the current power plants. These assumptions will affect the CO_2 emissions from 2020 to 2100. It has been assumed that emissions from new power plants (which consist of renewables and nuclear) on the other hand will be zero. Therefore, in the scenario, all contributions to CO_2 emissions from the power sector are due to the ongoing operation of current power plants.

At this stage, it is worth assessing that energy supply to both industry and buildings sectors in the form of commercial heat is to be abandoned in the future in parallel to recommendations of this study. Electricity will replace the commercial (district and process) heat. The reasoning behind this recommendation is the fossil or biomass fuel dependence of heat generating plants. Therefore, rather than producing heat with large CO_2 emissions, it would be reasonable to employ electric energy in the future.

To assess the electricity supply potential of the current power plants, detailed data (that have polished further during the study) by WRI were processed. However, this is not enough; also, certain rules need to be set for their future operation principles. To this end, it has been assumed that by the end of 2030 all coal fired (this includes waste and petcoke fired power plants) should be phased out. After all, they are the major contributors to CO_2 emissions in the sector. The remaining power plants will be decommissioned when they reached the average plant life for the corresponding type. No power plants other than wind, solar PV, and nuclear will be newly commissioned.

Processing the WRI data, the future electricity generation by the current power plant has been evaluated, assuming that they will operate with a load factor, which corresponds to the average of the relevant type. The list of the average plant life and load factors for different plant types is given in Table 5-1 [115] [116].

Table 5-1 Load Factors and Plant Lifetime of Various Types of Power Plants

Plant Type	Load Factors	Plant Life (Year)
Biomass	39.81%	45
Coal	52.56%	45
Cogeneration	50.00%	30
Geothermal	79.64%	30
Hydro PP	44.83%	60
Hydro Storage	50.00%	40
Natural Gas	48.89%	30
Nuclear	74.40%	60
Oil	36.40%	40
Other	24.23%	40
Petcoke	40.00%	45
Solar	12.18%	30
Waste	58.78%	45
Wave &Tidal	40.00%	60
Wind	25.52%	30

Using the average plant life and commissioning year data (which are completed for all plants), a decommissioning year has been assigned to each plant in the list. At this stage, another difficulty has been encountered in the list. Some power listed as in operation has commissioning year as early as the 1930s. This type of problem exists mostly in Russia and the USA. Investigation of large units with such surprising information lead to the conclusion that the naming procedure for these power plants cause the inconsistencies. The same plant, which was in operation early in the previous century, has undergone major changes and an entirely new power plant has been installed at the site. In some cases, there is more than one unit (with even different fuels) installed at the site. However, the name of the power plant remained the same; hence, the commissioning year data refer to the old, already decommissioned plant. This is consistent within itself; after all, the new plant has not been renamed. To render data consistent with the actual situation and since the commissioning year of each and every one of the new units cannot be identified, a minimum has to be assigned to the decommissioning year calculated based on commissioning year and average plant life. This minimum year has been set in 2030, based on the inspection of large-scale units with early commissioning year data [114].

Upon correcting the data for decommissioning year, the electricity beyond 2020 of the current power plants has been determined, in accord with the assumptions and recommendations adopted in the study. The results are presented graphically in Figure 5-1.

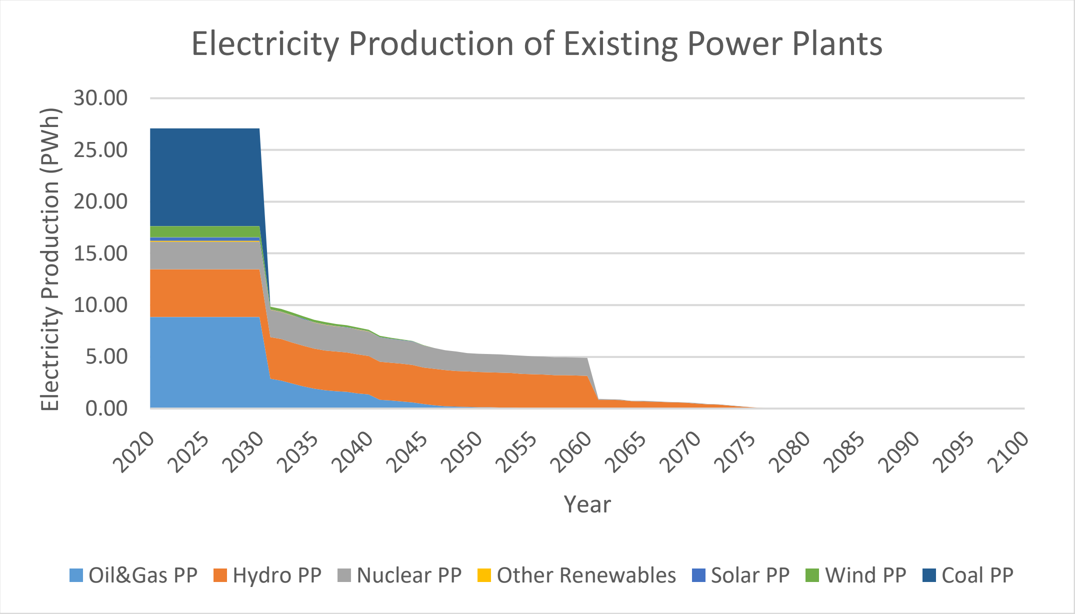

Figure 5-1 Electricity Production of the Existing Power Plants

5.4. Emissions from the Power Sector

Once the future operation principles are set for the current power plants, not only their electricity generation have been forecasted, but also the CO_2 emissions resulting from their operation. The latter also constitutes the total emissions from the power sector, as the new plants will not contribute to emissions.

Assessing the savings achieved with the use of renewables and nuclear in the future electricity generation requires a forecast of the Business As Usual (BAU) emissions. To this end, predictions of the RTS Scenario by IEA [39] have been used. Electricity demand under BAU conditions was provided for the year 2014, and forecasts are available from 2025 to 2060 for every 5 years. Linear interpolations have been performed for years that are not listed, as usual. Beyond 2060, a flat electricity demand has been assumed, which is clearly an underestimation. Emissions that would result from the generation of the needed electricity have been evaluated by assuming the ratio of the emissions to the generation in 2018 will remain constant. It is worth emphasizing that determining BAU conditions in the power sector differs from the others, as the electricity demand is in correlation with other sectors. Hence, an independent analysis of the BAU is not possible and is performed solely to demonstrate the magnitude of savings that are achieved in the scenario. Descriptive evolution of the emissions in comparison with BAU emissions is shown graphically in Figure 5-2.

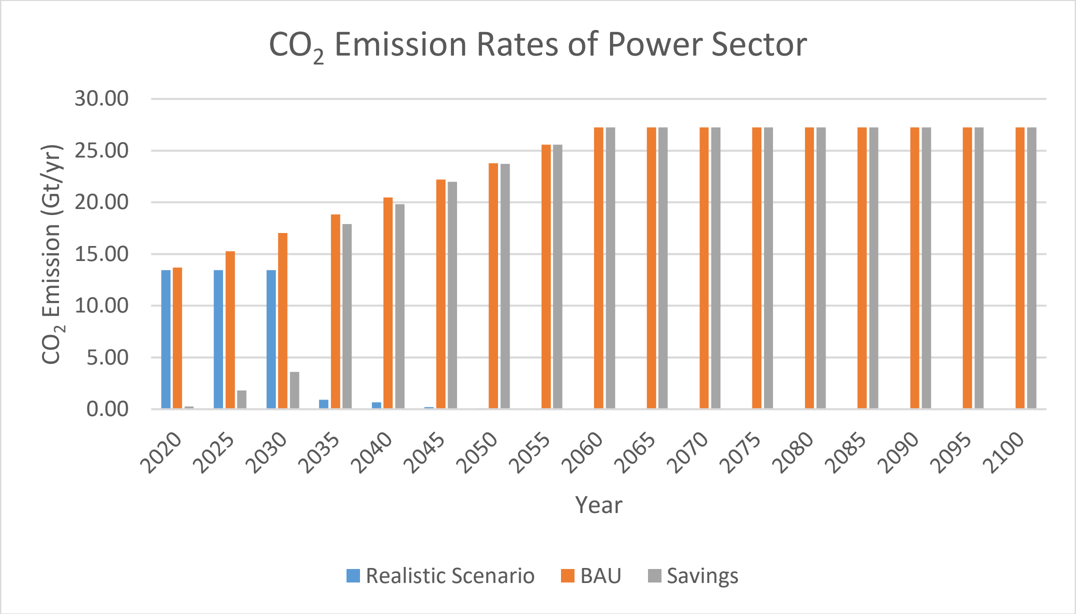

Figure 5-2 CO_2 Emission Rates of Power Sector

Cumulative CO_2 emissions until 2100 in the REALISTIC Scenario, which is 159.77 Gt, remains extremely small when compared to the BAU emissions, which escalate to 1,928 Gt in the same period, hence more than 1,700 Gt of CO_2 emissions can be prevented. However, even when stringent restrictions are imposed, such as the early closure of all coal fired power plants by the end of 2030, still, non-negligible emissions are expected to occur, which are shown graphically in Figure 5-3.

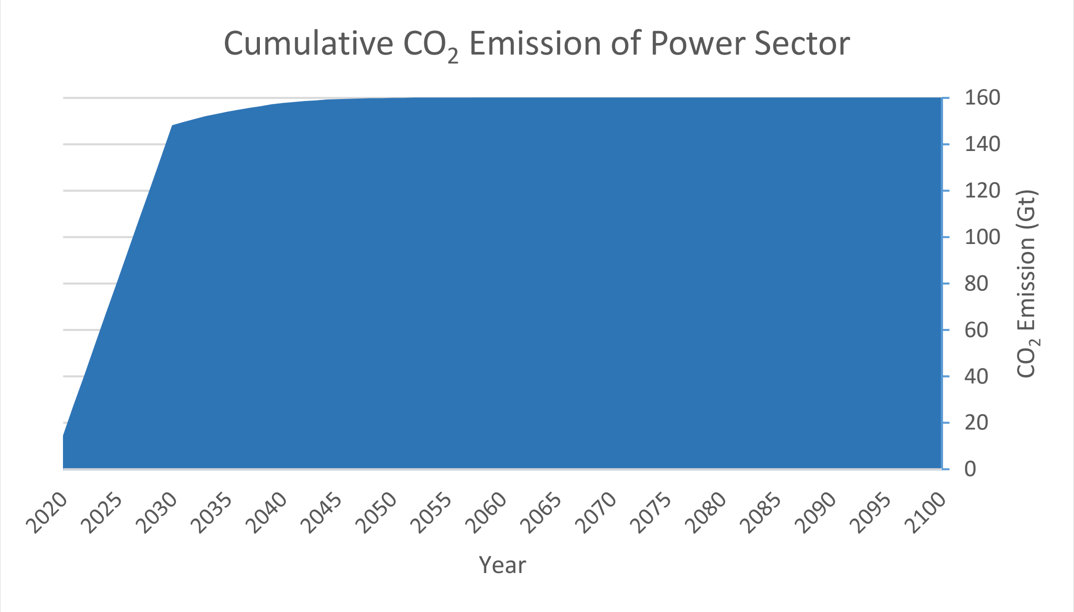

Figure 5-3 Cumulative CO_2 Emission of Power Sector

5.5. Summary and Novelty of the Approach

Properties of power plants in operation throughout the world have been collected from the literature. Many inconsistency issues and missing data problems have been resolved, through manipulation of the data in the developed computer codes. As part of the mitigation efforts, a prospective shutdown date has been assigned to each plant. Emissions resulting from the operation of these plants have been evaluated, together with their yearly electric energy supply, according to the scenario that is specific to this study.

CHAPTER 6

FUTURE OF THE ELECTRICITY GENERATION

In the previous chapters, sectors responsible for direct CO_2 emissions have been analyzed: industry, transportation, buildings, and power. Investigation of the power sector is mostly restricted to the contribution of current power plants to electricity production and CO_2 emissions. The future structuring of the sector constitutes the subject of the current chapter. Regardless of the energy mix (shares of renewables and nuclear), emissions from the newly constructed power plants will be nil according to the adopted assumptions. However, the future composition of the power sector needs to be identified, to better determine various needs and study the possible constraints, such as geographical space or uranium supply.

Remediation strategies in the former three sectors rely on either more intense use of direct electric energy or the use of electrolytic hydrogen, which necessitates further electricity generation. Therefore, upon forecasting the electricity demand in the future, which results from the implementation of measures that are taken to reduce CO_2 emissions, the total electric demand can be determined. To this end, sources, other than proposed for CO_2 reductions that will employ electricity, need to be identified.

6.1. Electricity demand related to indirect emissions

Electricity as an energy carrier is currently being used in all three previously studied sectors. CO_2 emissions due to these consumptions of electric energy are accounted for in the indirect emissions. It is instructive to investigate each sector separately, to identify the extent to which these indirect emissions have been included in the calculations.

6.1.1. Industry Sector

In the industry sector, the use of electrolytic hydrogen has been proposed as the preferred energy carrier, over fossil fuels. Upon determining the yearly consumption rate of electrolytic hydrogen, the electricity required for the electrolysis has been evaluated. Therefore, the demand that has been specified is related to the replacement of fossil fuels primarily with electrolytic hydrogen and partially with direct electricity. However, the industry currently is using and expected to continue to use electricity as an energy carrier, independent of its consumption of fossil fuels.

To determine the demand for electric energy in the industry sector, detailed data provided by IEA [39] have been consulted. Reference Technology Scenario adopted by IEA has been previously used, in determining the needs in the buildings sectors as well. Data has been provided for 2014 and forecasts are available for every 5 years from 2025 to 2060. Linear interpolation has been performed for years in between, until 2050. Beyond 2050, it has been assumed that the material demand from the industry (steel, cement, chemicals, and other industrial products) will remain constant, as saturation has been reached. This last assumption has been used in calculating the electrolytic hydrogen demand in the iron & steel, cement, and chemical sectors. This way, the parallelism between the evaluations of both direct and indirect emissions from the industry sector has been maintained. Thus determined indirect electricity (e.g., non-related to remediation efforts involving the production of electrolytic hydrogen) demand of the sector is shown graphically in Figure 6-1. This demand reaches 15.01 PWh in 2050 and remains constant according to the adopted assumptions until 2100.

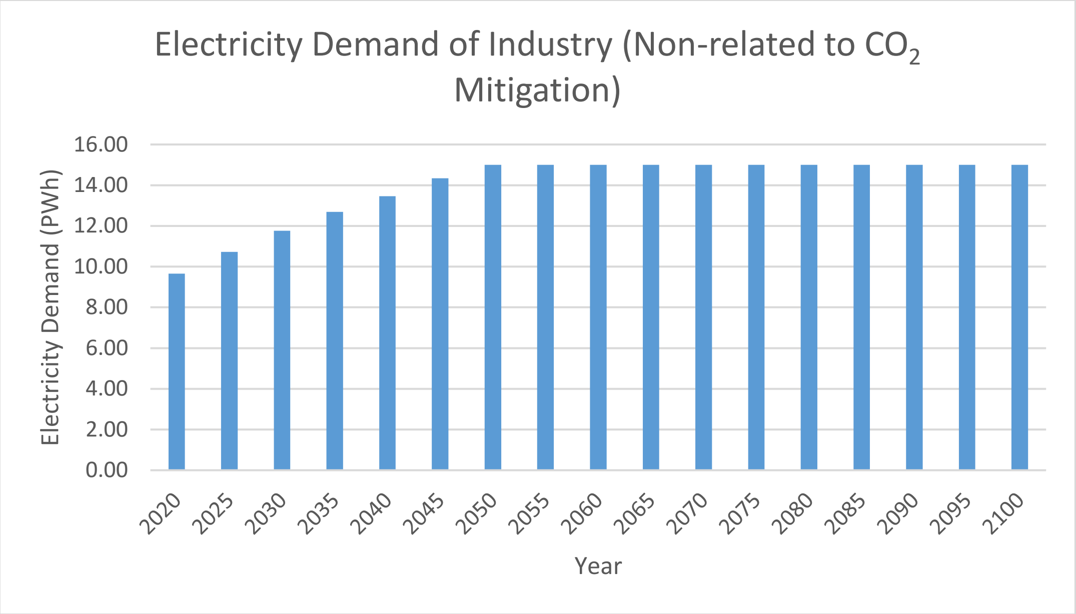

Figure 6-1 Electricity Demand of Industry (Non-related to CO_2 Emission Mitigation)

To determine the total electric requirement by the industry sector, these indirect electricity figures have been combined with the yearly electricity demands resulting from the CO_2 mitigation efforts that have been determined in earlier chapters. The mitigation strategy proposed for the industry sector implies an additional electricity demand reaching 37.39 PWh in 2100. Its evolution from 2020 to 2100 is presented in Figure 6-2. The total electricity demand, which is the sum of indirect electricity (non-CO_2 mitigation related) and the CO_2 mitigation related electricity requirement, reaches 52.40 PWh in 2100 and its forecasted evolution is plotted in Figure 6-3.

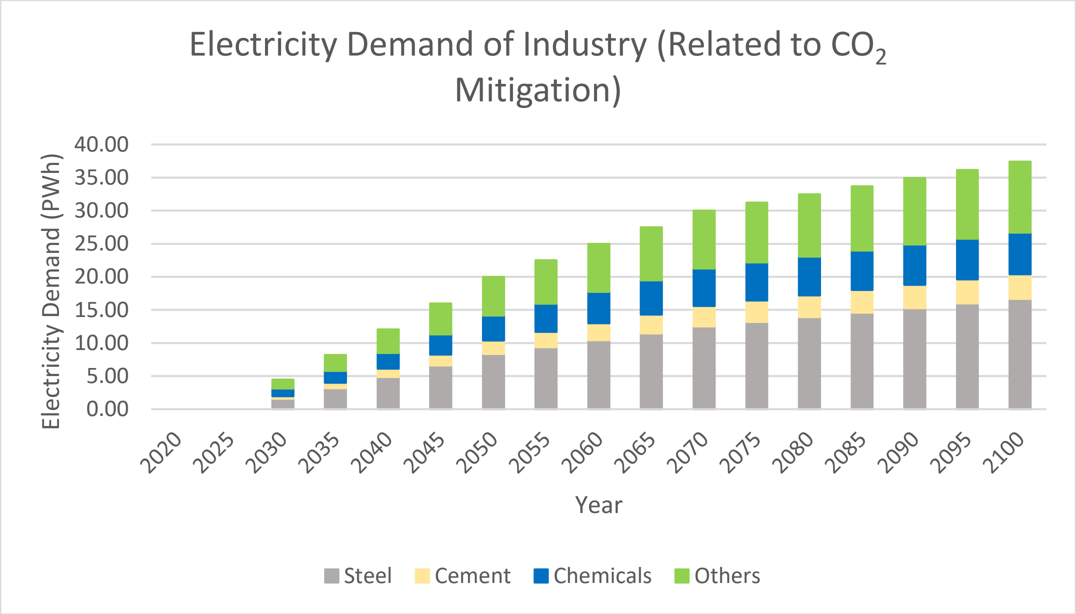

Figure 6-2 Electricity Demand of Industry (Related to CO_2 Emission Mitigation)

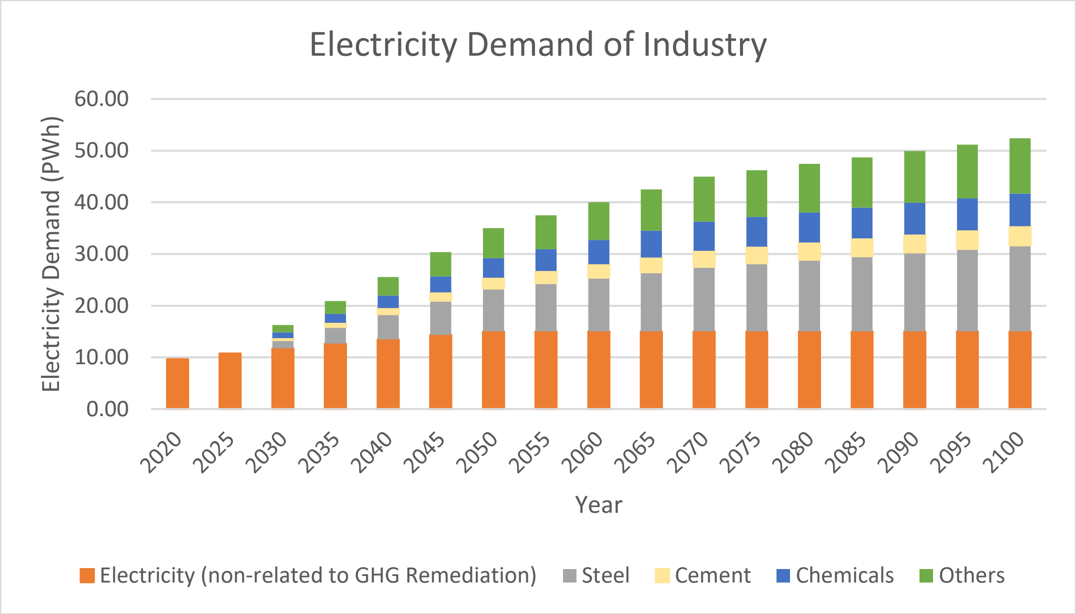

Figure 6-3 Electricity Demand of Industry (Total)

6.1.2. Transport Sector

The transport sector currently consumes electricity, primarily for rail passenger and freight activities. A relatively small amount of electricity is also being used in road transportation. In analyzing the transport sector, the electricity demand both for direct use (i.e., use of electricity as an energy carrier) and for electrolytic hydrogen generation (use of hydrogen as an energy carrier) have been estimated. Calculations incorporate the already ongoing use of electricity in the sector. Therefore, no additional indirect emissions need to be included in determining the electricity demand of the sector in the future. For the sake of completeness, the electricity demand forecast of transportation, which reaches 51.30 PWh in 2100, is shown graphically in Figure 6-4.

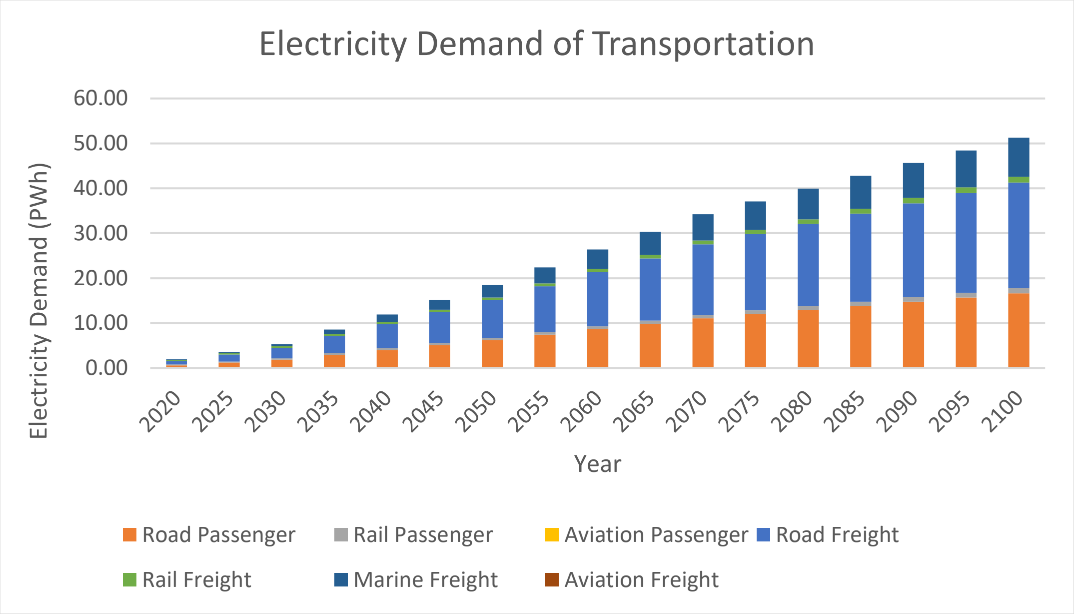

Figure 6-4 Electricity Demand of Transportation

6.1.3. Buildings Sector

In identifying the electric energy demand of the buildings sector, energy needs have been classified under 7 end-uses: space heating, water heating, cooking, lighting, space cooling, appliances, and miscellaneous equipment. In the previous analysis, emphasis was on the remediation actions in the former three end-uses, because they rely heavily on fossil fuel consumption. The three end-uses analyzed previously, are also consuming electricity, hence generate indirect emissions. These consumptions of electricity have already been taken into account in the calculations, therefore no additional contribution from indirect emissions need to be included in the final evaluation of the electric demand of the sector.

However, the remaining 4 end-uses (lighting, space cooling, appliance, and miscellaneous equipment) rely mostly on electric energy. Hence, no remediation related to these four end-uses has been proposed, after all, they are zero direct emitters of CO_2.

To be able to accurately assess the future electricity demand of the buildings sector, forecasts of the non-analyzed electricity requirements of the four end-uses have also been evaluated. Once again, the data provided in the RTS Scenario by IEA have been employed to this end. The detailed data group appliances and miscellaneous equipment under one category. Statistics are provided for 2014, forecasts for energy consumptions from 2025 to 2060 with 5 years steps. Although a large fraction of the energy demand is forecasted to be supplied by electricity, small amounts are also allocated to fossil fuels and biomass. Assuming that an average 35% conversion efficiency would be involved when fossil fuels and biomass are employed, the equivalent electricity requirement has been determined to include the energy to be supplied by them. Even though the amounts are small, this approach also takes into account the efforts for reducing CO_2 emissions from the sector, this time related to the other end-uses.

Linear interpolation has been performed for years not listed in the data. Beyond 2060, it has been assumed that the energy (hence the electricity) demand will grow with the population increase. To this end, population growth forecasts by the UN have been used. This assumption is entirely parallel to the growth assumption in the sector that has been employed in the analysis for reducing emissions from space heating, water heating, and cooking. Thus determined electricity forecasts for lighting, space cooling, and appliances & misc. equipment (grouped under a single end-use), reaching 21.91 PWh in 2100, is presented graphically in Figure 6-5.

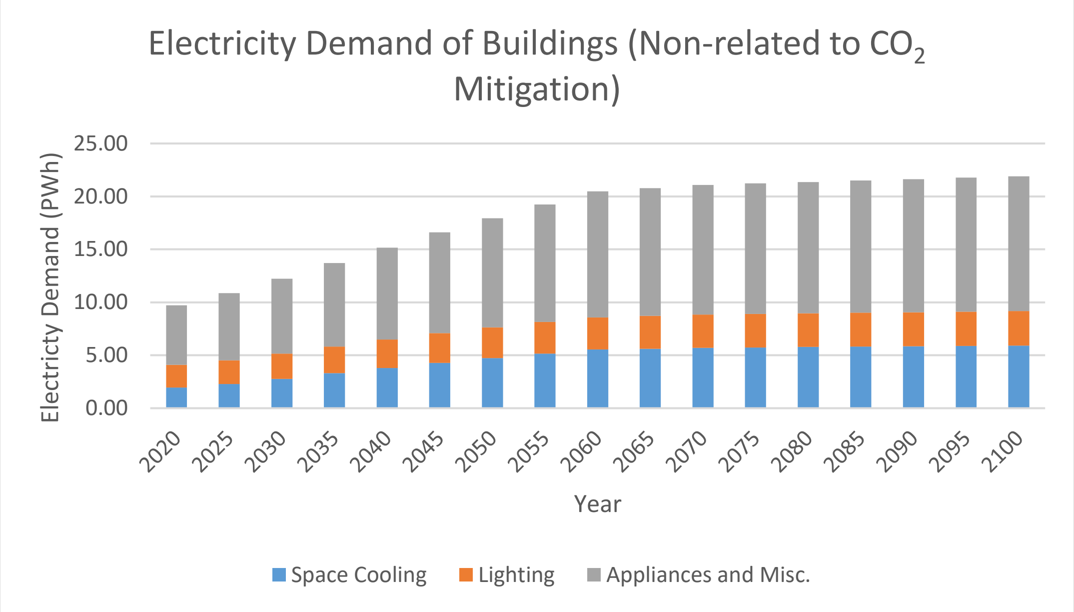

Figure 6-5 Electricity Demand of Buildings (Non-related to CO_2 Emission Mitigation)

Our proposal for CO_2 emission reductions was restricted to space heating, water heating, and cooking. These efforts resulted in an additional electricity demand that have been analyzed in a previous chapter. The evolution of this additional demand, which escalates to 13.22 PWh in 2100, is presented in Figure 6-6.

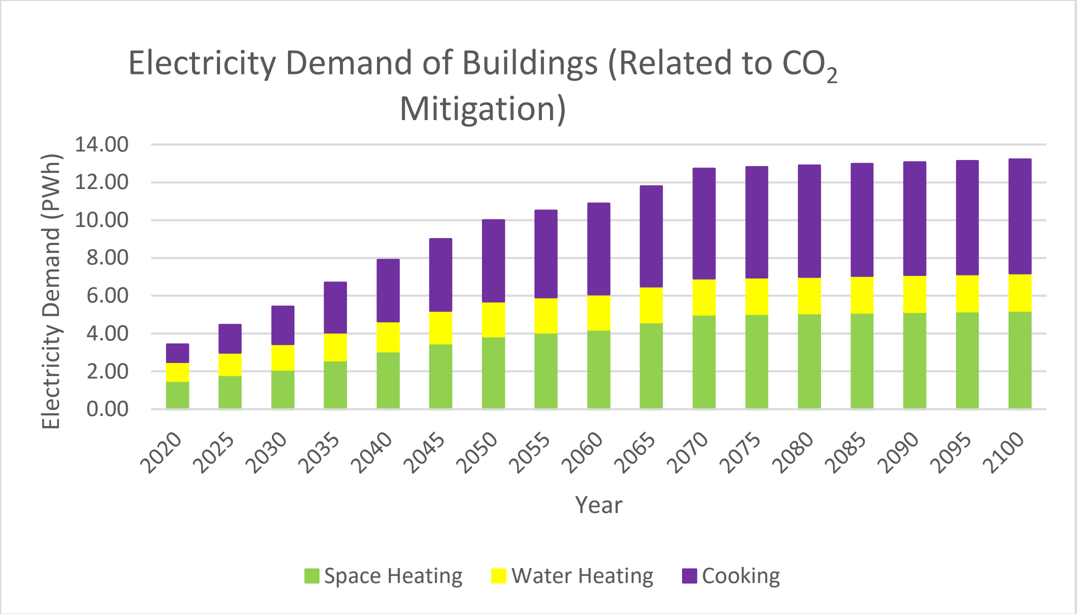

Figure 6-6 Electricity Demand of Buildings (Related to CO_2 Emission Mitigation)

Combining the electricity demand for all end-uses, hence the ones that are related and not to remediation efforts the evolution of total electricity of the buildings sector has been determined, which reaches 35.13 PWh in 2100. The results are shown graphically in Figure 6-7.

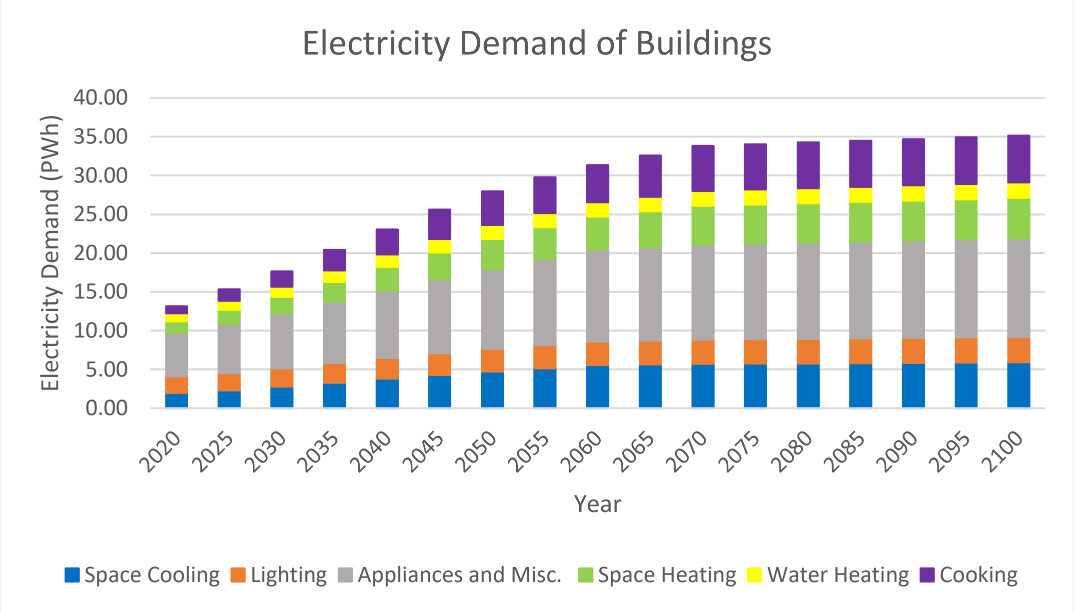

Figure 6-7 Electricity Demand of Buildings (Total)

6.1.4. Miscellaneous Sectors

So far, three sectors that contribute to CO_2 emissions with a large share have been investigated: industry, transportation, and buildings. The most CO_2 emitting sector is the power Sector, however in order to assess its contribution the electricity demand from all other sectors needs to determined. The task has been completed to a great extent, nevertheless there exist still other sectors that require electricity (although with much smaller amounts) as an energy carrier. These sectors, which are classified under miscellaneous sectors, are also included in the RTS Scenario by IEA. In the study by IEA, they are classified under Agriculture, Forestry, and Fishing (AFF) Sector.

Statistics for 2014 and forecasts from 2025 to 2060 are available for the AFF Sector as well, in the IEA Reports. Only electric energy demands have been taken into account, as the remaining sources have extremely small shares. In parallel to other analyses, linear interpolation has been performed for years not listed in the data set. Extrapolation beyond 2060 has been performed by using the UN's population growth rates. This selection can be justified by establishing a one-to-one relation between agriculture and fishing with cooking, for which the latter growth rate has been employed.

Thus determined (total) electricity demand for the miscellaneous sectors for years 2020 to 2100 are presented in Figure 6-8.

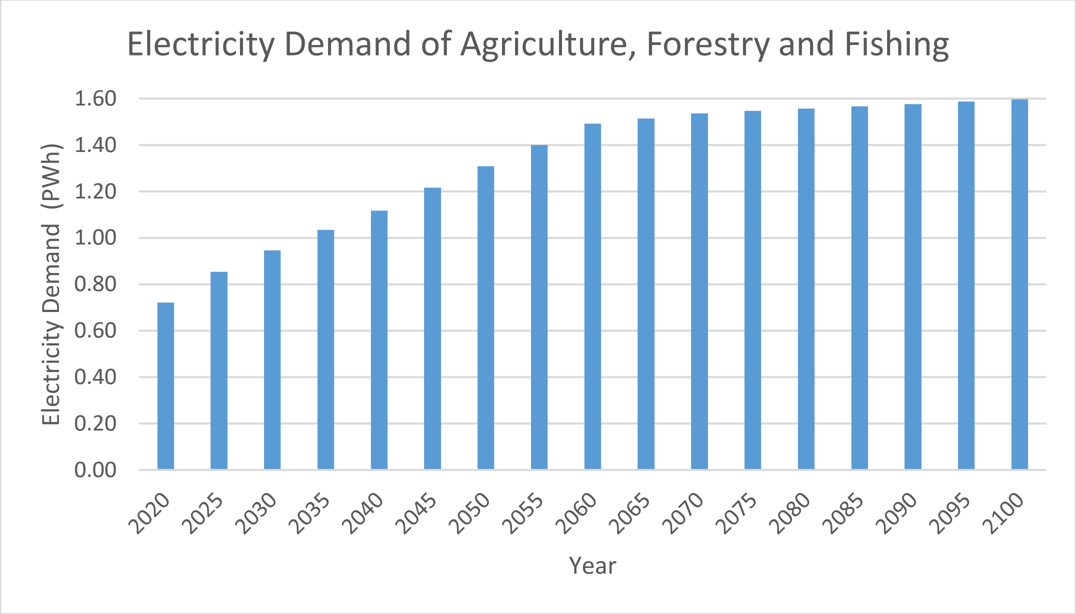

Figure 6-8 Electricity Demand of Agriculture, Forestry, and Fishing

6.2. Overall Electricity Demand in the Future

Individual electricity demand forecasts have been evaluated for 4 sectors: industry, transportation, buildings, and miscellaneous. The majority of these demands are a direct implication of the here proposed mitigation efforts, in the former three. Combined electricity requirements resulting from the suggestion to replace fossil fuels and biomass with electric and electrolytic hydrogen are presented graphically in Figure 6-9. Its total reaches 101.91 PWh in 2100.

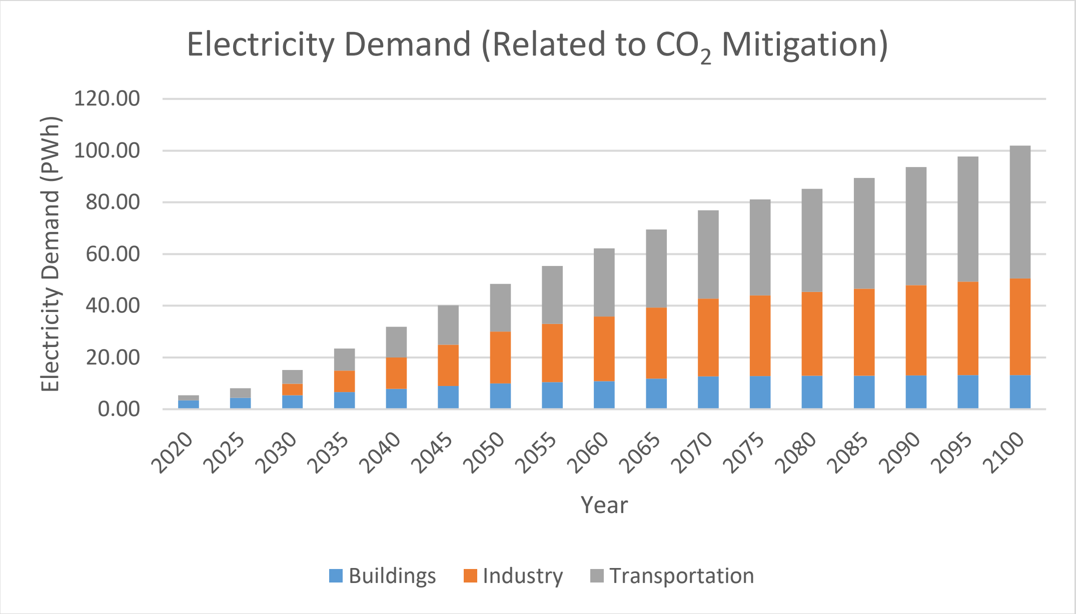

Figure 6-9 Electricity Demand (Related to Mitigation of CO$_2$ Emission)

As is discussed in this chapter, there exists an ongoing electricity demand in each sector. These demands are treated as indirect emissions related electricity requirements in this study. They refer to electricity demand in each sector, which exists regardless of whether the remediation efforts are realized or not. This electricity demand, which is independent of the proposed suggestions escalates to 38.51 PWh in 2100 and is shown graphically in Figure 6-10.

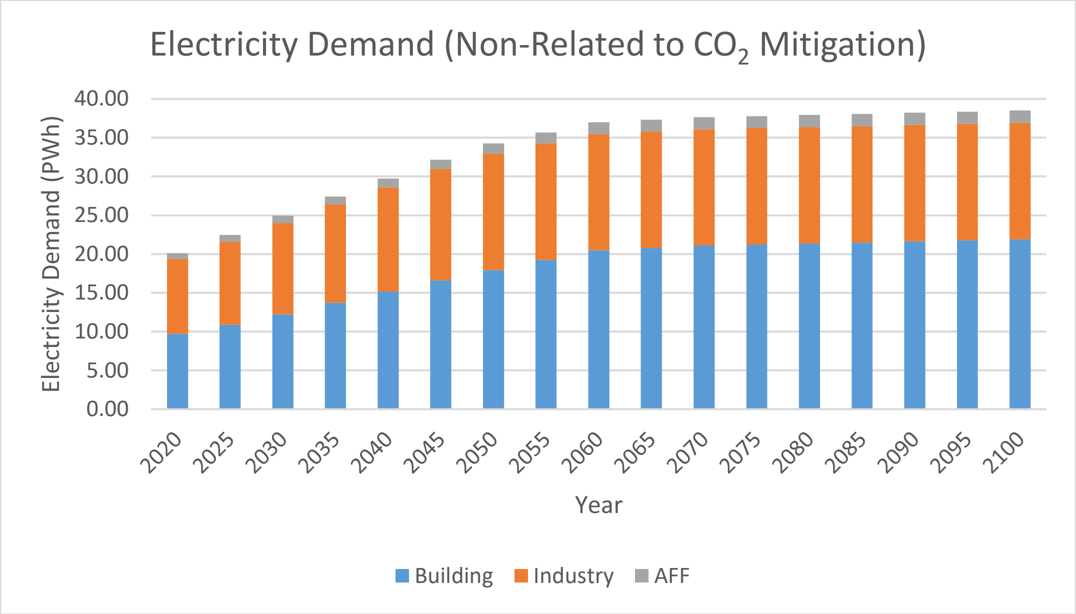

Figure 6-10 Electricity Demand (Non-related to Mitigation of CO_2 Emission)

Combining electricity demands both due to remediation efforts and independent from CO_2 emission actions, the overall electricity requirement forecast in the World has been determined. This total demand is not identical to the electricity production from the power plants, however; there exist important losses in the transmission and conversion of electric energy (from low voltage to high voltage, and back to low voltage). The magnitude of these losses is available in the literature [117], [118]. Analyses for the years 2014 and 2018 by IEA indicate that around 9% of electricity demand is being lost through transmission. Therefore, the final electricity that needs to be supplied by the power plants can be taken 9% larger than the total demand and reaches 153.06 PWh in 2100. The evolution of the total electricity generation demand is presented in Figure 6-11.

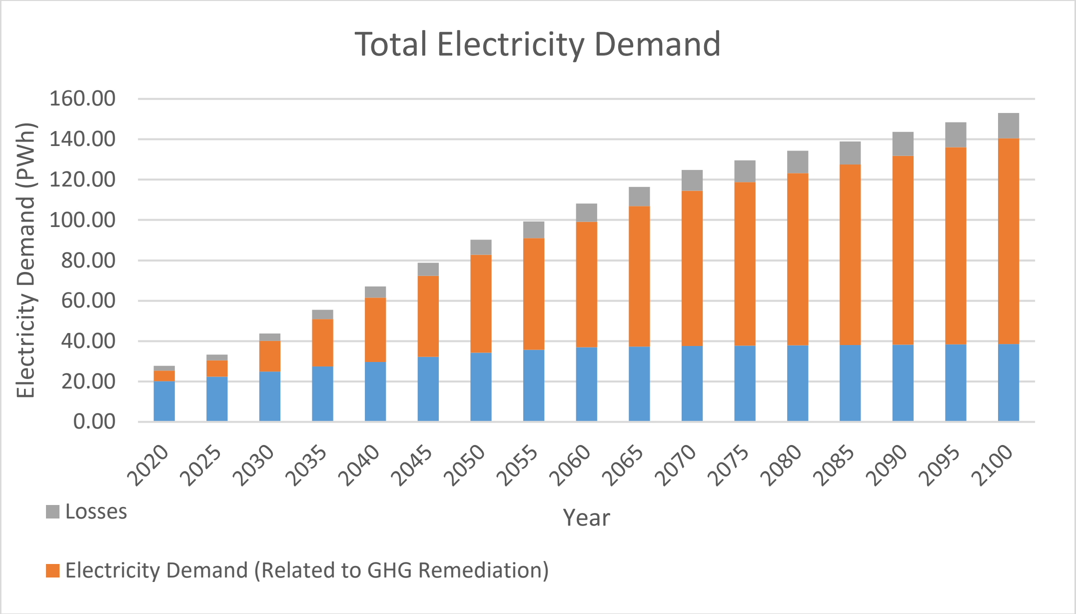

Figure 6-11 Electricity Demand (Total)

6.3. Future of the Power Sector

Upon determining the magnitudes of the future electricity generation, these may be compared with the electricity to be produced by the current operating power plants. The latter has been evaluated in the previous chapter. Accordingly, the current power plants (as listed by the beginning of 2019) are expected to produce less and less electricity as they are subject to decommissioning, starting from 2030 based on the adopted assumptions. No new fossil or biomass fueled power plants are to be constructed. For the hydroelectric power plants, it has been assumed that no new addition is expected, as they have reached a high saturation. Possible new hydroelectric power plants will partially replace the renewables that are proposed in this study.

Electricity supplied by the currently operating power plants meets the actual demand, as of 2020. However, when the CO_2 emission mitigation efforts start affecting the demand by 2030, simultaneously with the closure of coal fired power plants, an energy gap of almost 10 PWh will appear. The gap is expected to grow at an increasing pace reaching more than 80 PWh in 2050. Therefore, immediate actions need to be taken in the construction of new power plants with almost nil emissions: renewables and nuclear.

6.3.1. The Need for an Energy Mix

One may argue that the sole use of either renewables or nuclear would suffice to meet the future electricity demand. However, this is not the case. Nuclear power plants still have low public acceptance and they consume a limited natural resource: uranium and possibly thorium. Whereas renewable sources that are considered, wind and solar PV, are fed from the sun. Thus, renewables, for practical purposes have an unlimited (in terms of duration) supply. Furthermore, financially the energy provided by Sun is considered to be free and therefore humankind tends to favor its use as much as possible.

The fundamental difficulty in employing renewable energy lies in the lack of its dispatchable generation. The notion of “dispatchable generation” is practically born with the intense use of renewable sources. It can be defined as the ability of a power plant to produce electricity in a reliable and predictable fashion, to meet the instantaneous electricity demand. Renewable sources that are focused on this study are wind and solar photovoltaic (PV). The selection of these sources is based on the degree of maturity that has already been achieved.

Wind power plants that are considered are basically the onshore version. Offshore wind power plants are also mature, but their connection to inland is still being debated. In the short term, it has been assumed that the newly built wind power plants will be of onshore type. However, with time offshore power plants will definitely contribute to electricity generation with an ever-increasing share.

In power generation, solar energy is being used through either a PV conversion device or a concentrated solar heat device. The latter has the advantage of storing solar energy, to keep producing electricity even when the sun is not shining. Only limited operational data are available for concentrated solar power plants, therefore, in this study for calculation purposes, only PVs have been considered.

Hydroelectric power plants are also listed among renewables. However, they are not going to contribute to electricity generation in considerable amounts: they have already reached a high degree of saturation (remaining available locations are not abundant) and they result in major local geological and climatic changes, hence the construction of newer large-scale damns are limited. Therefore, in meeting the future electric demand, the author does not rely on hydroelectric power plants in this study. Only the currently operating hydroelectric plants are assumed to contribute to the generation of electricity.

OECD-NEA [46] lists renewable sources that are considered in this study, the wind and solar PV, among the “Variable Renewable Energy (VRE)” power plants. Wind power plants' electricity generation depends on the instantaneous availability of an effective wind. Solar PV plants operate only during the daytime, that is when the sun is shining. Their production depends on the instantaneous atmospheric conditions, as well. Even at noontime, the presence of clouds in the sky drastically reduces the electric generation capability of a solar PV. For these reasons, both types of power plants are VRE and their inclusion in the network creates serious operational difficulties.

The study presented by OECD-NEA [46] indicates that a 10% penetration of VREs into the generation system results in power fluctuations that are still manageable by today's power plants (other than VREs). Non-VRE power plants in the system must compensate for the fluctuation in power generation that is caused by the non-dispatchable character of VREs (sudden changes in atmospheric conditions, such as abrupt changes in wind conditions or cloudiness in the sky). This can be realized only if the non-VRE power plants have adequate power ramping characteristics. However, for large thermal power plants, especially coal fired and combined cycle gas turbine (CCGT) power plants; there exists important restrictions in power increase and decrease rates. These plants do not have good load follow characteristics; hence, they operate in baseload as much as possible. Similar power ramping (flexibility) restrictions do also apply to large scale hydroelectric and nuclear power plants. Therefore, the non-dispatchable VREs necessitate the inclusion of other power plants with high flexibility. This problem currently has started to demonstrate itself and the use of open cycle gas turbines (OCGT) is becoming more frequent than ever.

The phenomenon of increased use of OCGT, which has already occurred in certain countries in Europe (Germany is a good example), has important drawbacks. OCGTs have relatively low thermal efficiencies (especially when compared to CCGTs), hence their operation result in more intense use of fossil fuels. The more pronounced consumption of fossil fuels results in higher CO_2 emissions (compared to the operation of CCGTs) and waste heat rejection. Needless to underline that it will also implicate a sooner depletion of the fossil fuel reserves. The situation has reached a serious level in Europe; certain CCGTs are being converted back to OCGTs to accommodate a more flexible operation. A condition that must be considered as an engineering disaster.

6.3.2. Proposed Energy Mix

Taking into account the individual drawbacks of renewables and nuclear, a strategy needs to be determined to reduce CO_2 emissions from the power sector as much as possible.

Recommendation of this study for the restructuring of the power sector lies in the combined use of wind, solar PV, and nuclear sources. The well-balanced composition of the three can provide the needed almost zero emissions from the power sector and help reducing the emissions from the other sector, with a transition to more intense use of electricity and electrolytic hydrogen.

The problem of future restructuring of the power sector is now reduced to determining individual contributions of wind, solar PV, and nuclear power plants. An important assumption adopted in this study is that current operating power plants will be decommissioned according to a calendar specified in the previous chapter. No new fossil or biomass fueled power plant will be constructed. Hydroelectric power plants will resume their operation until decommissioning, and no new plant will be added to the system, as they already have reached saturation. Hence, the power plants to be constructed starting from today will constitute (primarily onshore, but gradually include offshore) wind, solar PV, and nuclear power plants only.

To determine the composition of the new power plants, engineering characteristics of each type needs to be identified. Based on current operational experience solar PVs have the lowest load factor: 13%. Onshore wind turbines achieve 25%, offshore ones 35%, and nuclear power plants can readily attend 80% load factors. [46]; [119]. In the present analysis, taking into account possible further improvements, a descriptive load factor of 15% has been used for solar PV, 30% for onshore wind, 40% for offshore wind, and 80% for NPPs.

The penetration of a power plant type is defined to be the share of the electricity generated by the relevant type in the total yearly electricity generation. As discussed by OECD-NEA [46], a 10% penetration of VREs is expected to result in power fluctuations (due to the non-dispatchable character of VREs) that are still manageable in the entire power sector. It is important to note, the compensation of these fluctuations currently necessitates a more pronounced use OCGTs. In the model, it has been assumed that new nuclear power plants are capable of achieving the flexibility of the OCGTs, hence the compensation will be performed by NPPs. This can be justified by the fact there exist NPP designs with the required power ramping characteristics.

Before proceeding further with the penetration of VREs, the relative electricity generation ratios (penetrations) of wind and solar PV need to be specified. OECD-NEA recommends the selection of 75% wind – 25 % solar PV penetrations. The logic behind this selection lies in the daily power generating profiles of the types. Solar PVs operate only in the daytime, peaking around noon, during which winds are not pronounced. Similarly, seasonal changes in solar PV and wind tend to compensate each other; solar generation is higher in the summer season, whereas wind generation is larger in winter and spring. [120] , [121].

Upon specifying the relative penetrations within VREs, penetration of VREs and NPPs have been determined. The study by OECD-NEA indicates that a 30% value for the former, results in power curtailment of VREs' generation. This phenomenon can be described as abandoning the power generation of a VRE, because of the instantaneous excess generation in the system. This results in a further decrease in the load factors of VREs.

In the present model, to minimize power curtailment in VREs and power ramping requirements of the other power plants (mainly NPPs) to compensate power fluctuations, the use of "*hydrogen buffering*" has been proposed. Because large amounts of electrolytic hydrogen need to be produced in the model (to be fed to the industry sector and transportation), intermittent production of electrolytic hydrogen may serve as a damper. Unlike the electricity demand, which needs to be supplied instantaneously at all times (otherwise power shortages can happen), hydrogen production can be performed over a long time interval. Because of its storage capability, hydrogen production is not required to be continuous in time. It is worth reminding that, the operation of an electrolyzer cannot be ramped in an unlimited manner. However, technical potentials exist for their operation under swinging electric supply [122], [123].

The role played by hydrogen buffering is essentially to serve as a practical storage mechanism for the temporary excessive energy production from primary sources. There are other storage technologies proposed in the literature, pumped storage hydropower plants being one such examples. The use of storage technologies (other than hydrogen buffering) will greatly enhance the penetrations of VREs. In this study, hydrogen buffering has been proposed as the primary storage method (to enhance the penetration of VREs), due to the inherent heavy consumption rate of hydrogen fuel.

To demonstrate how dominant hydrogen buffering becomes in the model, the evolution of both direct electricity demand and the electricity required by the electrolysis are presented graphically in Figure 6-12. A 9% transmission loss figure has been added to both demands. Hydrogen buffering exceeds 1/3 of the direct electricity demand by 2050: Electricity demand of hydrogen buffering reaches 22.94 PWh, whereas the latter attains 67.25 PWh. In 2100 they are 51.15 PWh and 101.92 PWh, respectively.

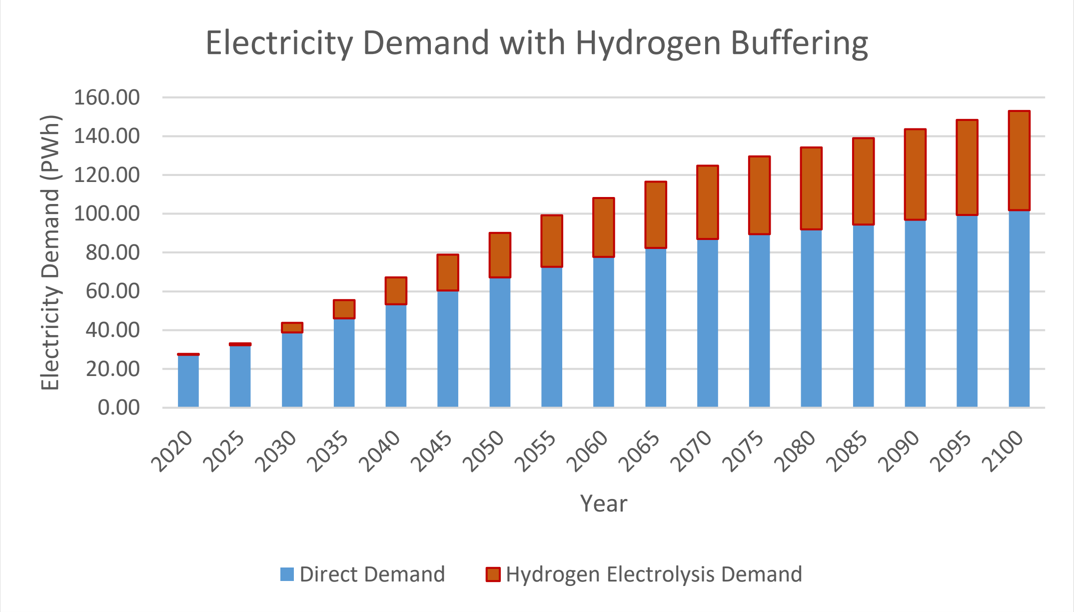

Figure 6-12 Electricity Demand with Hydrogen Buffering

The hydrogen buffering option, born with the use of electrolytic hydrogen as an energy carrier in the model, allows the adoption of higher penetration levels of VREs than considered practical by OECD-NEA. Therefore, target penetration levels have been set for VREs (the remaining power generation is to be supplied by NPPs and power plants currently in operation –until their decommissioning). The targets for VRE penetration that are employed in the basic REALISTIC Scenario are given in Table 6-1.

Table 6-1 Penetration Targets

Year	Wind	Solar PV	Current(Non-VRE) +Nuclear
2030	7.5%	2.5%	90.0%
2050	22.5%	7.5%	70.0%
2070	30.0%	10.0%	60.0%
2100	37.5%	12.5%	50.0%

According to the study performed by OECD-NEA, it would have been impractical to exceed 30% VRE penetration. Thanks to hydrogen buffering, the share of VREs in electricity generation has been extended up to 50%. The developed model indicates that the electricity generation by nuclear power plants should reach 76.53 PWh. Similarly, wind power is going to reach 57.40 PWh by 2100. In analyzing wind power, it has been assumed that offshore plants will grow from 0 (almost negligible) share in 2020 to 50% in 2100. The growth in the share of offshore plants is modeled to be linear. Therefore, in 2100 28.70 PWh is expected to be produced from onshore wind plants and another 28.70 PWh from offshore. Because a 75-25 ratio has been specified between wind and solar power generation, as in the OECD-NEA model, it has been determined that the solar PV electricity generation will escalate to 19.13 PWh in 2100. The evolution of the power generation in the nuclear, wind (onshore and offshore), and solar PV are shown graphically in Figure 6-13 through Figure 6-15.

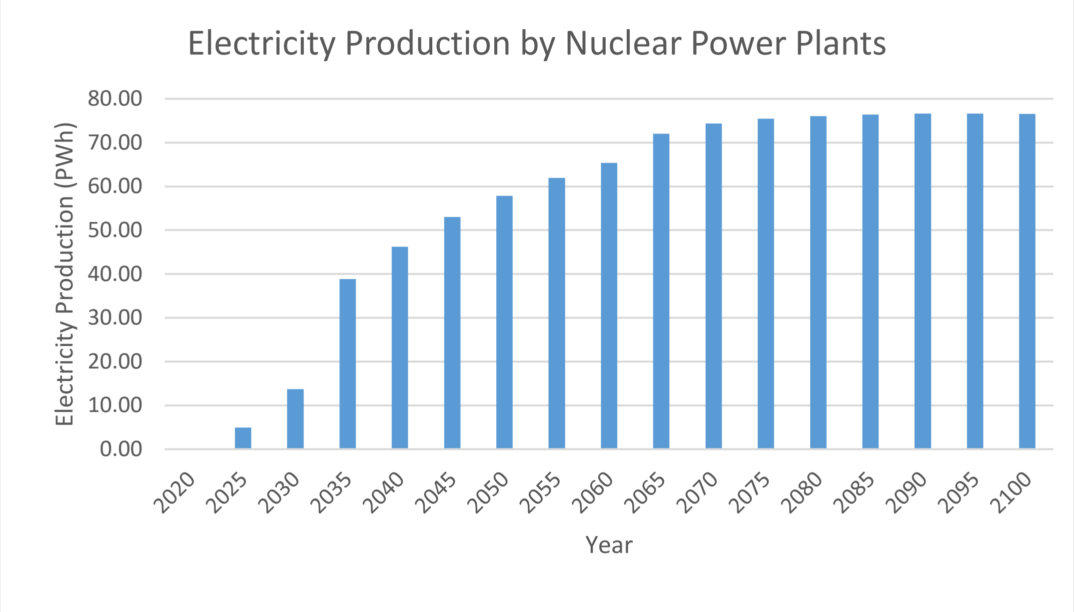

Figure 6-13 Electricity Generation via New Nuclear Power Plants (Excluding the existing NPPs)

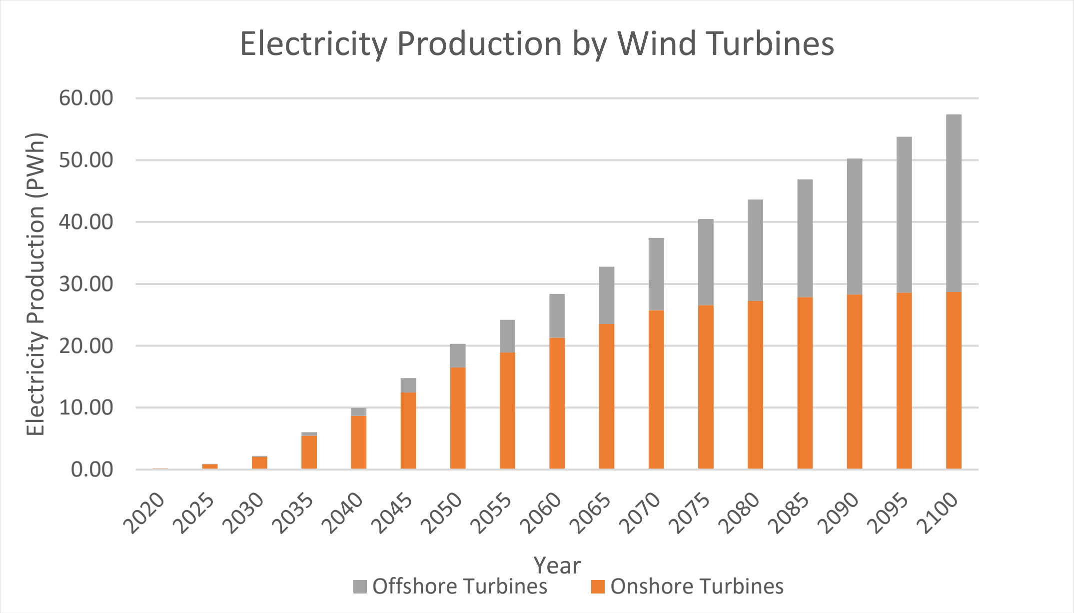

Figure 6-14 Electricity Generation via New Wind Turbines (Excluding the existing Wind Farms)

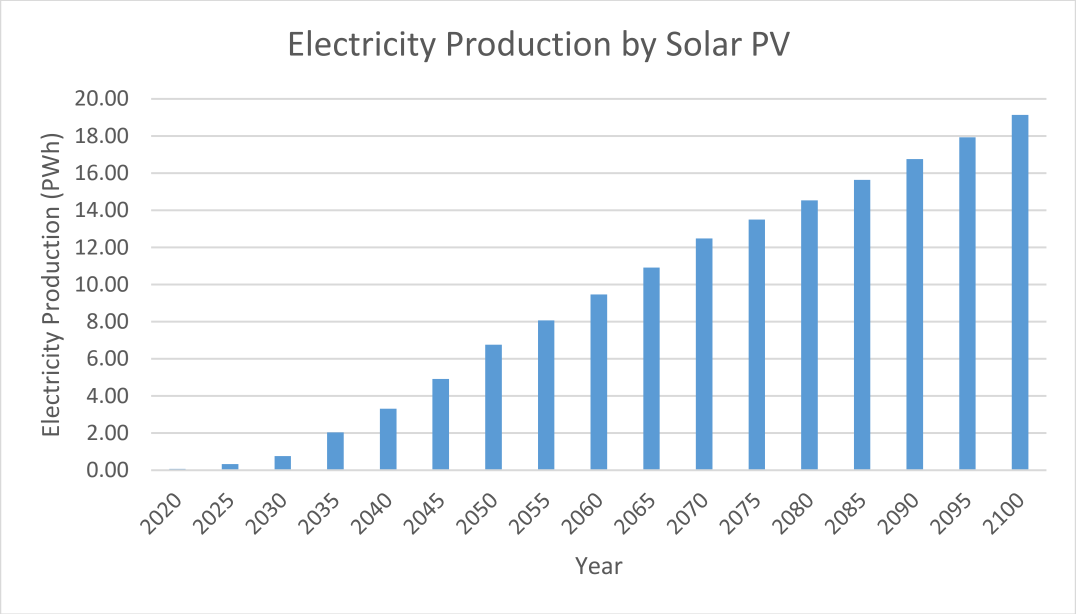

Figure 6-15 Electricity Generation via New Solar PVs (Excluding the Existing Solar Farms)

6.3.3. Capacity Distribution of Power Plants

Once the electricity generation by each source has been determined, the corresponding capacities of power generation have been calculated. The load factor for each plant type being different, the installed capacity needed to maintain the required electricity production should be evaluated separately. Upon consulting several sources in the literature, it has been noted that similar values are provided. For the sake of consistency with the other assumptions of the study, load factors used by OECD-NEA [46] have also been employed: Solar PVs will operate with 15%, onshore wind plants with 30%, and offshore wind plants with 40% load factors.

The load factor for NPPs has been taken 100% for modeling purposes in the OECD-NEA study. This figure has been altered to 80% to suit a realistic model. Using the appropriate load factors, the evolution of the installed capacity in all sources has been determined. Calculations reveal that nuclear power plants should reach a capacity of 10,920,472 MW in 2100. By then, onshore wind will also reach 10,920,472 MW, offshore 8,190,354 MW, and solar PV 14,560,629 MW installed capacity. The evolution of the installed capacities is shown graphically in

Figure 6-16 through Figure 6-18.

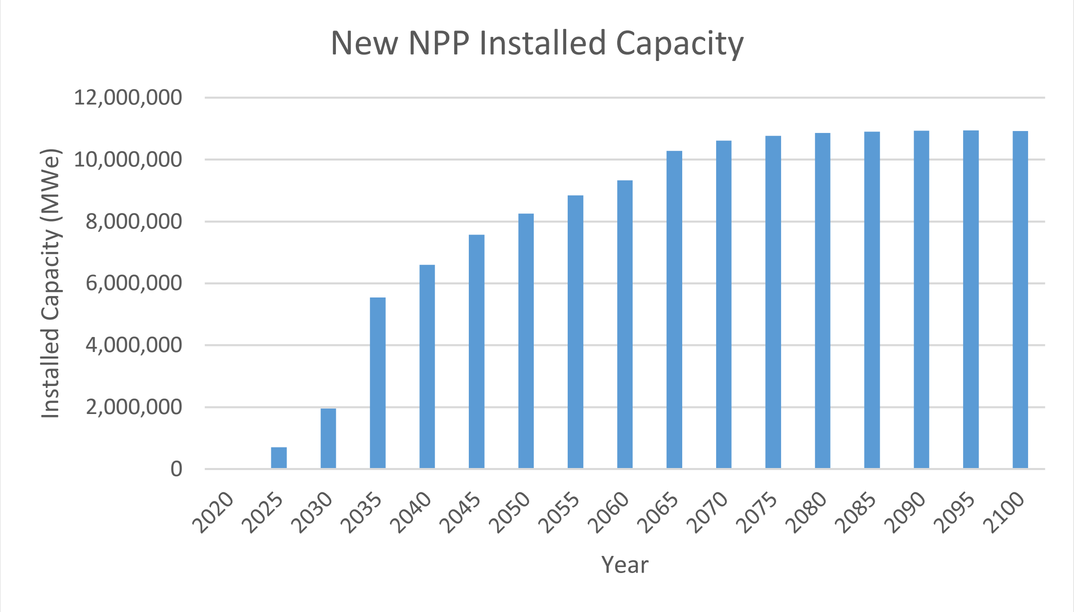

Figure 6-16 Newly Installed Nuclear Power Plants Capacity

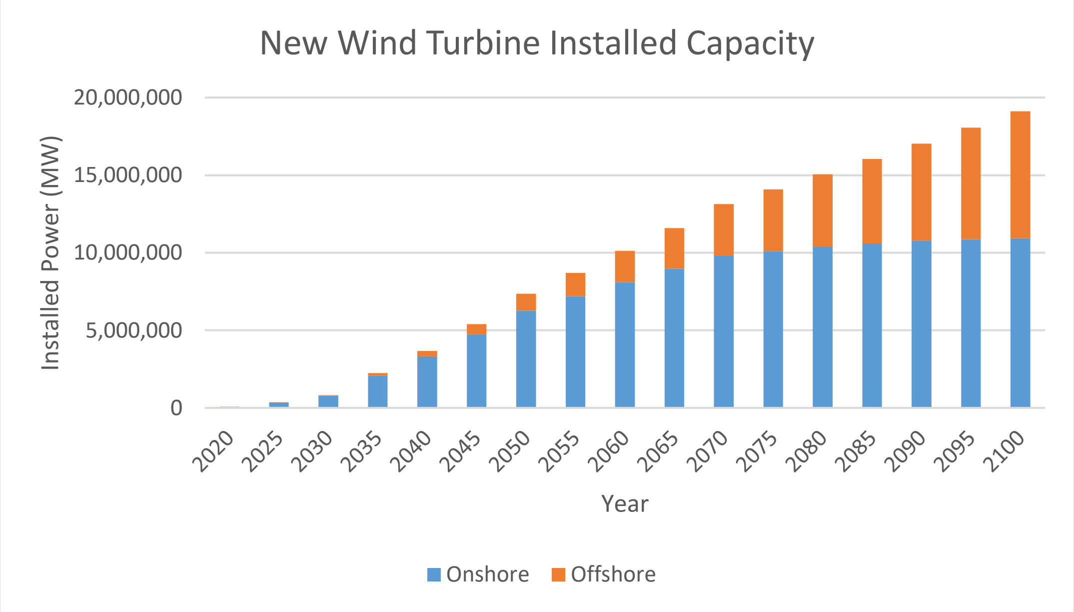

Figure 6-17 Newly Installed Wind Turbines Capacity

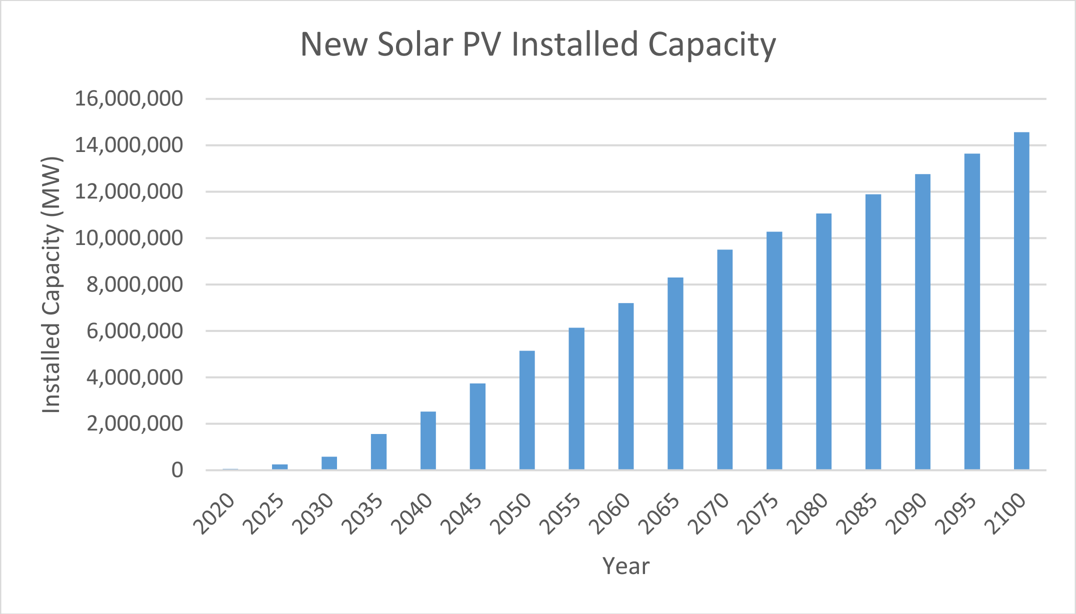

Figure 6-18 Newly Installed Solar PVs Capacity

6.4. Sensitivity to the Assumptions

Our analysis of both electricity demand and CO_2 emissions is based on a set of assumptions, which constitutes the scenario developed in the study. The basic scenario that is adopted is referred to as the REALISTIC Scenario. By altering how fast mitigation actions to reduce CO_2 emissions can be implemented, two additional scenarios have been constructed: AGGRESSIVE and RELAXED.

It is common to all proposed scenarios of this study that a more intense use of electricity and electrolytic hydrogen to replace fossil and biomass fuels. Needless to remind that the electricity, whether is used directly or for electrolysis, should be produced from almost zero CO_2 emitting sources: renewables and nuclear. A brief description of the idea behind the former scenario is that humanity takes necessary actions, without considering any financial restriction. Therefore, the limitations are dictated by technical challenges only. Whereas in the latter scenario, not only financial considerations are maintained, but the potential reluctance by the governments and institutions in making the transition to new energy carriers has been also modeled.

In addition to the pace of transition to new energy carriers, there exists another important set of assumptions: the modeling of the future energy demand. In the basic scenario of REALISTIC, the Reference Technology Scenario (RTS) developed by IEA has been employed to determine the demands in the buildings and industry sectors. Further fine-tuning has been applied to industry, where material demand forecasts are available. In the transportation sector, however, the more accurate forecast by ITF have been used. However, these forecasts are valid until 2050 or 2060. Beyond these dates, the demands have been extrapolated to extend the calculations to 2100. It would be convenient for ease of reading to briefly summarizing the adopted demand extending assumptions.

In the REALISTIC Scenario, it has been assumed that the industry sector reaches a saturation by 2050; hence, the activity of the sector is expected to remain at a constant level. Therefore, it is considered that the electricity demand beyond 2050 is going to exhibit a “FLAT” pattern. In the case of the transportation sector, the recommended direct relation between Gross Domestic Product (GDP) and transport activities has been used. Accordingly, transport activities beyond 2050 have been taken to be proportional to GDP, which in turn has been forecasted until 2100 by OECD. For the buildings sector, energy consumption appears almost proportional to population. Therefore, the demand beyond 2060 has been extrapolated such that it is proportional to population (“POP”), the growth of which has been studied extensively by the United Nations.

Because different indicators are used in the long-term forecasts of the energy demand, the sensitivity of the performed analyses to the selection of the indicators has been studied. Accordingly, it has been assumed that either FLAT extrapolation remains valid for all sectors, beyond the latest year for which data have been provided, or an electricity demand growth occurs proportional to population (POP) and GDP.

6.4.1. Pace of Transition

The first set of comparisons for the evolution of electricity demand involves the selection of targets for the penetration of direct electricity and electrolytic hydrogen uses. Target values set in each sector under the specific scenario have been previously described in the appropriate chapters. Combining the electricity demand in each sector (industry, transportation, buildings, and AFF) the World electricity requirement has been evaluated, as well as the generation capacity to accommodate the demand. In

Figure 6-19 electricity generation under REALISTIC, RELAXED, and AGGRESSIVE Scenarios are presented. The associated capacities for NPPs, wind turbines, and solar PVs are shown in Figure 6-20 through Figure 6-22.

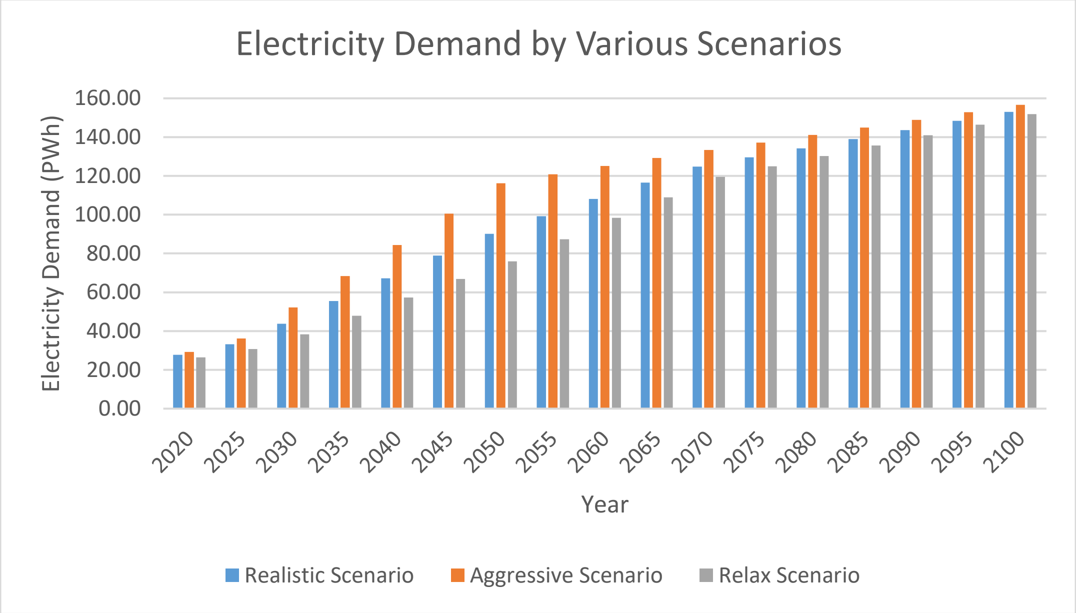

Figure 6-19 Electricity Demand by Various Scenarios

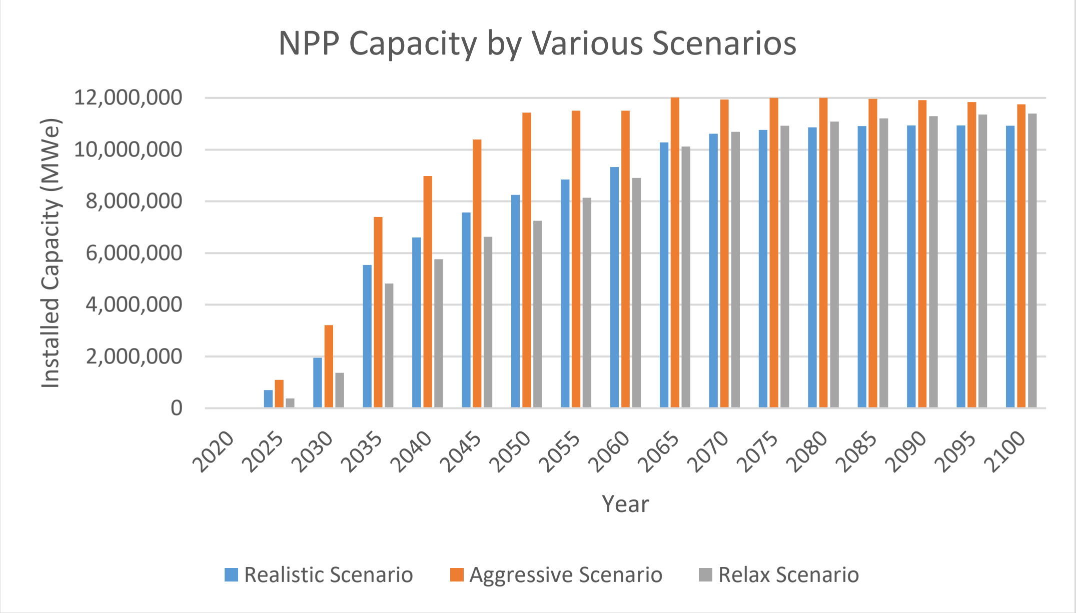

Figure 6-20 NPP Capacity by Various Scenarios

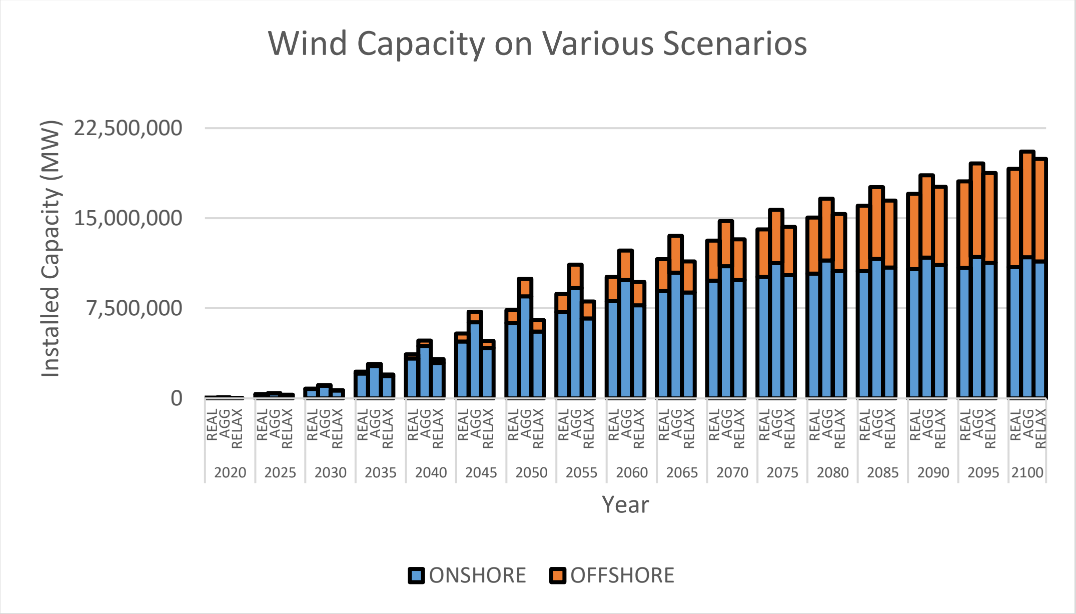

Figure 6-21 Wind Capacity by Various Scenarios

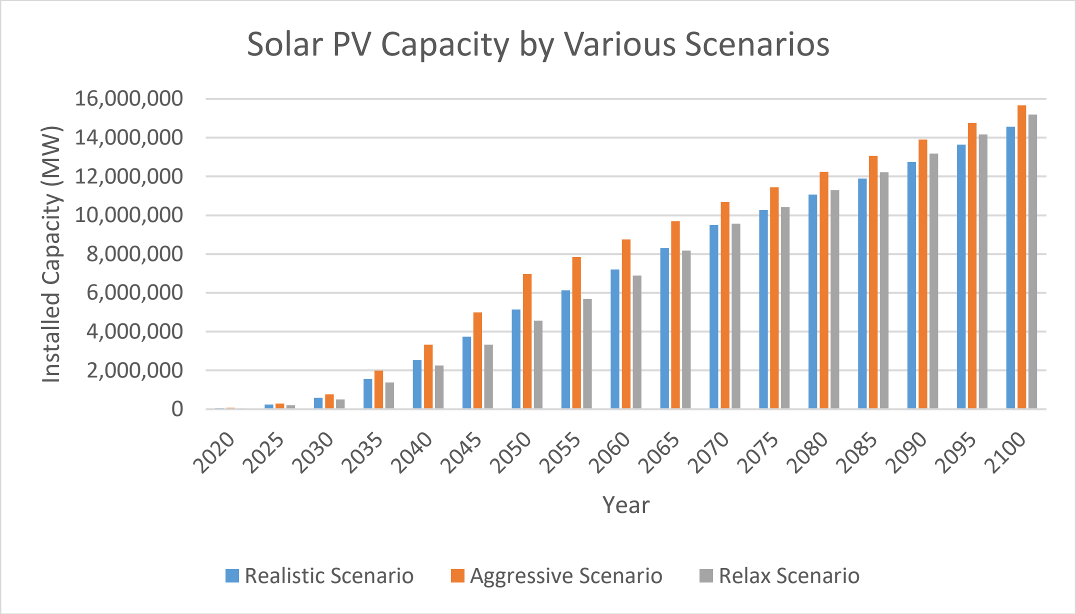

Figure 6-22 Solar PV Capacity by Various Scenarios

The adoption of the AGGRESSIVE Scenario results in rapid growth in the installed capacities between 2040 and 2060. The number of units to be constructed in the REALISTIC was extremely large; therefore, the practicality of the former Scenario remains questionable. The RELAXED Scenario is likely to be the probable one, simply affecting the number of units to be constructed in the specified range. By 2100, all three scenarios converge to each other; hence the transition period of 2040-2060 will determine the overall evolution throughout the world.

6.4.2. Long-Term Electricity Demand Forecast

The second set of comparisons involves the long-term growth forecast of the electricity demand. In evaluating the effects of the forecasts beyond 2050 and 2060, it has been accepted that the pace of transition to new energy carriers will occur as described in the basic scenario of REALISTIC. The evolution of the electricity generation and installed capacities are presented in Figure 6-23 through Figure 6-26.

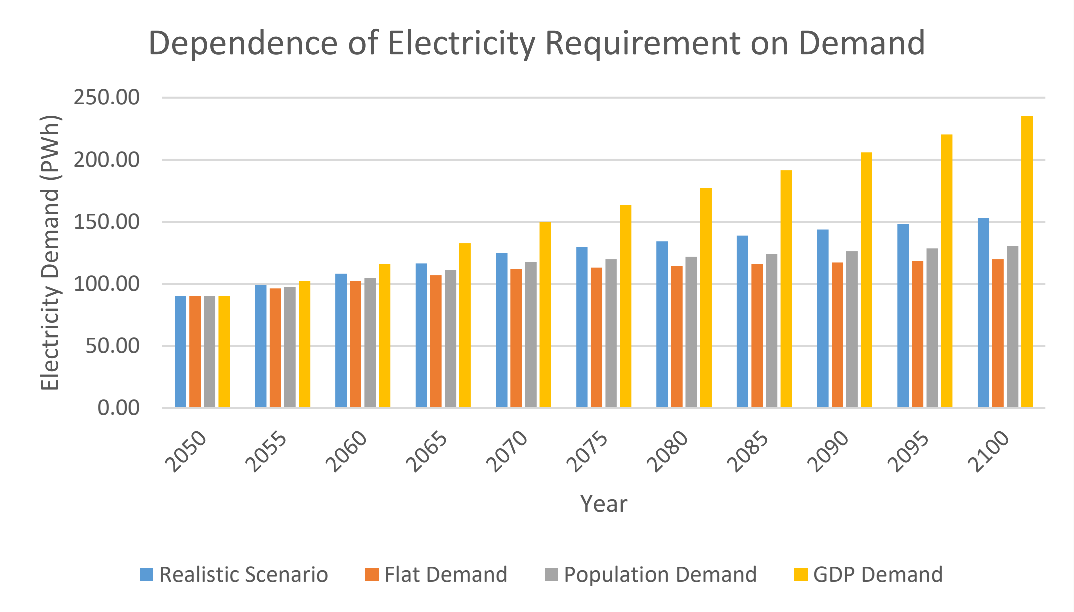

Figure 6-23 Dependence of Electricity on Demand Scenarios

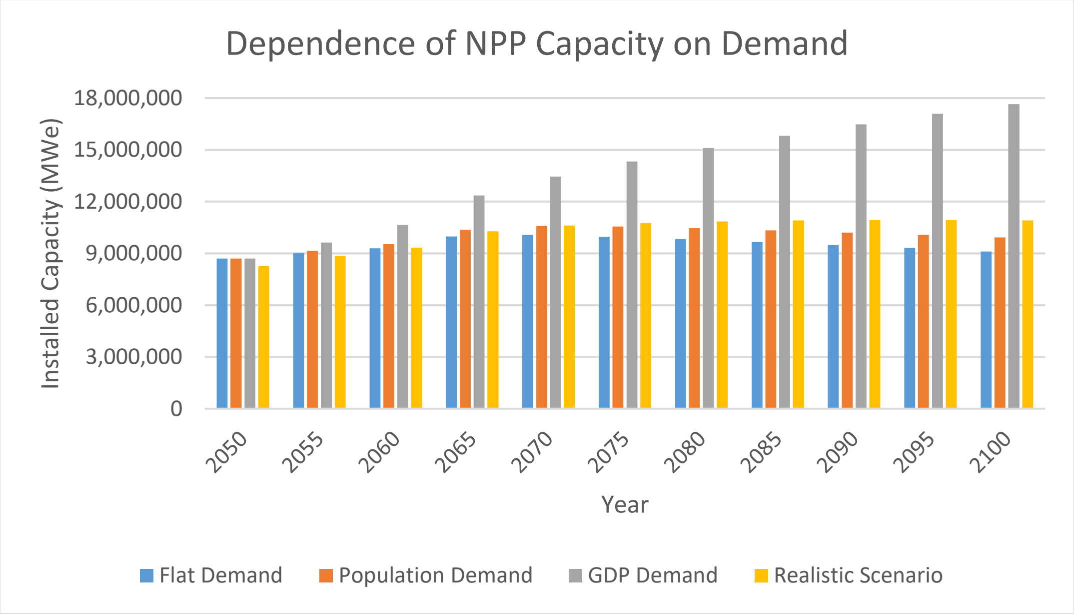

Figure 6-24 Dependence of NPP Capacity on Demand

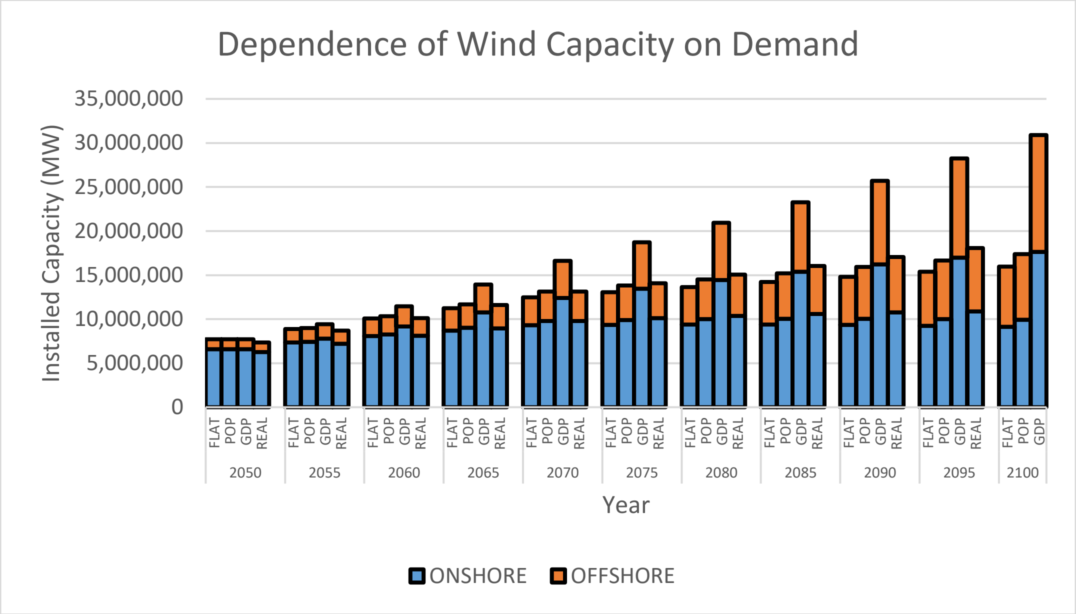

Figure 6-25 Dependence of Wind Capacity on Demand

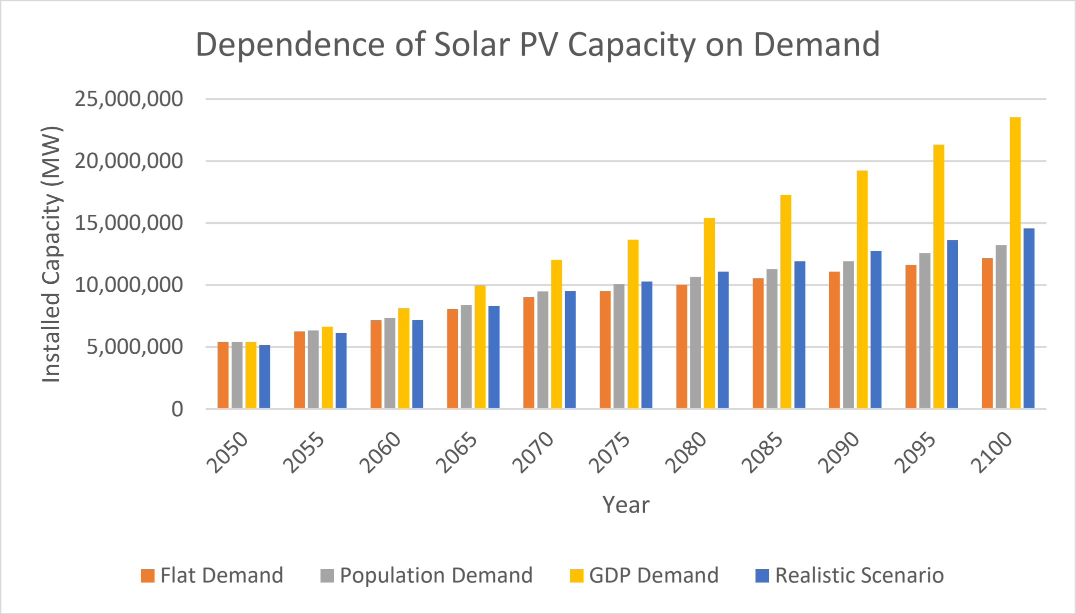

Figure 6-26 Dependence of Solar PV Capacity on Demand

A growth dictated by GDP implies an almost unrealistic evolution. The increase in the electricity supply and installed capacity becomes so excessive that, if such growth were to occur, humanity will take other actions in limiting the evolution. Selection of an overall growth proportional to either population or GDP have only limited effect on the evolution. However, both demand scenarios imply lower installed capacities when compared to the basic scenario of REALISTIC. This is attributed to the growth of transportation, the sector which will consume the majority of the energy in the future. Therefore, measures in limiting the transportation activities should be taken, independent of the proposed remediation efforts.

6.5. Challenges Associated with the Installed Capacity

The forecasted growth in the power sector can be better understood when challenges brought by the increase in the installed capacity are analyzed on energy sources basis. The analysis begins with the nuclear energy.

6.5.1. Nuclear Capacity

To demonstrate the magnitude of the growth in the installed capacity of nuclear power plants, first the number of units to be constructed in the future has been evaluated. In the developed model, only future NPPs are presented, hence, the more than 400 units of NPP under operation worldwide have been excluded.

As discussed a priori, it has been assumed that the new NPPs will consist of 1000 MW_e PWR type nuclear plants, as they have the highest level of maturity among all other types. The growth in the number of NPPs is given graphically in Figure 6-27.

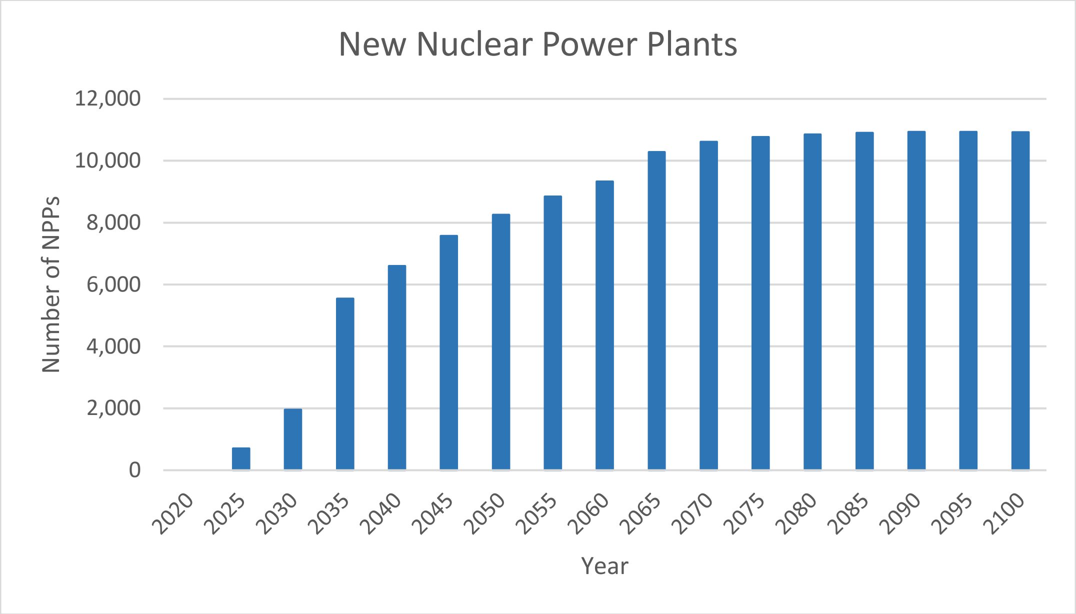

Figure 6-27 New Nuclear Power Plants

Analysis of the growth pattern indicates a sharp increase in 2031, where coal power plants are to be phased out and transition to electrolytic hydrogen use in the industry begins according to the model. Even until 2030, 1,952 NPP units must be constructed, assuming that no fossil or biomass fueled power plants are to be commissioned anymore. The number of NPP units jumps to 4,486 in 2031 and increases steadily until 2080 reaching almost 11,000 units. Beyond 2080, the number of NPP units remains fairly constant.

The uranium supply needed to sustain the operation of the proposed NPPs has also been investigated. A joint study performed by IAEA and OECD-NEA indicates that a 1,000 MW_e NPP consumes 150 ton/yr of U. Therefore, almost 100,000,000 t U will be consumed by the NPPs, according to the developed model. However, world uranium reserves are approximately 7,000,000 t. This observation concludes that supplying dispatchable electricity generation via nuclear is impossible. Some amelioration can be attained with employing breeding, thus making use of the fertile U^{238} and possibly Th^{232}. However, considering that the doubling time of mature reactor technologies (LMFBR) is on the order of 40 years, only limited improvements can be achieved.

6.5.2. Wind Capacity

To appreciate the magnitude that will be reached in wind power, the number of wind turbines to be installed has been calculated, as well as the land area required for the onshore plants. Although various wind turbine designs exist today, larger turbines are expected to prevail in the future, as it is the current trend in the sector. Accordingly, a 7 MW rating has been selected, for the future descriptive onshore wind turbine. Offshore turbines tend to have higher power ratings. They are not matured as their onshore cousins. Nevertheless, for evaluation purposes, a representative turbine power rating must be selected: A typical future offshore wind turbine is presumed to have an electricity generating capacity of 15 MW.

Employing the evolution of the installed capacity in wind power, the number of turbine units in the future has been determined. The results are presented graphically in Figure 6-28.

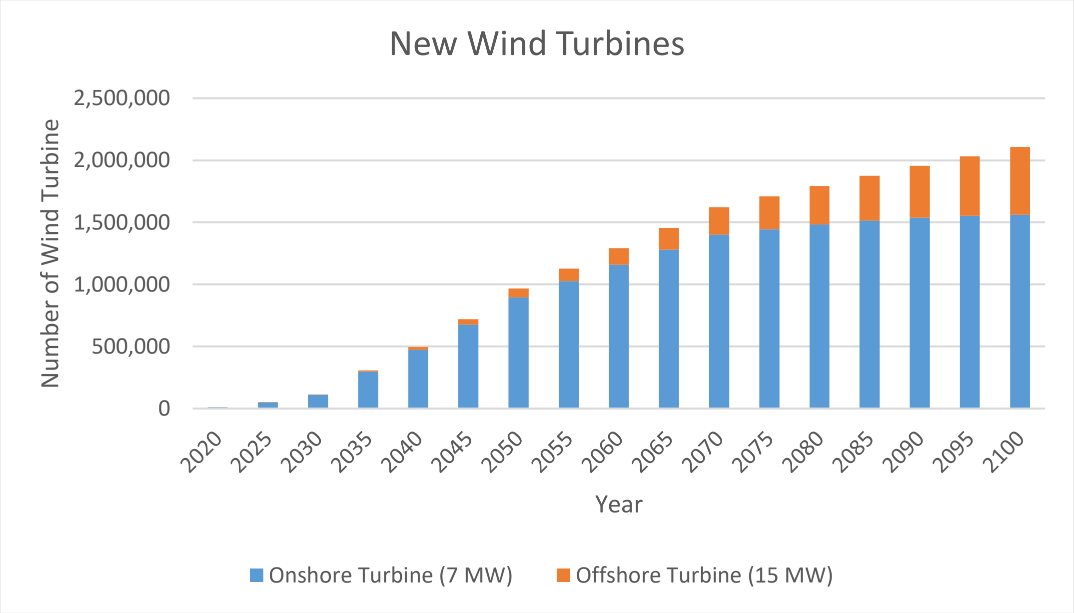

Figure 6-28 New Wind Turbines

The number of onshore wind turbines is 111,832 in 2030. Just like the case in NPPs, a sharp increase is expected to occur in 2031 and it reaches 180,299. It then increases steadily to reach 1,560,067 turbines in 2100. Similarly, the number of offshore wind turbines is 2,609, 4,659, and 546,024 in 2030, 2031, and 2100, respectively.

In addition to the number of units (wind turbines), it is worth analyzing the land area necessary for the installation of them. The investigation has been restricted to onshore plants, as the evolution of offshore units contains more ambiguities. Upon consulting various sources in the literature, 44.7 acres/MW (0.180895 km^2/MW) has been taken as a representative figure for land use [124]. It has been determined that a land area of 141,609, 228,306, and 1,975,455 km^2 is needed in 2030, 2031, and 2100, respectively. For comparison purposes, the surface area of Turkey is 783,562 km^2 and corresponds to the area to be occupied by onshore wind power plants by 2044, according to the model. The results are shown graphically in Figure 6-29.

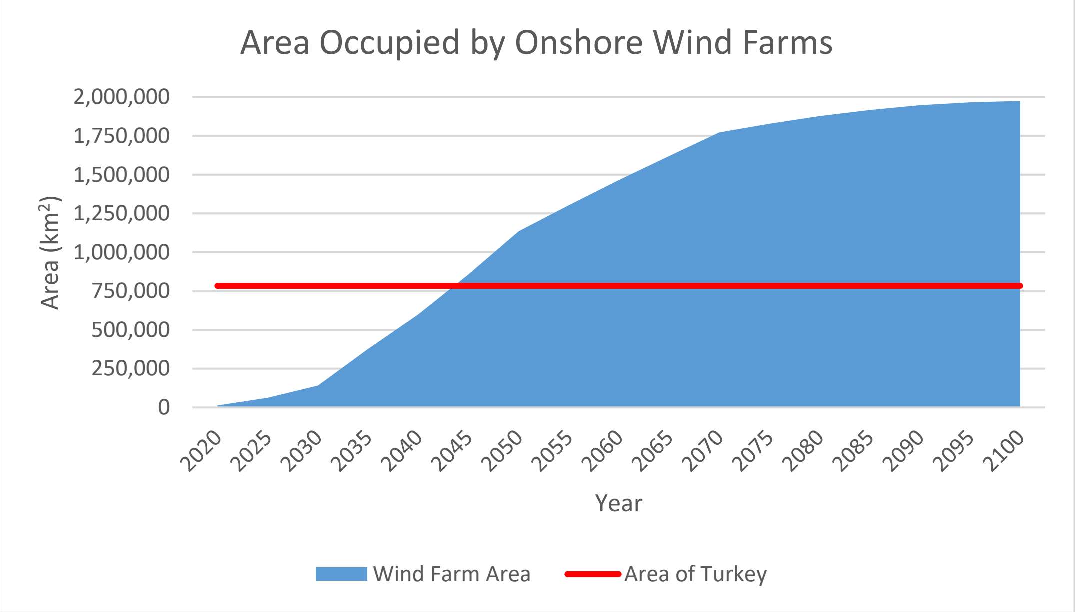

Figure 6-29 Area Occupied by Onshore Wind Farms

6.5.3. Solar PV Capacity

By its very nature, it is not meaningful to determine the unit numbers in solar PV; rather, the land area to be allocated for their installation has been determined. Consulting several sources in the literature, 6.1 acres/MW (0.024686 km^2/MW)

[124] has been selected as a representative figure. It has been determined that a land area of 14,466, 23,113, and 359,441 km^2 is needed in 2030, 2031, and 2100, respectively. The evolution of the land dedicated to solar PV is presented graphically in Figure 6-30.

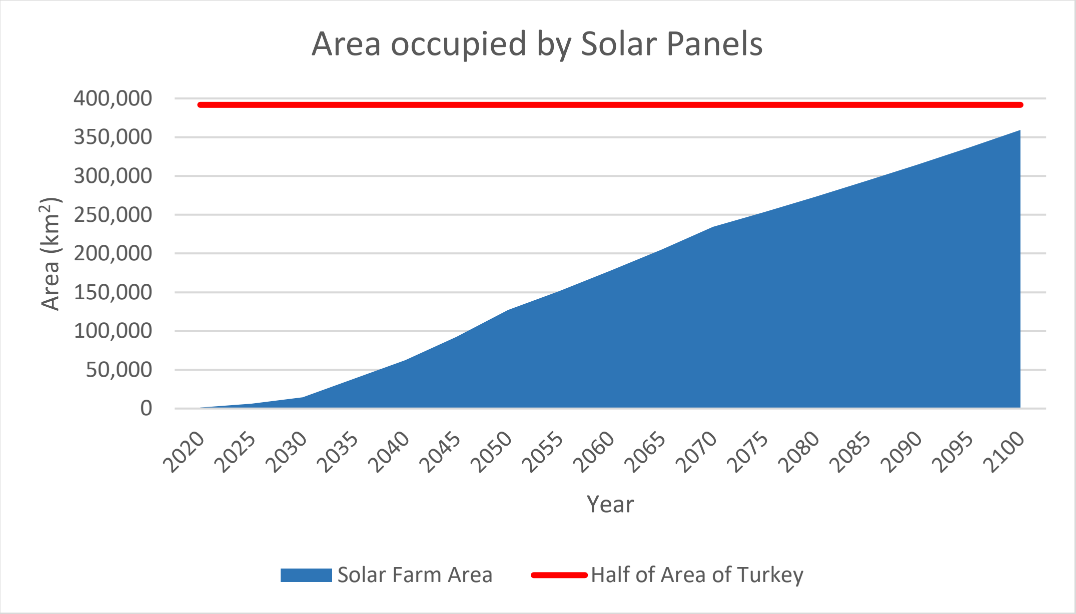

Figure 6-30 Area Occupied by Solar PVs

6.5.4. Discussion of the Installed Capacities

The literature contains various suggestions on the use of electricity as an energy carrier to reduce future CO_2 emissions. However, the size of the installed power plant capacity becomes immense, when appropriate actions are taken in all sectors.

Renewables alone are not capable of supplying the electricity demand in the grid. Even 30% penetration of renewables results in considerable instabilities. With the use of hydrogen buffering, this penetration has been expanded to 50% by 2100. Electrolytic hydrogen generation then serves as a storage mechanism. However, this is not without a payoff: Large electrolysis capacities should be installed with flexible operation characteristics, a technology that can be assumed mature. It is worth emphasizing that technological innovations seem inevitable to realize such a large electrolysis capacity. Current state of the art electrolysis units rely on noble metal electrodes and the supply of these metals being limited, alternative solutions should be provided in the future.

Even with the high penetration (50%) of renewables, a large electricity generating capacity should be maintained as a dispatchable source. In this study, the use of nuclear energy, hence NPPs have been proposed as the dispatchable capacity. There are two main problems associated with this recommendation: the number of NPP units to be constructed is extremely large and the current mature open cycle employed in NPPs is insufficient to meet the fuel demand.

The number of NPP units commissioned in a year has only a single digit. Therefore, the target for constructing more than 4,000 units by 2031 exceeds the capacity of the sector.

Open nuclear fuel cycles employed by the mature PWR technologies require the availability of almost 100,000,000 t of uranium until 2100 according to the REALISTIC Scenario. Given that the world's uranium resources are approximately 7,000,000 t, there exists a huge shortage in the supply of nuclear fuels as well. Nuclear fuel recycling, the potential use of breeder reactors can ease the situation. Even some contribution from fertile thorium can be provided. However, the practicality of reducing nuclear fuel demand by a factor of almost 15 is rather questionable, even though not impossible.

6.6. Summary and Novelty of the Approach

Mitigation efforts proposed in this study to reduce direct CO_2 emissions from industry, transportation, and buildings sectors necessitate the installment of a large electricity generation capacity. To these mitigation-related electricity requirements, future electricity consumption (which is not related to the aforementioned efforts) from all economic sectors are added. This allows the determination of the World’s total electricity requirement every year, from 2020 to 2100.

The crucial approach of the present study is to supply as much electricity as possible from clean primary energy sources of renewables (wind and solar PV) and nuclear. By taking into consideration the potential contribution of the already operating power plants, the share of each plant type in electricity generation has been determined by the author. The selection of plant types and their appropriate shares are specific to the present study.

It has been concluded that it would not be practical to supply the entire electricity requirement by employing the proposed sources only. Neither the uranium sources nor land to be allocated to renewable would suffice to meet the demand. Furthermore, especially the construction pace for nuclear power plants is found to be beyond reasonably acceptable, from both technical and financial perspectives.

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CHAPTER 7

CO_2 EMISSIONS UNTIL 2100

Four major sectors contributing to CO_2 emissions were analyzed in the previous chapters: industry, transportation, buildings, and power. Other sectors' contributions to CO_2 are negligible, especially when energy related emissions are considered. First, sources of the emissions have been identified in each sector. Next, mitigation actions have been proposed to reduce these emissions in the future. To assess how successful these suggestions are, the resulting emissions have been compared to those in the possible evolution of the sectors under BAU conditions, i.e., no special action is taken to reduce emissions. These comparisons provide a measure of the effectiveness of the proposed actions. Various scenarios are also studied to analyze the effects of the pace of implementation of the proposals of this study and the future evolution of demands in general (material, travel, heating, etc…) of humanity.

However, assessment of the effectiveness of the actions alone is not sufficient to conclude the sufficiency and necessity of the efforts. Further investigation is indispensable to understand whether thus achievable results (in terms of CO_2 emissions) would suffice in meeting the carbon budget, such that the world would not exceed the 1.5°C global warming limit by 2100. To perform the needed comparison, total CO_2 emissions from all analyzed sectors have been evaluated and presented.

7.1. Savings in CO_2 in comparison to BAU

In each chapter dedicated to the analysis of a specific sector, a comparison of the evolution of CO_2 emissions predicted by the REALISTIC Scenario and BAU has been performed. To display how effective the developed scenario is in reducing the emissions, the sum of CO_2 emissions from the three sectors having the highest contribution after the power sector (industry, transportation, and buildings) and savings achieved over the BAU, are presented in Figure 7-1.

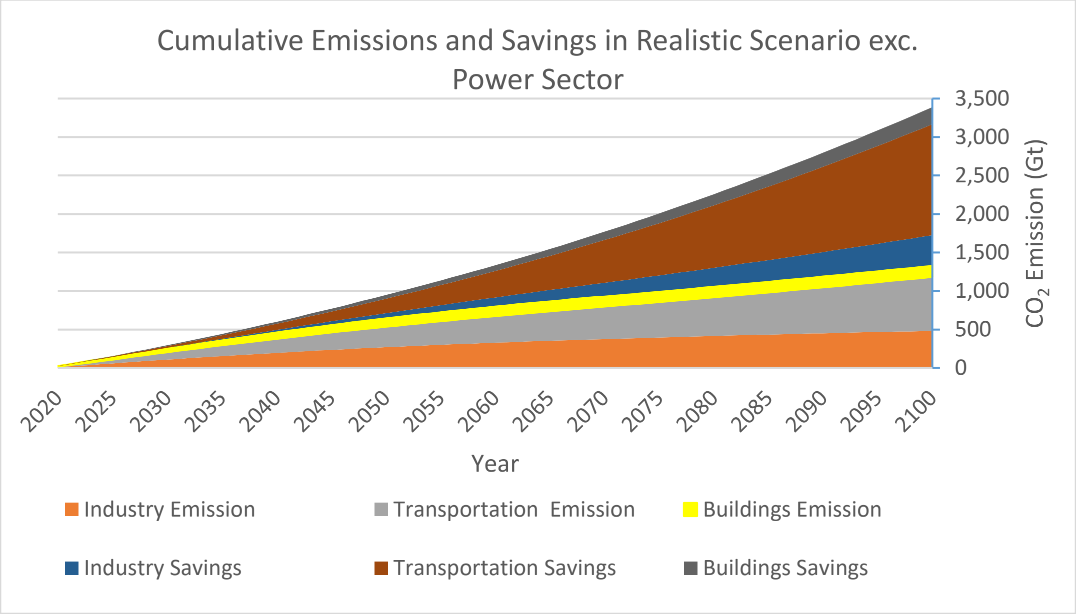

Figure 7-1 Cumulative CO_2 Emissions and Savings of Industry, Transportation and Buildings in Realistic Scenario

The reduction in the emission from the three sectors consists of only a fraction of the overall savings achieved in the scenario. The prevailing savings are obtained in the power sector. The analysis of the latter differs from all other three, as the electricity demand (power) is a strong function of the remediation efforts in the other sectors. Transition to the use of electricity and electrolytic hydrogen as an energy carrier inflates the electricity demand. Accordingly, the definition of BAU emissions from the power sector refers to emissions that would occur, when no CO_2 reducing actions are taken. With the mitigation scenario of REALISTIC, electricity demands will increase sharply in the future, when compared to BAU. Taking into account this increased electricity demand as well, all sectors' emissions have been combined to better assess the savings that can be achieved, which are presented in Figure 7-2.

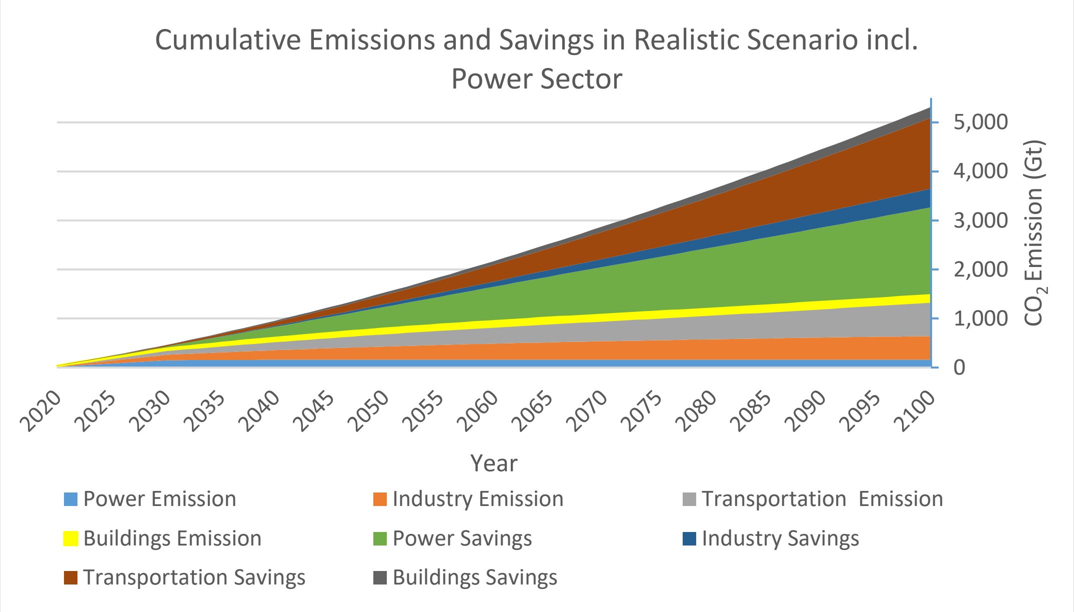

Figure 7-2 Cumulative CO_2 Emissions and Savings of Power, Industry, and Buildings in Realistic Scenario

7.2. Cumulative CO_2 Emissions until 2100

Even though a rather stringent CO_2 reduction strategy is being employed in the basic scenario (REALISTIC), an assessment of whether the goal in confining the emissions within the carbon budget set for not exceeding the 1.5°C global warming limit by 2100 has been successfully reached. To this end, cumulative emissions from all sectors (including the power sector) in the REALISTIC Scenario until 2100 are presented in Figure 7-3.

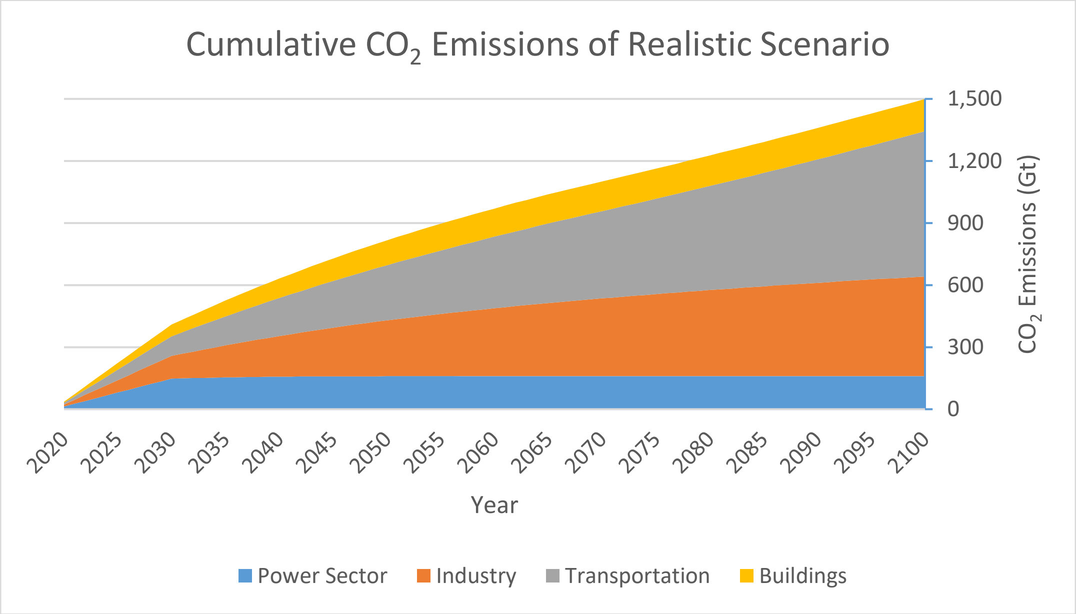

Figure 7-3 Cumulative CO_2 Emissions in Realistic Scenario

In the REALISTIC Scenario, it has been determined that in total 1,499.62 Gt CO_2 will be emitted to the atmosphere between 2020 and 2100.

To assess whether the World can remain within the carbon budget for not exceeding global warming limits by 2100, the findings are compared with the study by IPCC [8]. Including the emissions in 2018 and 2019, which sum up to 66 Gt CO_2 [125], emissions from 2018 to 2100 are calculated to be 1,565.62 Gt CO_2. This cumulative emission, which excludes non-CO_2 GHG and agriculture related emissions, corresponds to the 50th percentile for a 2.03°C global warming by 2100. This can be reformulated as, according to the study by IPCC, with a 50% probability it is expected that global warming will reach 2.03°C by 2100, with the reduced emissions of the REALISTIC Scenario. Therefore, it has been concluded that the 2°C global warming limit is an attainable target with the proposed remediation efforts of the study. However, achieving the 1.5°C limit would not be possible, solely by making a transition to electricity and electrolytic hydrogen as energy carriers.

The majority of the emissions in the cumulative REALISTIC Scenario arises from the following three sources:

- Aviation mode, which is considered indispensable in passenger long haul transport, will keep relying on fossil fuels.
- Maritime transport activities, which constitute the majority of freight activities, produce a large amount of CO_2 emissions. Long hauls involved in maritime, together with the lack of refueling options on the road reduces the possible alternative energy carriers. Hence, the marine mode is expected to rely on fossil fuels.
- Process emissions from the industry cannot be eliminated. Especially, CO_2 emissions resulting from cement manufacturing constitute a major problem.

It has been concluded that drastic measures need to be taken to limit marine and aviation mode activities in transportation. Alternatively, a viable energy carrier should be found. Currently, there exists no mature technology, which can provide an alternative. In addition, humankind should either limit the use of cement in construction or develop industrial processes for its production with much less emissions.

7.2.1. Remaining Carbon Budget

Analysis of Table 2.2 of the IPCC Special Report on global warming [8], which is also used as a reference by IEA to estimate global warming by 2100, indicates that the carbon budget of Earth is 580 Gt CO_2, between the years of 2018 and 2100. This value corresponds to the 50^{th} percentile in the assessed studies by IPCC.

This figure of 580 Gt is not restricted to energy related emissions; hence, it includes emissions resulting from agricultural, forestry, fishing, and miscellaneous activities. In this study, the latter emissions have been excluded. IEA estimates that 66 Gt CO_2 is emitted to the atmosphere in the years 2018 and 2019 [125]. If these emissions that have occurred before the period of coverage of the scenarios developed in this study (2020-2100) are also included, the carbon budget to be compared with the present results corresponds to 514 Gt only.

Analysis of the results reveals that in the REALISTIC Scenario the 514 Gt carbon budget will be reached by 2035, whereas in the RELAXED Scenario by 2034, and in the AGGRESSIVE Scenario by 2037. These findings demonstrate that humankind will consume its carbon budget in the near future. There are three fundamental conclusions that require special attention: the first is that mitigation efforts should be initialized immediately, the second that long-term demand decreasing measures (that are studied under long-term demand cases of FLAT, POP, and GDP) do not affect confining ourselves within the budget, and the third that actions beyond altering energy carriers are required.

7.3. Sensitivity Analysis for Cumulative Emissions

The cumulative emissions, which escalate to 1,500 Gt by 2100, are the results of an evolution that is based on a set of assumptions. In this study, a transition to direct use of electricity to the highest extent has been recommended, if not possible the use of electrolytic hydrogen instead needs to be favored as an energy carrier. However, how fast these transitions can be implemented is a question that can be answered only by the willingness of the participation of the involved parties (governments, institutions, and people) and by the availability of the financial sources that can be allocated for this purpose.

7.3.1. Sensitivity to the Pace of Implementations of the Measures

To analyze the effect of the pace of implementation of the recommendations, cumulative emissions from the RELAXED and AGGRESSIVE Scenarios have been evaluated. In essence, the former represents a slower transition to new energy carriers, whereas the latter a faster one in comparison to the basic REALISTIC Scenario.

Cumulative emissions in the RELAXED Scenario reach 1,727.11 Gt CO_2 by 2100. The growth of the emissions from 2020 to 2100 is presented in Figure 7-4.

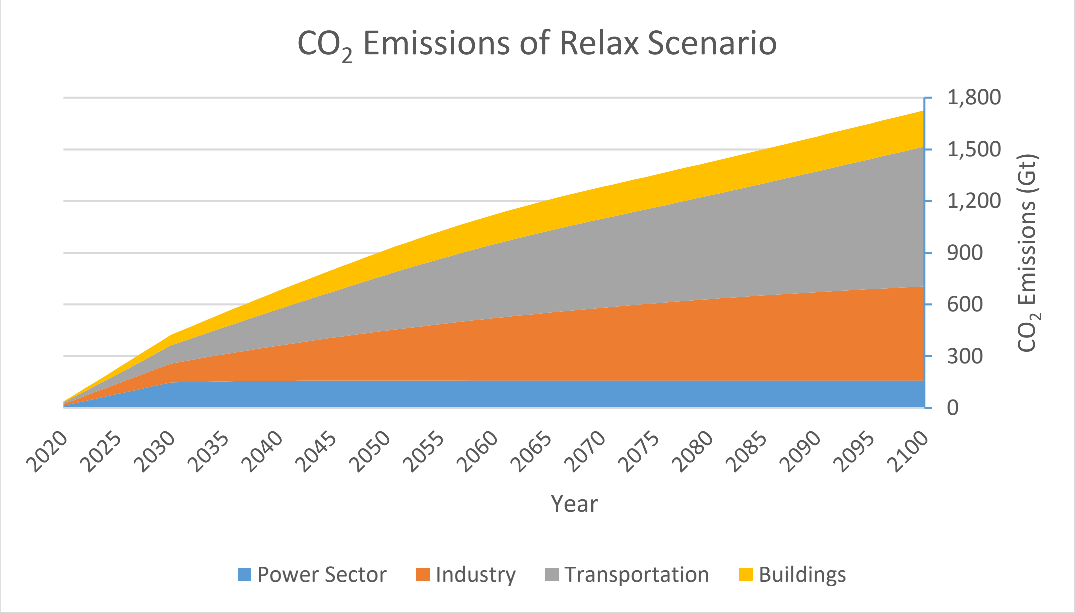

Figure 7-4 Cumulative CO_2 Emissions in Relax Scenario

Consulting the analysis performed by IPCC it has been concluded that with a 50% probability of global warming until 2100 (taken into consideration the emissions in 2018 and 2019) will be 2.16°C if a transition to new energy carriers occurs with the pace dictated by the RELAXED Scenario.

Cumulative emissions in the AGGRESSIVE Scenario reach 1,134.15 Gt CO_2 by 2100. The growth of the emissions from 2020 to 2100 is presented Figure 7-5. In the AGGRESSIVE Scenario, a transition to new energy carriers as early as possible has been modeled, neglecting almost all financial burdens. The transition's pace is determined by technical limits mostly. Under such aggressive measures, IPCC's study predicts that the global warming until 2100 (including the emissions that have already occurred in 2018 and 2019) will be 1.84°C with a 50% probability. Still, the 1.5°C target is beyond the reach of this study. Measures other than replacing fossil fuels and biomass with electricity and electrolytic hydrogen are required if humankind were to meet the latter upper limit.

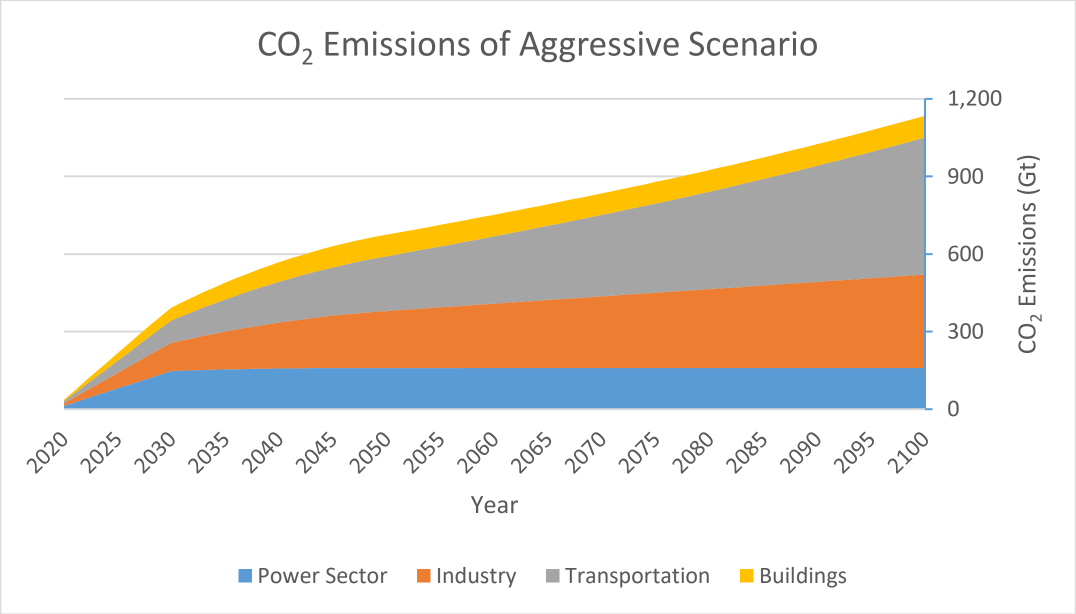

Figure 7-5 Cumulative CO_2 Emissions in Aggressive Scenario

7.3.2. Sensitivity to the Long-Term Demand

Cumulative emissions that have been evaluated and presented in the previous section are functions of the demand for industrial products, transportation activities, and daily needs (such as heating, cooling, or cooking) of humankind. In the REALISTIC, these demands have been taken from various sources in the literature: IEA, ITF, and World Steel Association. However, the forecasts are available only until 2050 or 2060, depending on the source. Making predictions beyond is subject to a large degree of uncertainty. However, assumptions should have been made beyond 2050 or 2060 to complete calculations until 2100. To this end, it has been assumed that:

- Industrial production will reach saturation by 2050, hence beyond 2050 will remain constant (which is referred to as FLAT evolution),
- Transportation activities beyond 2050 are proportional to GDP (which is referred to as GDP evolution and growth rates are obtained from OECD database),

- The buildings sector's needs are proportional to population beyond 2060 (which is referred to as POP evolution and growth rates are collected from the UN database).

It is apparent that cumulative emissions until 2100 strongly depend on these long-term forecasts for the demands. To analyze the sensitivity of the findings to the long-term projections on demands, results of the REALISTIC Scenario results have been compared to the FLAT, GDP, and POP cases, in which the long-term demands for all three sectors are appropriately determined.

Cumulative emissions resulting from the three long-term demand evolution models are presented in Figure 7-6 through Figure 7-8.

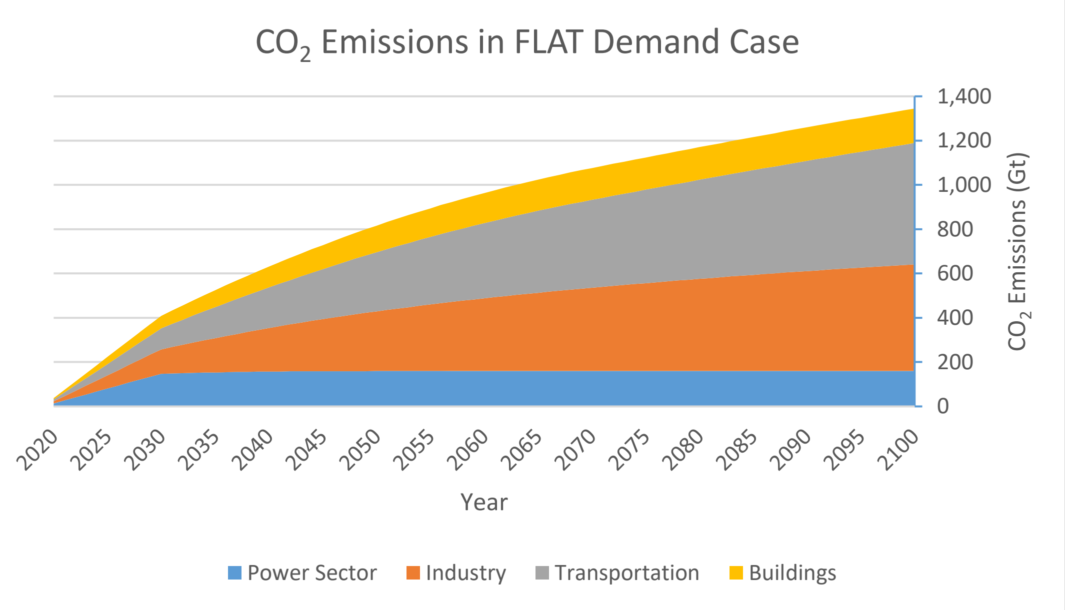

Figure 7-6 Cumulative CO_2 Emissions in FLAT Case

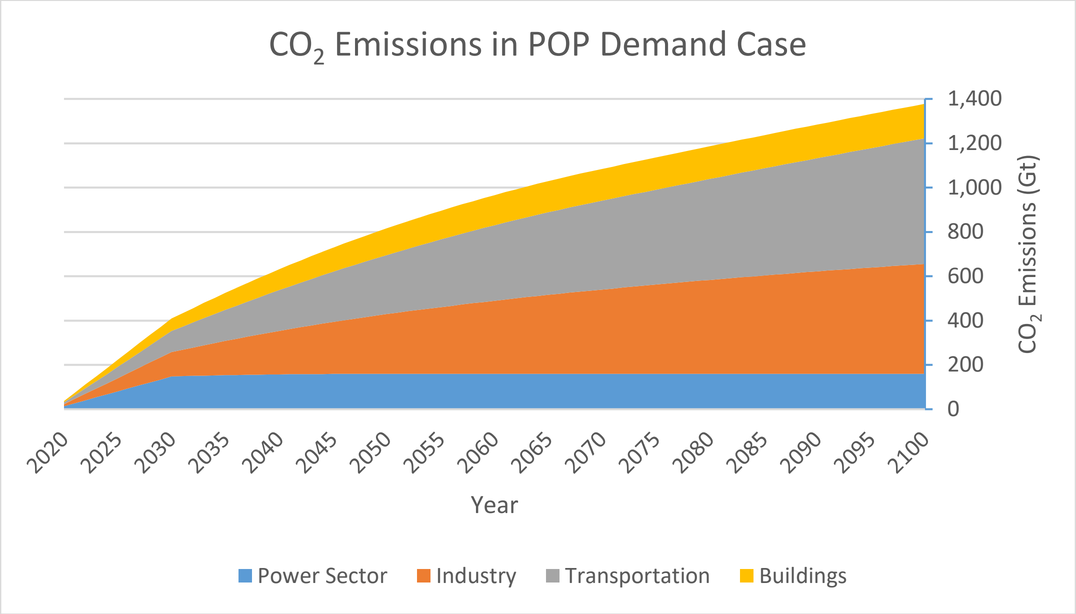

Figure 7-7 Cumulative CO_2 Emissions in POP Case

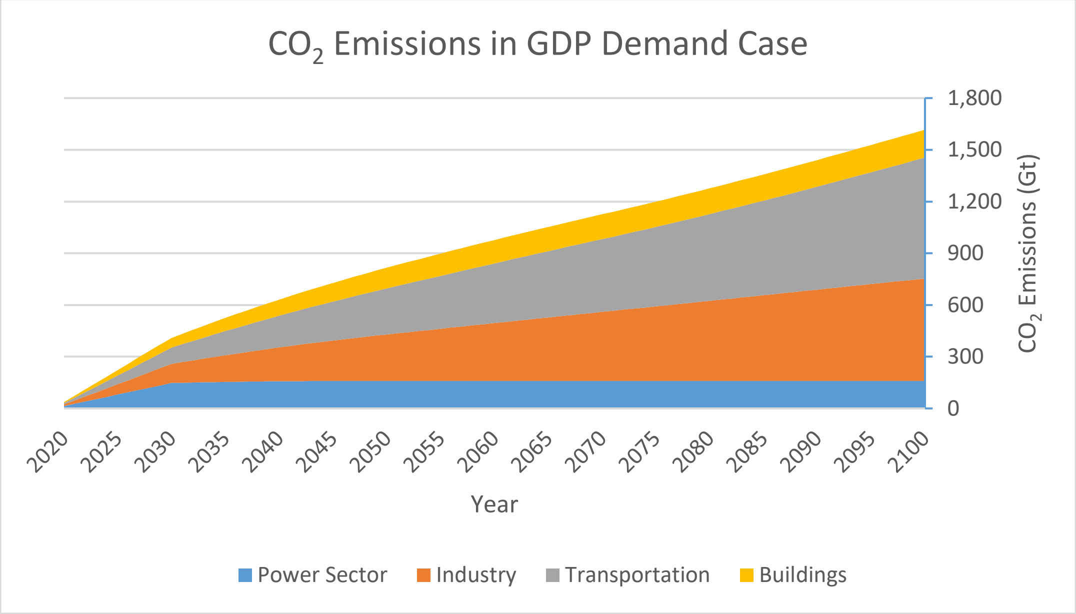

Figure 7-8 Cumulative CO_2 Emissions in GDP Case

The lowest emissions should and do occur in the FLAT demand case. Recalling that the industry sector's long-term demand has already been considered flat in the REALISTIC Scenario, the difference arises from the transportation and buildings sectors' long-term evolution. In the REALISTIC Scenario, the major contribution to cumulative emissions was coming from the transportation sector (especially from maritime and aviation modes), which was considered to be growing in parallel to GDP. Therefore, almost all further decreases from the REALISTIC Scenario are associated with the lowering of the transport activities beyond 2050. It has been calculated that cumulative emissions in the FLAT demand case still reach 1,344.76 Gt (to which 66 Gt emissions that have already occurred in 2018 and 2019 need to be added), corresponding to global warming of 1.95°C with a 50% probability according to IPCC's study.

The achievement of lowering the global warming estimate by 0.08°C (from 2.03°C to 1.95°C) underlines the importance of reducing transport activities in the future.

However, if the long-term demands are to increase, cumulative emissions would also grow. In the POP demand case, cumulative emissions remain fairly constant and are 1,378.09 Gt. This new value still produces 1.97°C of global warming with a 50% probability according to IPCC. Still, there has been an advantage over the REALISTIC Scenario, which again can be explained in the relatively slow growth in the transportation activities in the long term (POP vs. GDP).

Finally, when GDP demand growth has been applied to all three sectors, it has been observed that the cumulative emissions attain 1,617.14 Gt, which corresponds to 2.09°C global warming (with a 50% probability), according to IPCC: This 0.06°C increase from the REALISTIC Scenario is associated mostly with the growth in the industrial activities.

This last observation indicates the importance of keeping the materials demand of humanity under control. Less material demand implies less industrial activity, which in turn results in the lowering of the energy demand and hence CO_2 emissions in the industry sector.

7.4. Comparison with IEA's Net Zero by 2050

It would be fruitful to compare the findings of this study with the recently published Net Zero by 2050 report by IEA [41]. Clarification of the points where the present study deviates from the report are presented below.

As discussed in section 7.2.1, none of the three scenarios that have been developed cannot remain within the carbon budget (set for 2100 by IPCC) even by 2050. It is worth emphasizing that the IEA report attributes considerable importance to carbon capture technologies to maintain emissions within the preset limit. Both the IEA report and the present study agree that without the use of carbon capture technologies, humankind cannot keep the accumulation of CO_2 emissions in the atmosphere under control.

Long-term disposal technologies of CO_2 still are under development. They are far from being accepted as mature. Their energy consumptions and financial costs, which are expected to be paramount, are still undetermined. However, it becomes clear that introducing carbon-free or carbon-neutral fuels is not sufficient to keep emissions within the carbon budget, even by 2050. Therefore, humankind needs to develop technologies to dispose of atmospheric CO_2 for a long period (to which, geological disposal is an example).

In all scenarios developed in this study (REALISTIC, RELAXED, and AGGRESSIVE), emissions from aviation and marine transport modes are largely unresolved. The main reason for the forecasted ongoing emissions from these two modes is the lack of an effective alternative energy carrier to the fossil fuels heavily use in the sector. In the IEA report, several strategies are proposed to lower the emissions from the two transport modes.

One suggestion in the IEA report is to employ biofuels as energy carriers in aviation and marine modes. Biofuels are not non-CO_2 emitting fuels, but rather considered as carbon neutral fuels. Their manufacturing involves the capture of CO_2 from the atmosphere, through biological entities. The fundamental question in biofuel production, which is beyond the scope of this study, is sustainability. IEA report assumes that sustainability can be achieved, such that there will be no (or minimal) impact on the agricultural activities of humankind.

In addition to biofuels, synthetic fuels are also proposed in the IEA report. Synthetic fuels with similar physical and chemical characteristics to conventional fossil fuel derived liquid hydrocarbons are in one category. Such fuels are ideal for aviation and can readily be used in marine applications. The manufacturing of these fuels recalls carbon capture, as in the case of biofuels. It will be the industrial facilities producing synthetic fuels that will capture the CO_2 from the atmosphere (or from an industrial facility, before its release to the environment), rather than biological entities. As in the case of biofuels, technologies are not mature and the commercial feasibility of such units is a big unknown. Synthetic fuels different from the ones similar to conventional hydrocarbons are also considered in the report. In marine transportation, where fuel storage difficulties can be dealt with, hydrogen and ammonia are recommended as energy carriers. As discussed in this study, the production of the latter from electrolytic hydrogen is extremely energy inefficient. Even the use of electrolytic hydrogen is very inefficient. Energy efficiency becomes acceptable when hydrogen (used either directly or in ammonia production) is produced from natural gas. In such a case, however, the synthetic fuel industry needs to recover the generated CO_2. This recalls the use of carbon capture technologies that are yet to be matured and need to be shown economically viable.

It is worth underlining that the transport activities adopted in this study and the IEA report differ. Marine transportation figures are slightly larger in the IEA report when compared to the present study, in which data are collected from ITF as shown in Table 7-1. Despite the larger activities in marine transportation, emissions are lower in the IEA report, namely because of the more intense use of synthetic fuels and biofuels in the sector. IEA envisions that in 2050, 46% of the energy demand in marine propulsion will be supplied by ammonia (a synthetic fuel), 17% by hydrogen (mostly synthetic fuel, as is produced from natural gas), and 21% sustainable biofuels. In scenarios developed in the study, carbon capture technologies were excluded; hence, there were no contributions from synthetic fuels and biofuels. In the REALISTIC Scenario, it has been targeted that 15% of the energy requirement in marine propulsion will be delivered by electrolytic hydrogen (in terms of hydrogen use, both studies coincide, however, production techniques differ) and 5% by direct electricity (to which, IEA associate minor importance as well). Increasing marine transportation is a reasonable strategy; after all, it represents the most energy efficient transportation mode. If sustainable biofuels and competitive synthetic fuels can be produced, it is advisable to enhance marine transportation.

Table 7-1 Marine Freight Activity Comparison

MARINE FREIGHT ACTIVITIES (billion t-km/yr)		
Year	REALISTIC Scenario	IEA-Net Zero by 2050
2030	120,983	155,621
2040	194,825	209,905
2050	268,667	291,032

In the case of aviation, the situation is somewhat different. Passenger activity figures in the report are inferior to those adopted in this study, as presented in Table 7-2. The discrepancy cannot be attributed to the long-term (beyond 2050) forecasts, which are based on the GDP growth, because it occurs before 2050. IEA report assumed that a major behavioral change would occur in societies, so that aviation transport activities will remain far below the predictions adopted here. In this study, any strategy that recalls such behavioral changes have been excluded, therefore, there exist considerable differences between the two forecasts.

Table 7-2 Aviation Passenger Transport Activity Comparison

AVIATION PASSENGER TRANSPORT ACTIVITIES (billion p-km/yr)		
Year	REALISTIC Scenario	IEA-Net Zero by 2050
2030	13,532	10,250
2040	17,754	12,060
2050	21,976	15,650

Not only that activity in aviation passenger transport has been reduced (achieved mostly by behavioral changes) by IEA, but also major energy contributions come from synthetic fuels and biofuels. IEA presumes that by 2050, 45% of the aviation fuel will be supplied from sustainable biofuels and 33% by synthetic fuels (in the form of liquid hydrocarbons). Whereas, in the REALISTIC Scenario both fuel types have been excluded from consideration on the ground that sustainability and technological maturity are not guaranteed. Hence, a 100% fossil fuel in aviation has been assumed, even in the future.

Important deviations from the IEA report exist in the industry sector analyses in this study. IEA report assumed a decrease in the future material demand. Such decreases in material demand, whether associated with the advances in material performance or with behavioral changes of humankind to consume fewer goods, are not considered in this study. Demand forecasts for goods and services are taken to be given, then efforts are towards reducing emissions while meeting the preset demands. A comparison of demands for selected industrial goods covered in this study and the IEA report is given in Table 7-3.

Table 7-3 Industrial Production Rate Comparison

INDUSTRIAL PRODUCT DEMANDS (Mt/yr)						
	Steel		Cement		Primary Chemicals	
Year	REALISTIC	IEA*	REALISTIC	IEA*	REALISTIC	IEA*
2030	2,097	1,937	4,377	4,258	628	641
2040	2,298	1,958	4,539	4,129	726	686
2050	2,500	1,987	4,700	4,032	825	688

* IEA- Net Zero by 2050

7.5. Discussion of the Results

An assessment of the success of the mitigation actions proposed in this study for reducing CO_2 emissions needs to performed. It has been aimed at making a maximum use of electricity as the energy carrier. In cases where the direct use of electricity is not practical, such as in high temperature requiring sub-sectors of the industry, electrolytic hydrogen would be the second alternative energy carrier. To maintain CO_2 emissions within an acceptable limit, it has been suggested to employ renewables and nuclear for the generation of electricity that would be used either directly or in the electrolysis of the hydrogen.

Technical and financial constraints set an upper limit for the pace of the transition to new energy carriers that will replace the CO_2 emitting fossil fuels and biomass. Targets have been defined for the corresponding transition, which represent a strong willingness for humankind to reduce future CO_2 emissions, with minimum resistance presented by governments, institutions, and people to such a change. This scenario is referred to as the REALISTIC. If the resistance to such a transition is not negligible, then targets have been modified to develop the RELAXED Scenario, in which a slower pace for the transition has been predicted. Assuming that humankind has acquired enough awareness about global warming, the financial aspect of the transition may be left out of consideration and more stringent targets may be set, which determine the AGGRESSIVE Scenario.

Cumulative emissions (from 2020 to 2100) resulting from all three scenarios, when combined with the emissions in 2018 and 2019, which reach 66 Gt, can be expressed in the following compact form: According to the study by IPCC, with a 50% probability, AGGRESSIVE Scenario implies global warming of 1.84°C, REALISTIC 2.03°C, and RELAXED 2.16°C. None of the scenarios can maintain the emissions below the necessary limit to confine the global warming within 1.5°C, as recommended by IPCC.

7.5.1. Insufficiency of the Proposed Mitigation Efforts

The conclusion that can be drawn from these results is that actions to eliminate fossil fuels and biomass alone would not suffice to attain the extremely stringent emission limits set by IPCC. Therefore, additional measures and actions will be required, if, as humankind, we were to take global warming under control. It is important to assess the current condition and feasibility of some such actions.

Replacement of fossil fuels and biomass with direct electricity and electrolytic hydrogen as discussed in this study requires the implementation of an enormous electricity generation capacity. Renewables alone cannot meet the demand. Even with a 50% penetration target set for renewables for 2100 results in land use, that is almost three times the surface area of Turkey. The use of renewables necessitates the availability of other power plants that can supply dispatchable electricity. If nuclear fission were to be employed in meeting the dispatchable power demand, neither the construction capability for new nuclear plants (which climb up to 11,000 units by 2100) exists, nor the world uranium resources would be sufficient.

In addition to the extensive use of land for the construction of renewable and nuclear power plants, large quantities of construction materials will be required. Such a heavy investment in the power sector will further increase the material requirement (of steel and cement primarily) from the industry sector, which will result in additional emissions.

7.5.2. Reducing the Demand in All Sectors

As demonstrated by the FLAT demand long-term scenario, it is necessary to reduce transport activities to the highest extent, to achieve major savings in CO_2 emissions. The majority of the emissions in the developed scenarios result from transport activities in the marine and aviation modes. Both modes rely heavily on hydrocarbons and no viable alternative energy carrier, for which a mature technology exists, has been identified.

One possible solution to reduce activities in marine and aviation modes would be to transfer these activities to the rail mode, which can make use of electricity readily. An even more efficient method would be to reduce the need for transportation activities. Optimization of the distribution of production sites can also prove useful by reducing freight transport. Increasing awareness about the high CO_2 emissions from aviation through better education may reduce “unnecessary” air transportation demand. Developments in telecommunication also help in reducing the demand for various transportation, which can be avoided.

In addition to the transportation sector, an important contribution to cumulative emissions comes from the process emissions in the industry sector. Production of cement has the highest share in them. Process emissions, like the ones in cement production, cannot be reduced by altering the energy carrier. Therefore, humankind needs either to reduce the cement requirements or develop production technologies with less process emissions. Cement-free construction techniques, which rely on the use of alternative materials, and reduced cement use by improving the performance of concrete with equal cement content should be further developed and placed in action.

Efforts along developing technologies for cement production with less process emissions include the use of pozzolanic materials to replace the clinker in cement production. There are numerous difficulties associated with this substitution; availability and conformance to local regulations are among them.

Steel being an ideal material for recycling, in the iron and steel industry, importance should be attributed to the enhancement of recycling. Such actions will greatly contribute to lowering the energy consumption and hence, the emission of CO_2. Improving the performance of produced steel by altering manufacturing techniques will also lower the demand for steel, which translates into lower emissions.

In the case of the buildings sector, the adoption of building codes to achieve better insulation of buildings, as well as continuous energy improvements in appliances will lower the energy demand. Humankind should never give up on its quest for higher efficiency.

7.5.3. Alternative Energy Carriers

Electricity is promoted as the preferred energy carrier to replace CO_2 emitting fuels. However, in this study, it has been determined that such a transition will require a paramount electricity generating capacity that is beyond the reach of renewables and nuclear. Therefore, humankind may need to recall alternative energy carriers. Two such carriers are concentrated solar and biofuels.

Concentrated solar power can prove to be an ideal alternative to electrolytic hydrogen and electricity, where high temperature thermal energy is required. In its non-concentrated form, solar energy is already being used extensively in the buildings sector, for water heating. Demonstrations are performed for the feasibility of solar power, where much higher temperatures are required. An important example of such an application is the SOLPART project [72], where concentrated solar energy is used in industrial calcination processes. The use of concentrated solar energy will have a much higher process energy efficiency, as no conversion to electricity is involved.

Nuclear energy can be regarded as another energy carrier. Although there are recommendations for direct use of the heat generated nuclear plants in high temperature applications, the technologies are not mature. On the other hand, nuclear energy proved very successful in marine propulsion. This success is limited to military applications, however. Although there were several trials of its use in commercial applications, the only (commercially) successful examples are the Russian icebreakers. Public acceptance was the prime obstacle in the widespread of nuclear propulsion. If the issue can be resolved, nuclear energy will represent a good alternative for an energy carrier in marine transportation, where major emission reductions have not been achieved in this study.

Another energy carrier with little or no overall CO_2 emissions is biofuels. Biofuels are typically carbon-based fuels produced by biological entities. Their combustion will produce CO_2 emissions comparable to those of fossil fuels, yet their production consumes an (almost)equal amount of CO_2. If humankind can achieve sustainable production of biofuels, their use will help us limit CO_2 emissions. Biofuels produced under sustainable conditions can be regarded as ideal future fuels for maritime and aviation transports. However, the assessment of the sustainability and the land (or ocean/sea for algae) requirement for such production of biofuels are beyond the scope of this study. The development of biofuels is also the subject of the following section, where carbon capture technologies have been investigated.

7.5.4. Carbon Capture Technologies

Carbon capture technologies have been ruled out in this study based on their lack of maturity. Production of biofuels may be presented as a counter-argument. Bioethanol primarily is in use for almost half a century. Bio-diesel has also been demonstrated to be an effective fuel, for diesel engines, as well as many vegetable oils. The fundamental issue related to biofuels is sustainability, i.e., whether we can sustain agriculture accordingly. Land used for biofuel production will compete with the land required for the food related agriculture of humankind. Algae are also being proposed for biofuel production, in which case similar assessment need to be performed for the sea/ocean allocation to their cultivation that may compete with fishing and the potential food production in sea/ocean.

One other example of a mature carbon capture application is urea production in the fertilizer industry. It is a common practice that CO_2 resulting from syngas manufacturing is captured by the produced ammonia to form urea, which is used as a fertilizer. Such technology exists, yet, CO_2 trapping in urea does not constitute its final disposal. Urea used as a fertilizer releases its CO_2 content in a matter of months to the atmosphere. Therefore, methods that lead to long-term disposal of CO_2 are in need, which are not yet mature.

One method for long-term disposal is the curing of concrete with CO_2 rather than water, as currently being done [52]. The technology has not yet matured, but is promising and gives a good example of how we can dispose of the CO_2 that we inevitably produce.

Further attention should be attributed to carbon capture technologies, as it seems rather difficult to completely eliminate the anthropogenic CO_2 emissions. It seems that humankind should learn how to live with its own emissions. Successful implementation of carbon capture technologies will allow us to extend the use of fossil fuels, thus reduce the load on renewables and nuclear, as well.

7.6. Recommendations for Future Works

It needs to be emphasized that the generation mix that has been considered, is based on studies with predetermined penetration levels of renewables. The model can be further improved to include grid modeling to suit the proposed generation mix, not restricted to wind, solar PV, and NPPs but that includes other sources. A tailored design of the electric grid would provide a better simulation of the generation capacity. Similarly, hydrogen buffering that has been employed to deepen the penetration of renewables requires detailed analysis. The use of noble metals as electrodes and their limited availability is one problem to be solved. The feasibility and potential of the buffering need to be assessed, which requires essential contributions from other engineering disciplines. Alternative energy storage options should be assessed.

In summary, mitigation of CO_2 emissions cannot be limited to the use of alternate energy carriers, but serious measures need to be taken to reduce the demand for materials, travel, and goods by humankind, to achieve sustainable biofuel production, and to develop commercially feasible carbon capture technologies with long-term disposal of CO_2. Additional energy carriers, such as concentrated solar, should also be included in further analyses.

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WORK EXPERIENCE

Year	Place	Enrollment
2020-2020	Aydem Holding	Director of Mining and Coal Supply
2019-2019	Mitsubishi Heavy Industries.	General Manager
2016-2019	Mitsubishi Heavy Industries.	Director of Sinop Nuclear Power Plant Project
2014-2016	Mitsubishi Heavy Industries.	Senior Manager
2013-2014	Parsons Brinckerhoff	Project Manager
2012-2013	Bilgin Enerji Holding	Contract Manager
2010-2012	GAMA Power Sytems	Business Development Manager
2008-2010	GAMA Power Systems	Proposal Engineer
2008-2009	GAMA Power Systems	Procurement Engineer
2007-2008	İşbir Holding	
2001-2008	Aktel Yapı Sanayi	Proposal Engineer

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