CHALMERS
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Key Performance Indicators to Characterize the Evolution of the Future Electricity System

A study with a Sustainable Development perspective

Master's thesis in Sustainable Energy Systems

DAVID ELOFSSON & CASSANDRA HELLMAN

Department of Energy and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017

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Abstract

The electricity system is facing extensive challenges in the coming years transitioning towards a low-carbon economy by 2050. Understanding the characteristics of this transition can play a key part in facilitating its implementation. This thesis investigates using Key Performance Indicators (KPIs) to characterize the evolving electricity system and to visualize the system's progress towards sustainability over time, a topic which is identified as a gap in the current literature. Three distinct policy scenarios for 2050 are analyzed using a set of eight KPIs developed in this study. These KPIs are conceived by a process of brainstorming and extraction through selection criteria. Furthermore, a method for visualizing sustainable development is conceived by aggregating KPIs into an index. This index represents multiple aspects of sustainable development and illustrates scenario progress towards sustainability over time. In addition, creating a matrix-representation of relative scenario acceptance provides a tool indicating challenges in policy implementation. The findings suggest that the KPIs and visualization method developed in this study can serve as a tool to understand and visualize the development of the electricity system as described by a techno-economic model. While individual KPIs gives limited representation of sustainability, the aggregation of several KPIs into one index contributes with a multifaceted perspective. Presented methods for visualizing sustainability do not provide a holistic representation of sustainable development but contributes to the research field with expedient tools.

Keywords: Key Performance Indicators, indicators, energy systems modelling, sustainable development.

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Abbreviations

KPI	Key Performance Indicator
CM	Climate Market
GP	Green Policy
RP	Regional Policy
EC	European Commission
RES	Renewable Energy Source
GDP	Gross Domestic Product
CCS	Carbon Capture and Storage
GHG	Greenhouse gas

1 Introduction

The European energy system is facing great challenges and changes. Ambitious targets are set with 2020 energy and climate package as described in EC (2009a), EC (2009b), and EC (2009c) and in the 2030 climate and energy framework (EC, 2012b). Targets are aimed at reducing emissions, increasing renewable generation and improving energy efficiency. Also, the target for a low-carbon economy by 2050 will require a major transformation of the energy system (EC, 2012a). To meet the targets for energy and climate policies that EU has decided for towards 2050 the energy system has to transform in coherence with reduced emissions, increased share of renewable energy and reduced energy demand or energy efficiency measures. The energy system of today is still heavily reliant on fossil fuels and business as usual will be impossible to maintain in order to reach the set targets. Therefore, the future energy system must contain a significant share of low-carbon energy sources, as elaborated by EC (2012a), of which a multitude exists to choose from. National policies and preconditions will influence the direction of development implying that individual countries will have different ways of reaching the same targets.

As elaborated by Johnsson et al. (2014), the transformation of the energy system could be achieved by multiple scenarios, also referred to as pathways, but there are difficulties in foreseeing the most favorable path of change. The pathways to the future energy system of different European countries are distinguished by different policies and technological focuses. As Díaz et al. (2017) and Polatidis et al. (2007) indicate, difficulties in foreseeing how energy systems will transform can stem from the perspectives of the different stakeholders in society and their perception of a favorable path of change. The stakeholders can also have differing views on what uncertainties and considerations one should observe when transforming the energy system, i.e. to regard economic, environmental or social factors. These three aspects are commonly known as the three dimensions of sustainable development and can be used deliberately to discuss and reflect upon the degree of sustainability in a certain proposed path of development.

To assess these issues this thesis was designed based on a set of research questions that aims at characterizing development and sustainability in the future electricity system in Europe. The aim and research questions are presented in more detail below as well as a literature review to identify and present the literature gap that is considered in this study.

1.1 Aim and Research Questions

The aim of this thesis is to develop a method of visualization and characterization by using Key Performance Indicators (KPIs) that will facilitate understanding of the sustainable development and the consequences arising in the evolution of the European and Nordic electricity systems. By visualizing and characterizing the consequences of different development scenarios, policy-makers and stakeholders will be allowed an explicit view and in-depth understanding of the paths to the future electricity system.

A set of KPIs, also referred to as indicators, will be developed that will allow explicit characterization and visualization of pathways for the future electricity system from 2015 to 2050. The KPIs will be used to study and evaluate model results by being applied to data output from Chalmers' Electricity Investment model ELIN described by Odenberger et al. (2010) in regard to three pathway scenarios that are presented in the Pathways Programme (Johnsson et al., 2014). The KPIs will assess sustainable development by covering social, economic and environmental aspects of the distinctive scenarios. The intention is that a KPI-based analysis will provide a more coherent view of the scenarios, by adding transparency and a better understanding of their implications. Also, the implication for sustainable development will be assessed by developing a method for visualizing sustainability in the future pathways.

Concretely, this study will identify and develop indicators that provide a clear comprehension of the pathways as well as a method to evaluate future sustainable development. This analysis will contain comparisons between Europe and the Nordics as well as for different European countries to identify and highlight significant characteristics of the future electricity systems. The following research questions are established to set the framework for this thesis and will be assessed in this work:

- Which KPIs can be used as an appropriate tool for evaluation and characterization of the different paths of evolution for the electricity system?

- Can selected KPIs visualize and characterize sustainable development in the future electricity system over time?

1.2 Literature Review and Gap

In order to describe the future development of energy systems, models are used to simulate the system development over time. To characterize and better understand certain aspects of this development, parts of the existing literature rely on indicators. In relation to sustainable development, indicators are used in a number of different contexts.

IAEA et al. (2005) outline a set of *energy indicators* related to sustainable development and their use therein. These indicators aims at capturing and portraying the characteristics and effects of energy use and production in society as well as representing relations and interactions between dimensions of sustainability in the context. This application typically involves tracking the progress of the indicators over time to measure development towards sustainability.

Stechow et al. (2016) use indicators to characterize fulfillment of energy-related sustainable development goals and sustainable energy objectives in the context of models describing climate change mitigation. Stechow et al. (2016) present indicators representing social, environmental and economic aspects based on model output from Integrated Assessment Models[1]. On the same topic, Gambhir et al. (2017) explore the feasibility in achieving long-term mitigation goals to limit global temperature change by analyzing model scenarios of different temperature changes in the year 2100. To accomplish this, the authors develop a set of indicators that allow systematic comparison of feasibility across the scenarios.

In the reviewed literature, several approaches to working with indicators, sustainability and energy systems are identified. The practice of aggregating single sustainability indicators into indices is described by multiple authors, e.g. Iddrisu et al. (2015), Ness et al. (2007), and Singh et al. (2012). The greater share of this literature concerns sustainability metrics in a wide sense. Few publications focuses distinctly on quantifying the progress towards sustainability in electricity systems, as proposed in this thesis. In line with the research questions posed in this thesis, this is identified as a potential gap to fill within the literature.

[1]Integrated Assement Models (IAM) denotes models in environmental science which are constituted by an inter-disciplinary representation of the world and are commonly used to analyze and assess climate change (Schneider, 1997).

2

Theory

This chapter presents the relevant theoretical background on the topics of sustainable development and KPIs in order to provide the reader with an adequate framework for understanding the rest of this work. Section 2.1 describes the definiton on sustainable development that is relevant to this thesis. In section 2.2 the fundamentals of KPIs are presented.

2.1 Sustainable Development

The concept of sustainable development is generally held to have been established by the Brundtland Commission (*World Commission on Environment and Development*). The commission concluded that "*Sustainable development is development that meets the needs of the present without compromising the ability of future generation to meet their own needs.*" as is outlined in Brundtland (1987, p. 41). In order to substantialize this wide concept and narrow in on what aspects must be considered to both *meet the needs of the present* while not *compromising the ability of future generations to meet their own needs*, a distinction consisting of three dimensions of sustainable development is common (Hedenus et al., 2016). The distinction makes out the three dimensions as: *social, environmental* and *economic.* These dimensions are held by the UN to be closely interconnected and mutually reinforcing (UN General Assembly, 2005). The differentiation is used by the EU to establish long-term goals for sustainability (Pallemaerts et al., 2006). Hedenus et al. (2016) lay out the following distinction of the three dimensions which is central in this work:

- The **social dimension** considers aspects such as social institutions and structures that facilitate human prosperity.
- The **environmental dimension** emphasizes aspects that concerns sustaining ecological systems that serve humanity with productive and assimilative capacity. This involves services and systems such as clean water and natural processes absorbing CO_2.
- The **economic dimension** considers economic aspects and is closely linked to the management of resources in terms of both natural resources and monetary capital.

2.2 Key Performance Indicators

As elaborated by Parmenter (2015), the term Key Performance Indicator can denote a wide range of measures related to the performance or the results of a business (or any subgroup thereof) and the term "key" emphasizes the importance of that specific measure. This nomenclature is common in business management in particular, where KPIs are used to track or anticipate strategic development within an organization (Reh, 2017).

In this thesis the term KPI is used in the denotation of "indicator", which is commonly found in the energy policy literature. OECD (1993) define indicators as parameters, or the values thereof, that represent or describe phenomena larger and more significant than the individual parameter. Furthermore, OECD (1993) elaborate that indicators should serve the purpose of streamlining the communication of results to the user. As both Latawiec et al. (2015) and OECD (1993) point out, indicators should together be able to provide a wide depiction of the situation using only a limited number of indicators to prevent cluttering.

According to Patlitzianas et al. (2008) and Vera et al. (2005), wisely applied indicators can be important instruments for understanding and communicating the effects of policies or strategic decisions to the general public or to policy-makers. As Vera et al. (2005) suggest, indicators can bring clarity on factors relating to economics, energy, environment and social well-being as well as to provide an indication on how these factors may be directed and improved. Latawiec et al. (2015) also point out that indicators can be valuable as a proxies for other correlated factors which are not captured directly by the indicator itself. As IAEA et al. (2005) exemplify, an indication on deforestation related to energy use may be deduced from data on non-commerical fuel use and the total rate of deforestation.

3
Methods

The purpose of this chapter is to provide the reader with adequate insights into the methodological procedure and choices made during this work. An essential part of this work was centered around ELIN which provided the model results that constituted the main data input to the developed KPIs. This model and its associated pathway scenarios are described in section 3.1. The main part of this work's method was focused on developing and selecting a set of KPIs adequate to the purpose of answering the outlined research questions. The criteria and procedure of how the KPIs were selected are presented in detail in section 3.2 where also the KPIs considered in this work are presented in detail. To provide an answer to the second research question, regarding visualization of sustainable development using the selected KPIs, two additional tools were developed. These two tools, Pathway Acceptance and the Sustainability Index, are presented in section 3.3.

3.1 Electricity System Model

This work utilized model results from the techno-economic investment model ELIN, described in Odenberger et al. (2010). This model included the electricity supply system with a yearly resolution from 2010 until 2050. However, in this thesis the period between 2015 and 2050 was regarded due to recency and relevance. Regions represented were EU27 plus Norway and Switzerland which further on are referred to as the European region or simply Europe. The Nordics are defined as the Nordic region excluding Iceland. The output consisted of data that described e.g. fuel use, electricity generation and installed capacity. Model output data applied in this work can be found in Appendix B. It is possible to examine output data on a national as well as on a European level. The model provided output based on three pathways scenarios that are described below.

Meeting the energy and climate policy targets set by EU towards year 2050 will demand that the European electricity system rapidly transforms to conform with the stringent targets. Furthermore, the road to reach these target is paved with uncertainty but using predetermined scenarios can be a way of contextualizing these uncertainties. This work was based on policy scenarios that were developed and refined within the European Energy Pathways programme and were outlined in Johnsson et al. (2014). Four scenarios were presented: *Reference scenario, Climate Market, Regional Policy* and *Green Policy.* The Reference scenario was not regarded in this work since this scenario only meets the targets for the 2020 energy and climate package. This work focused on Climate Market, Regional Policy and Green Policy, which are three scenarios with distinct differences. To capture diversification in the future development the scenarios are influenced by different parameters and constraints in policies and energy technologies, among other assumptions that influence the output. A short summary of the most distinct features is given in Figure 3.1 and a brief description for each of the three scenarios follows below.

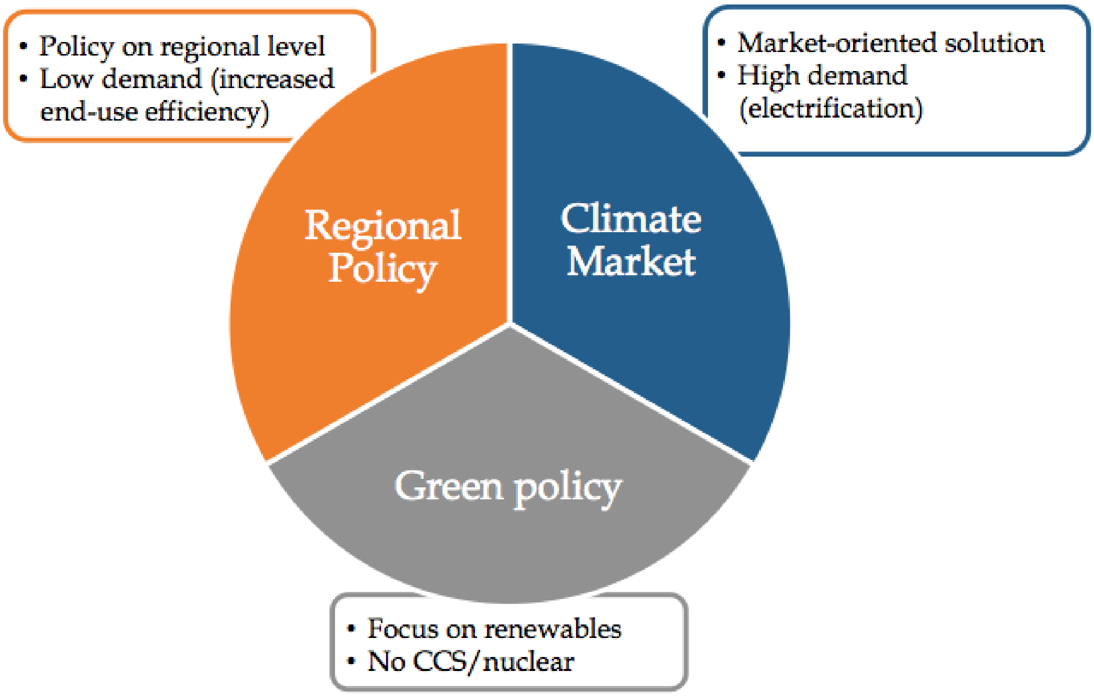


Figure 3.1: *The three scenarios from the Pathways programme used in this work*

Climate Market (CM)

Policy intervention after 2020 dictates a 93% CO_2 emission reduction by 2050 compared to 1990 levels. This target is implemented as a common cap to be met at European level. In addition, this scenario is assumed to experience an increase in electricity demand due to an expected electrification of other sectors (e.g electrification of transportation). In Figure 3.2 it can be observed how the Climate Market scenario has a considerably higher electricity demand compared to the other two scenarios.

Regional Policy (RP)

National targets on renewable electricity generation are applied as well as a common European CO_2 emission constraint. The target on renewables is approximately 65% of total electricity generation on an aggregated European level and the CO_2 emission constraint prescribe a 99% emission reduction by 2050 compared to 1990 levels. Due to assumed energy efficiency measures, by the end user, the demand profile is limited as illustrated in Figure 3.2.

Green Policy (GP)
Regulated by a target of 95% renewable energy sources (RES) in 2050 and a stringent CO_2 emissions target which causes nuclear to be phased out while renewables become more important. In addition a regulation on energy technology limits the entrance of Carbon Capture and Storage (CCS) to the market. It is assumed that the electricity demand will increase, however not as drastically as in the CM scenario, which can be observed in Figure 3.2.

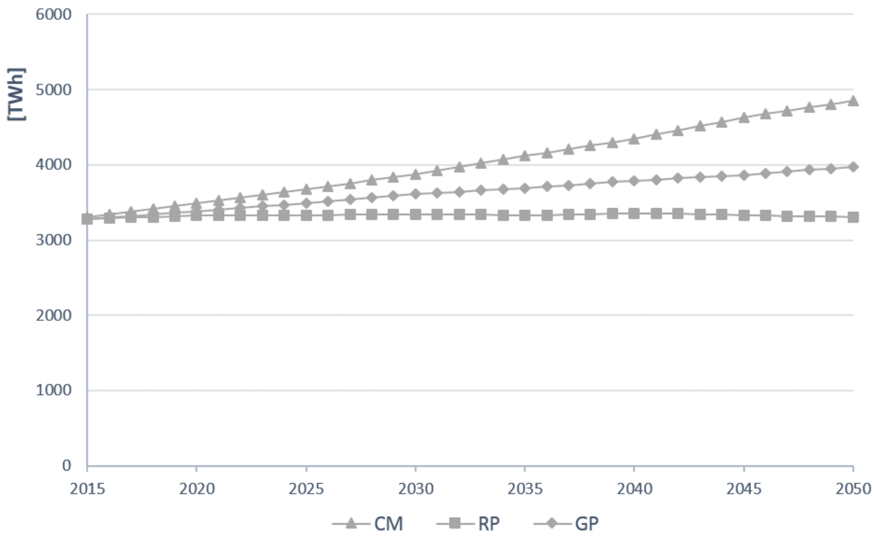


Figure 3.2: *European electricity demand for the three pathway scenarios as given by ELIN (see Appendix B)*

3.2 Key Performance Indicators

This section describes the indicators developed and applied in this work. The purpose of these indicators is to provide a tool to evaluate and characterize the pathways and to investigate the aspect of sustainability in the future electricity system.

The criteria for selecting KPIs were based on the purpose of this work, to characterize future pathways and sustainable development. This emphasized the importance of indicators able to visualize change over time and to provide a comprehensive view of the future electricity system. It was also important that the indicators could characterize the pathways scenarios in order to identify differences between them and how they were distinguished. This also facilitated discussion and analysis concerning how the outcome is affected by the pathway scenarios pre-set framework. Another central criterion was the emphasis on sustainable development and how indicators could characterize it focusing on the three dimensions: social, economic and environmental. Each indicator was evaluated from a sustainability perspective to assess their connection to sustainable development and what dimension the indicator can represent. It was also important that the indicators were able to provide information on whether the trend is positive or negative with regard to sustainable development.

The initial stage of finding appropriate KPIs was based on a brainstorming process which generated a gross-list of potential indicators, given in Appendix A. Reflections from Latawiec et al. (2015) and OECD (1993) regarding the importance of limiting the number of indicators and while disclosing relevant information with each indicator established the target of reducing the gross list to a limited number of selected indicators.

Table 3.1: *Indicators selected in this work*

Indicators	
Indicator	Unit
Electric Power Production Intensity	[MWh_{el}/MEUR]
Electric Power Consumption Intensity	[kWh_{el}/capita]
Average Capacity Investment Costs	[MEUR/GW_{new}]
Capacity Utilization	*Ratio*
Share of RES	[TWh_{RES}/TWh_{total}]
CO_2 Emissions	[Mton]
Import Dependency	[%]
Unit price of electricity as share of GDP per capita	[%]

The gross-list that contained up to 20 indicators was narrowed down to the final version of eight indicators in regard to the criteria described above. In Table 3.1 the set of selected indicators for this work is presented. The following section will in detail explain the build-up of each individual indicator and how it satisfies these criteria. Some indicators rely on external sources describing GDP and population projections until 2050. The relevant figures pertaining to these two parameters are presented in Appendix C.

3.2.1 Electric Power Production Intensity

Electric power production intensity is defined as the generated electricity over Gross Domestic Product [MWh_{el}/MEUR]. Generated electricity includes surplus or deficit relative to domestic demand since the total volume is closely connected to the economic activity in a country. The indicator attempts to describe the correlation between generated electricity and economic growth and is similar to the *Energy use per unit of GDP*-indicator presented in IAEA et al. (2005). Energy and electricity has been a principal requirement for economic growth which has resulted in severe consequences for the environment. The relevance of this indicator to sustainable development is illustrating the decoupling of economic growth with energy and resource use (IAEA et al., 2005). New technologies and energy efficiency measures provide the possibility for decoupling and the indicator assists the analysis to determine if and when this decoupling can occur and under what circumstances.

Since this work only accommodates the electricity system the analysis is limited to electric intensity while a total primary energy supply (TPES) intensity would have provided a more comprehensive view. Covering only the electricity system can result in substitutions between sectors that will not be accounted for, even though they can directly affect the results.

3.2.2 Electric Power Consumption Intensity

Electric power consumption intensity is expressed as annual electricity demand per capita [MWh_{el}/capita]. This indicator describes the relationship between electricity demand and the size of the population and reflects energy-use patterns and the energy intensity of a society which is relevant for sustainable development (IAEA et al., 2005). The indicator includes domestic consumption only and not generation surplus/deficit since consumption is of greater relevance in this context. The results can differ due to individual preconditions for member states. The indicator is important for illustrating these differences between variously developed countries. Because of the limited access to cheap energy in less developed countries and the level of development display dissimilarities in energy-use patterns (IAEA et al., 2005).

3.2.3 Average Capacity Investment Costs

This indicator is defined as annual total investment costs [MEUR/yr] divided by the annual total capacity increment [GW_{new}/yr]. This indicator expresses the yearly average cost of the capacity increment, where all technologies are included. The indicator uses a three year moving average to smoothen data fluctuations. From a sustainability point of view this indicator encompasses economic aspects by indicating how large capital investments are required for each unit of new installed electricity generation capacity. This indicator provides characteristics of capital costs for each scenario which can be important for signalling economic implications of the pathways' build-up in capacity. The average capacity investment costs are calculated as follows:

$$\frac{\text{Annual Total Investment Cost [MEUR/yr]}}{\text{Annual Total Capacity Increment [GW}_{\text{new}}\text{/yr]}}$$

3.2.4 Capacity Utilization

For the purpose of this thesis, capacity utilization is defined as the ratio of total annual generation of all technologies in the considered system to the theoretical maximum generation which could have been achieved during one year using all of the installed capacity in the system. This definition draws on the description of *capacity factor* as outlined by NRC (2017). Results are presented in terms of a CUF (Capacity Utilization Factor) which is defined as the fraction of full load hours (maximum 100% load at 8760 hours per year) that the technologies are utilized. The ratio is a number between 0 and 1 and represents how large share of the theoretical maximum of generation (operation 24 h/day for 365 days/yr) that all accumulated technologies produce. It is calculated as below with i representing each technology:

$$\frac{\sum_i \text{(Annual Electricity Generation}_\text{i}\text{ [TWh])}}{\sum_i \text{(Rated Capacity}_\text{i}\text{ [GW])} \times \text{(24 hours/day)} \times \text{(365 days)}}$$

From a sustainability point of view this measure is relevant for economic purposes as it gives a hint on how efficiently existing resources (in terms of electricity generation units) are utilized. When the composition of an electricity system changes from traditional fossil plants to variable renewable energy sources such as wind and solar, the capacity factor of the fossil plants may decline (Randall, 2015) thus the overall system capacity utilization may change.

3.2.5 Share of RES

The share of RES[1] is expressed as RES electricity generation over total system electricity generation. This indicator draws on the *renewable energy share in energy and electricity*-indicator defined in IAEA et al. (2005). In a sustainability context this indicator is relevant in order to capture aspects of the development related to reduced environmental impact and air pollution, as well as increased security and diversity in generation that arises when a larger share of renewable generation is used (IAEA et al., 2005). As discussed in IAEA et al. (2005) this indicator also reflects international ambitions of increased shares of renewable energy.

[1]Technologies included in RES: hydro, wind, solar, bio & waste, tidal and wave power.

3.2.6 CO_2 Emissions

CO_2 emissions are expressed in Mton_{CO2} and this indicator is based on model output from ELIN. Emissions will also be presented on a capita base in the results to facilitate country-wise comparisons, since large differences in population between member states and regions could distort the outcome. On the other hand, it can be relevant to examine CO_2 emissions in absolute or accumulated numbers over time since CO_2 that is released into the atmosphere remains for thousands of years, regardless country or region of origin (Hedenus et al., 2016).

Since all of the scenarios are somewhat guided by stringent CO_2 emissions targets they will within close proximity reach similar levels of CO_2 emissions in 2050. In the time period of 2015 to 2050 the scenarios experience significant disparities that can be interesting to observe. From a sustainable development perspective CO_2 emissions have a severe effect on the environmental dimension since the emissions contribute heavily to climate change. The indicator allows identification of regions or member states that are responsible for the largest share of emissions and also to accentuate how challenging CO_2 emission targets can be due to the current levels of emissions.

3.2.7 Import Dependency

This indicator is presented as the share of generation by imported fuels over the total generation [$\text{TWh}_{\text{imported generation}}/\text{TWh}_{\text{total generation}}$]. The import dependency indicator is used for identifying dependency as the share of total generation to assess to what extent the European generation is dependent of extra-EU[2] imports.

Import dependency is an important aspect of security of supply which is a main objective for policy-makers as they seek to guarantee a safe supply of energy. The indicator is important for both economic and social aspects of sustainable development as elaborated by IAEA et al. (2005). The economic aspect regards the price risk that occurs when the cost of energy is increased while the social aspect refers to a quantity risk due to a deficit of imported energy.

The imported generation stems from the assumption that the share of imported fuels in 2014 will be the same until 2050 and the assumed shares are presented in Table 3.2. The share of import in 2014 is retrieved from an report on European Energy Security (EC, 2014). Import dependency is presented for the whole European region and for no individual member states. The imported generation is calculated as follows with i representing each fuel:

$$\frac{\sum_i(\text{Import Dependent Generation}_\text{i}\ [\text{TWh}] \times \text{Imported Share}_\text{i})}{\text{Total Generation [TWh]}}$$

[2]Extra-EU refers to all countries outside of EU27, Norway and Switzerland.

Table 3.2: *Imported dependent share of fuels for Europe (EC, 2014)*

Imported shares of fuel	
Fuel	Share
Uranium	95 %
Natural Gas	40 %
Hard Coal	63 %
Oil	80 %

3.2.8 Unit Price of Electricity as Share of GDP per Capita

This indicator is defined as the percentual cost of one unit of electricity (1 MWh_{el}) in relation to the GDP per capita. To establish the cost of one unit of electricity, the average marginal electricity price from ELIN is used. This price is the annual average marginal price of electricity in the region or area considered. The intention of the indicator is to represent the price development of electricity in relation to the general development of prosperity and to provide an estimate of how tangible the cost development is for the average citizen. The indicator's relevance to sustainable development is the social aspect by reflecting on the volatility of electricity price in relation to the development of wealth of society.

While GDP per capita is not an ideal measurement of social wealth, according to Eurostat (2015), it was used in this work as a proxy. GDP per capita is a well known measure of wealth and data for projections until 2050 were available in EC (2016).

3.3 Visualizing Sustainable Development

In this section two instruments used to visualize sustainable development over time are presented. First, the Pathway Acceptance, a qualitative matrix-based tool used for relative indication of scenario implementation acceptance is presented. Second, a Sustainability Index is devised which allows visualization of the scenario progress towards sustainability over time by aggregating multiple KPIs into one combined measure. Together these instruments provides an understanding of scenario implications on how the progress towards sustainability differs. A sensitivity analysis of the Sustainability Index is described, which studies how different stakeholder perspectives can affect the outcome of the index.

3.3.1 Pathway Acceptance

This is a qualitative instrument that is used to answer the second research question on using KPIs as a means of visualizing sustainable development over time. The instrument does not rely on the set of indicators presented in the previous section but assesses different metrics that gives a relative measure on the degree of difficulty in scenario implementation. It identifies challenges in acceptance towards policy scenarios which is related to the social dimension of sustainability. When implementing new policies that regard generation and energy technologies a vast range of stakeholders may be affected. Satisfying all of these stakeholders at the same time can be difficult and the purpose of this instrument is to distinguish certain stakeholders and the specific acceptance challenges that the pathways may encounter. The instrument is divided into three elements that regard several perspectives of acceptance and challenges. The instrument is applied on an aggregated European level only.

The purpose of the first element of this instrument is to estimate industries' acceptance or resistance towards the policy scenarios. The second element regards stranded assets and assesses the acceptance of increased or decreased stranded assets. The third and last element examines the public opinion and acceptance of controversial technologies, in this work nuclear technology and CCS. Based on the two surveys *Europeans and Nuclear Safety* (EC, 2010) and *Public Awareness and Acceptance of CO2 capture and storage* (EC, 2011), a relative measure on the public's view of the development of nuclear and CCS technology in the different pathway scenarios is given.

A coloring-scheme of red-yellow-green is used to give a relative measure of scenarios' development compared to each other. A red color indicates a critical transformation of e.g. the industry or asset use within a scenario while a yellow color indicates more moderate change. The green coloring indicates the scenario wherein the stakeholders are least affected in compared to the other scenarios.

Industry acceptance and resistance
Industry acceptance and resistance is evaluated for every scenario based on the supposition that development deviating from a business-as-usual scenario may be perceived as negative or positive from an industry point-of-view. Acceptance of policies amongst industry stakeholders (e.g. utilities or power generation companies) can thus be expected to be affected by the extent of how policies influences their business. A comparison is made between the coal and gas industry to account for in what scenario the industries will encounter the most substantial changes. By using quantitative data from ELIN with 2015 as a baseline year it is possible to identify changes in the system that will to various extent affect industries. Table 3.3 gives a description of the preconditions of the industries at the baseline of 2015. The scenarios are only compared to each other and not to any external sources, surveys or equivalent.

For the coal and gas industry some scenarios lead to idled or retired capacity, which can be expected to incite resistance from the industry. While the reduction in capacity may both be derived from expected decommissioning due to plants reaching their life time as well as forced decommissioning due to economic reasons, a net reduction in capacity is assumed to be associated with lost business opportunities for utilities and power generators. In some scenarios the retirement of traditional hard coal and lignite plants is alleviated by the deployment of CCS-based coal-fired plants. This may be experienced as a positive development amongst industry stakeholders since it allows operation to remain within their natural business area, as long as they adopt the new technology. While this may allow them to remain in business, it can perceived as a deviation from a business-as-usual path in which traditional non-CCS plants are their main business. Adaptation to CCS may implicate significant financial investments, retraining of labor and require development of new skills. This change may be necessary in order to survive in a changing landscape but can be burdening to the industry stakeholders. The scenarios anticipate different courses of development for the existing capacity and have different preferences toward investing in new coal- or gas-fired capacity (with or without CCS).

Table 3.3: *State of the coal and gas industries in 2015 as given by ELIN (see Appendix B)*

Coal industry	Europe has approximately 134 GW of traditional (non-CCS) coal-fired capacity in all scenarios.
Gas industry	Europe has approximately 261 GW of traditional (non-CCS) gas-fired capacity in all scenarios.

Stranded assets in resources
Fossil fuels have for a long time been the most dominant energy source and play a central role in the world economy. However, the current focus on climate change mitigation have put fossil fuels in a rather critical situation because of the clear connection to Greenhouse Gas (GHG) emissions. Stranded assets is defined by Caldecott et al. (2014, p. ii) as "*assets that have suffered from unanticipated or premature write-downs, devaluations or conversion to liabilities*". In this study stranded assets are evaluated quantitatively by measuring resource use (fuel) for coal and natural gas comparing the use in 2015 with 2050. The regarded assets are limited to coal and natural gas since they are the largest contributors to GHGs in the electricity system. The use of coal and natural gas are connected to an unsustainable development as it implies long-term resource depletion and short- to medium-term consequences in terms of climate change contribution. However, this element assumes an investor perspective which assumes that an increase in stranded assets of coal and natural gas is an unfavorable outcome.

Table 3.4: *State of coal and natural gas assets use in 2015 as given by ELIN (see Appendix B)*

Coal resources	Europe has a coal fuel use of approximately 2900 TWh_{fuel} in all scenarios.
Natural gas resources	Europe has a natural gas fuel use of approximately 855 TWh_{fuel} in all scenarios.

Public acceptance of controversial technologies
Public acceptance regards the acceptance of nuclear power and CCS. The future importance of nuclear and CCS technology differs in extent across the scenarios and this element examines to what degree the public accepts an increase or reduction in any of the two technologies. The element is based on data that examines the role of nuclear and CCS technology in 2050 compared to 2015 levels. The technology developments were valued with respect to the popular opinion based on Special Eurobarometer 324 (EC, 2010) and 364 (EC, 2011) and the assumptions presented below.

Both of these technologies are heavily debated and are known for being controversial. They are subject to evaluation of not only economic and environmental impact but also political and emotional consideration (Breeze, 2017; Kuckshinrichs et al., 2015). Nuclear accidents have had a large effect on public perception of the risks involved with nuclear power. The fear of such accidents as well as the risks of terrorist attacks and proliferation is notably affecting the view on nuclear technology. There are also unknown factors arising since nuclear waste and waste management is a complicated issue (Breeze, 2017). Despite the controversy over nuclear technology, Eurobarometer 324 indicate that 56% of the public does not want to see nuclear power reduced as total share of energy supply (EC, 2010). The statistics that are used for this study were based on public opinions gathered before the Fukushima accident. Consequently the result may be outdated and if the material was collected today the outcome could be different.

There are similarities to the nuclear controversy with regard to CCS and options for CO_2 disposal, since one of the major concerns is the safety of the CO_2 storage. The evaluation in this work is based on the result that according to Eurobarometer report 364, 55% of the public see CO_2 storage as a future risk (EC, 2011). An additional concern to why CCS perceptions are problematic is due to the lack of knowledge about CCS technology and how it works (EC, 2011). This results in that large shares of the public do not have an opinion about how and if CCS could be effective for fighting climate change.

3.3.2 Sustainability Index

To achieve a comprehensive view on the sustainability representation of the indicators developed in this work, a Sustainability Index was composed. The purpose of this index is to visualize the progress in sustainable development in the studied scenario over time by combining the KPIs into one aggregated result. Using a method of weighting and adding KPI results, a uniform index was formed that combined significant data pertaining to sustainable development in the scenarios. Results are presented as a trend line from 2015 to 2050 which allows visualization of the progress towards sustainability over time. A decreasing trend line indicates increasing sustainability in a scenario.

To establish the index, the eight indicators developed in this work were divided into three categories based on the dimensions of sustainable development; social, economic and environmental. Separating the indicators based on their characteristics into categories enabled the indicators to represent important aspects of each dimension in the index. The division is presented in table Table 3.5. Within the categories all indicators (illustrated as purple in Figure 3.3) are weighted equally with respect to each other. For instance, CO_2 emissions weighs equally as share of RES in the environmental dimension.

To create an aggregated index, to combine the information from various results and units of measure, the quantitative results from each indicator are normalized using 2015 as a baseline. This causes all index trend lines to start at one in the year 2015. By using a uniform starting point the movement in the trend lines will imply either a positive or negative trend with regard to sustainable development. In this work a positive, hence a sustainable, trend is assumed when the index is decreasing below one and moves towards zero.

Table 3.5: *Categorization of indicators in the Sustainability Index*

Social	Economic	Environmental
Unit price of electricity as share of GDP/capita	Electric power production intensity	CO_2 emissions
Electric power consumption intensity	Investment cost	Share of RES in generation
Import dependency	Capacity utilization	

An approach of aggregation by addition per category was used. The indicators concerning one category were summed up after which the dimensions were added together to form a uniform index. The structure and division of indicators connected to the different dimensions and the Sustainability Index are presented in Figure 3.3. When considering the addition of several indicators of non-conforming dimensions, a key aspect is to make a sensible weighting of each individual indicator into the aggregated index. As pointed out in the literature, e.g. Boulanger (2008) and previous works that have attempted to create indices related to sustainability e.g. Sköldberg et al. (2014), there is little scientific consensus regarding how to weigh indicators when forming an index. UNDSD (2001) point out that weighting is a societal consideration and will thus be influenced by society's values. As UNDSD (2001) also note, using a sensitivity analysis to evaluate different stakeholder perspectives on the sustainability dimensions may be a valuable tool to increase the reliability of an index. Therefore, this work will employ a sensitivity analysis that examines how a set of clearly defined weights, aimed at portraying the viewpoints and values of various stakeholders, would influence the outcome of the index. The sensitivity analysis is built on the assumption that for every dimension of sustainable development there is a stakeholder that will value this dimension above the other. Based on this assumption the sensitivity analysis was performed using four different focuses and weightings as given in Table 3.6. For the equally weighted focus all dimensions are weighted equally. For the remaining focuses, economic, environmental and social, the correlated dimension receives a higher weighting.

Table 3.6: *Stakeholder weights used in sensitivity analysis of the Sustainability Index*

Stakeholder perspective	Dimension of SD		
	Eco.	*Env.*	*Soc.*
Equal weights	33%	33%	33%
Economic focus	**50%**	25%	25%
Environmental focus	25%	**50%**	25%
Social focus	25%	25%	**50%**

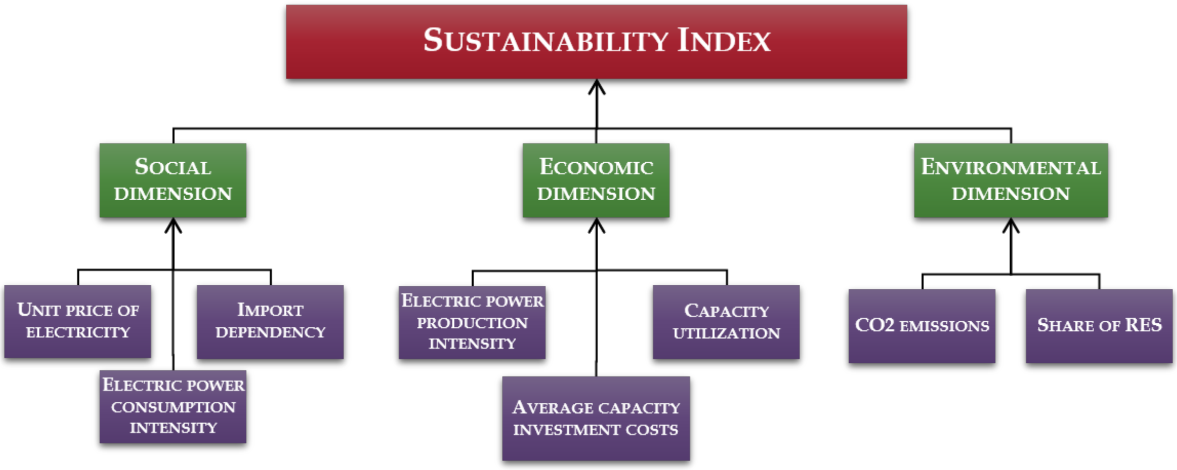


Figure 3.3: *Structure and distribution of indicators divided into the three dimensions of sustainable development*

4
Results

In this chapter the results in section 4.1 pertain to the first research question of this work: if selected KPIs can be used as an appropriate tool for evaluation and characterization of the different paths of evolution for the electricity system. For that purpose, the KPIs are applied to the ELIN model for every policy scenario. Results on Europe, Nordics and particular countries are presented if relevant.

Following that, section 4.2 presents results relating to the second research question: whether selected KPIs can visualize sustainable development in the future electricity system. This part focuses on the Sustainability Index and the Pathway Acceptance instruments as means of visualizing sustainable development in energy system models.

4.1 Evaluating and Characterizing the Evolution of the Electricity System

Key findings of the results in this section suggest that the each indicator presented provides the ability to evaluate a certain characteristic of the evolving electricity system. Furthermore, it is apparent how the distinction of the scenarios are prominent throughout the results. Also, it is exemplified for the CO_2 emissions indicator how the indicator's objective and presentation can alter the perception of the results. Therefore, it is essential to take notice of how indicators are displayed. Another important finding is the different outcomes for the aggregated European region and individual member states. Europe can indicate a positive trend in development while individual member states can experience a negative development. Member states' preconditions and respective energy system strategy influence their individual challenges to reach EU targets.

Another key finding is that although results for each indicator provides the possibility to evaluate a pathway, complementary indicators or data can be necessary when analyzing the impact of the development. Some indicators will by themselves indicate a positive trend, e.g. a decline in the electric power production intensity, but without complementary information on for example capacity mix or CO_2 emissions it is difficult to say whether the decline is positive in a wider context.

4.1.1 Electric Power Production Intensity

In Figure 4.1 the electric power production intensity for the Europe and the Nordics is presented. The result indicates a declining trend in electric power production intensity for both regions. The economic growth for the regions are given by a GDP increase of 69% for Europe and a doubling of GDP in the Nordics from 2015 until 2050 (see Appendix C). Since both Europe and the Nordics experience a growth in the economy the resulting decline in electric power production intensity indicates a decoupling of economic growth and generated electricity. Large differences in the rate and extent of the decline can, however, be observed for the each pathway scenario. Both regions, especially in the Nordics, the RP pathway stands out as the most progressive. In the Nordics, CM and GP does not diverge from each other and remain similar until 2050. In the European region, the scenarios' distinction are significant with CM experiencing a relatively small decline in electric power production intensity until 2050 while RP and GP experience steeper declines.

It is notable how the electric power production intensity for the Nordics is primarily 1.4 times higher than the intensity in Europe, which may be explained by several reasons. Between countries or regions the intensity can differ significantly caused by diverse conditions. Countries that for e.g. experience colder climates or have energy intense industries will have a higher demand for electricity.

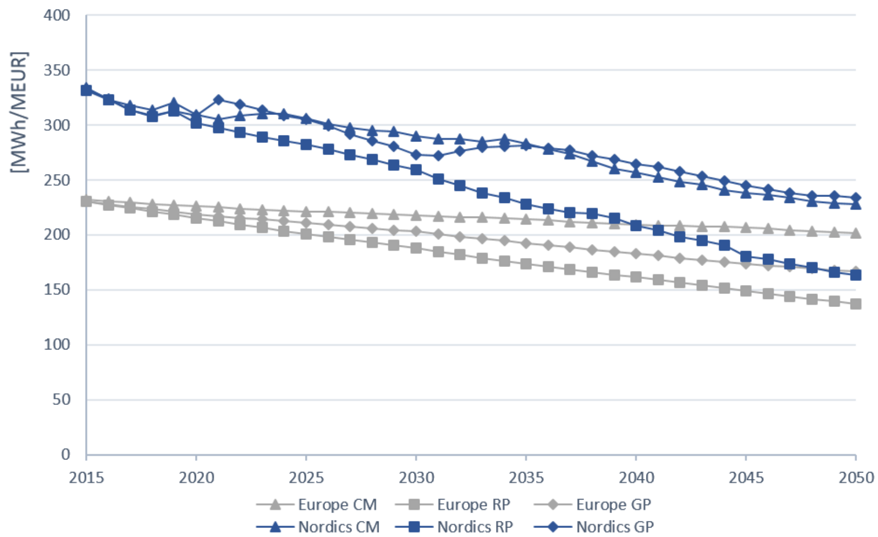
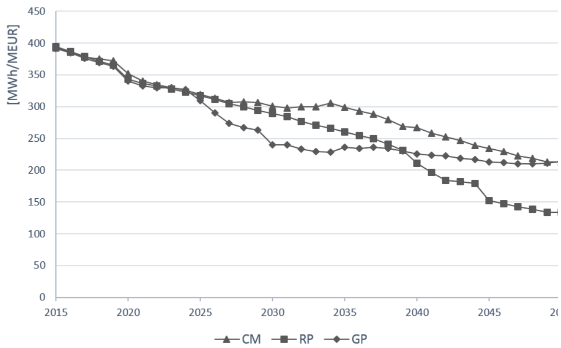
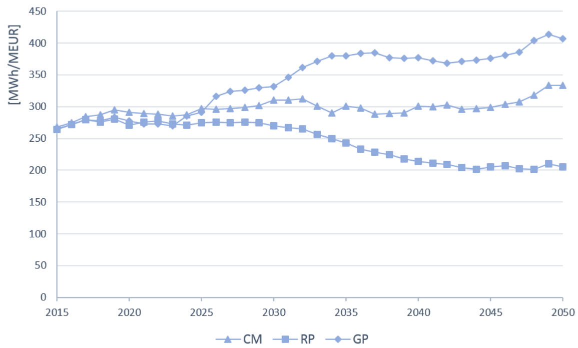


Figure 4.1: *Electric power production intensity in the Nordics and Europe until 2050 for all policy scenarios. Data on electricity generation and GDP are presented in appendices B and C respectively.*

In Figure 4.2 the electric power production intensity is presented for Sweden and Poland. An important observation is how different the intensity developments until 2050 is between the countries. The Europe average indicates a declining trend until 2050 in Figure 4.1, but the results for Sweden and Poland concludes that all member states must not experience a similar development. Sweden experience a significant decrease in electric power production intensity and has a declining trend towards 2050 for all scenarios. On the other hand, Sweden has a much greater initial electric power production intensity starting at around 420 $MWh_{el}/MEUR$ compared to Poland's intensity which is rather low at around 260 $MWh_{el}/MEUR$. However, Poland experience an increase in intensity for both the GP and CM scenarios while only RP shows a downward trend until 2050.



(a) *Electric power production intensity in Sweden*



(b) *Electric power production intensity in Poland*

Figure 4.2: *Comparison of country level electric power production intensity for Sweden and Poland for all policy scenarios. Data on electricity generation and GDP are presented in appendices B and C respectively.*

4.1.2 Electric Power Consumption Intensity

Figure 4.3 illustrates the electric power consumption per capita for the Nordics and Europe. Comparing the two regions, a significant difference in 2015 is noted. Nordic countries start out at 2.3 times higher levels in electricity consumption per capita. All scenarios typically involve a slight increase in consumption per capita or remain at 2015 levels as in the case of Europe in RP. This stagnation can be traced to the scenario setup where the European electricity sector in RP grows insignificantly compared to development in the other scenarios. Also, the European population increase is just 4% to 2050 (see Appendix C). Most notably a quite substantial change for the Nordics is observed in RP where consumption per capita drops by a quarter to 2050. This can be traced to the decrease in demand in RP for the Nordics coupled with a population growth of 17% in the region.

Both CM and GP scenarios experience a growth in per capita intensity for Europe where CM is more proliferate than GP (and RP). Again, this behaviour can be traced to the scenario setup where CM is a more expansive scenario than GP (and RP) in terms of electricity demand. For the Nordics a greater variation is observed where only CM increases in intensity until 2050 and both GP and RP decline. As for the European case, this is explained by the fact that CM is a more expansive scenario and that both GP and RP demand profiles are modest or declining, respectively. As stated above, Nordic population growth is also a significant factor.

To further highlight the contrasts in this indicator, Poland is investigated as an additional example. Figure 4.4 reveals that most notable is that this country exhibits a clearly expansive evolution until 2050, irrespective of scenario. CM is as expected the most prolific case where demand intensity more than doubles. Electricity consumption intensity increases by 45% in RP, a scenario which a more restrictive development in other regions. The Polish case accentuates the existence of intra-European disparities in scenario characteristics. Poland indicates an adverse path of development compared to Europe in general.

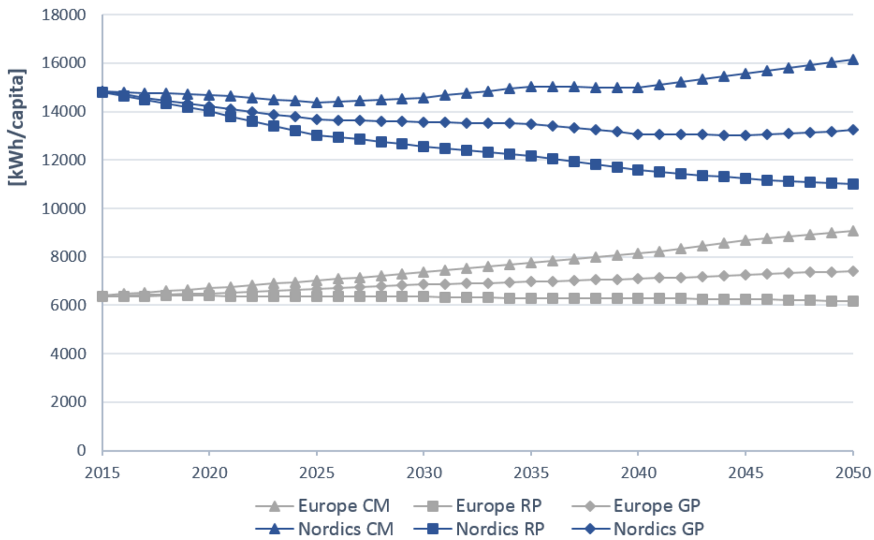


Figure 4.3: *Electric power consumption in the Nordics and Europe until 2050 in all policy scenarios. Data on electricity demand and population are presented in appendices B and C respectively.*

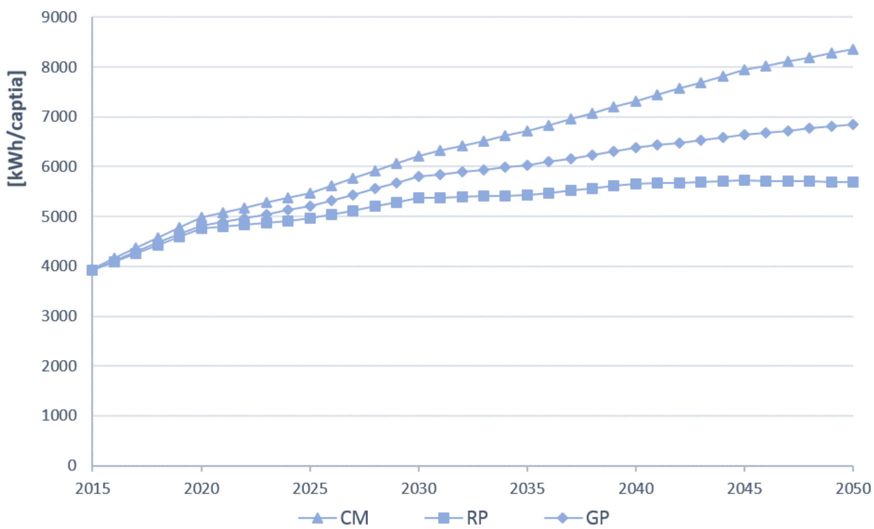


Figure 4.4: *Electric power consumption per capita in Poland until 2050 in all policy scenarios. Data of electricity demand and population are presented in appendices B and C respectively.*

4.1.3 Average Capacity Investment Cost

This indicator reflects the annual system-wide average cost of the capacity increment. Figure 4.5 illustrates the indicator trend for Europe in all policy scenarios. Most notably, CM implies a generally higher average cost of the capacity increment while RP and GP generates approximately the same average costs until the 2040's. In the decade running up to 2050 average cost in RP becomes increasingly higher. CM average cost is higher since the scenario features capital-intense investments in nuclear. The RP scenario average cost increases in the last decade as a consequence of CCS investments which are costly. The consistently low average cost of the GP scenario is explained by the relatively low capital cost of the RES technologies which are in focus of the scenario's investments.

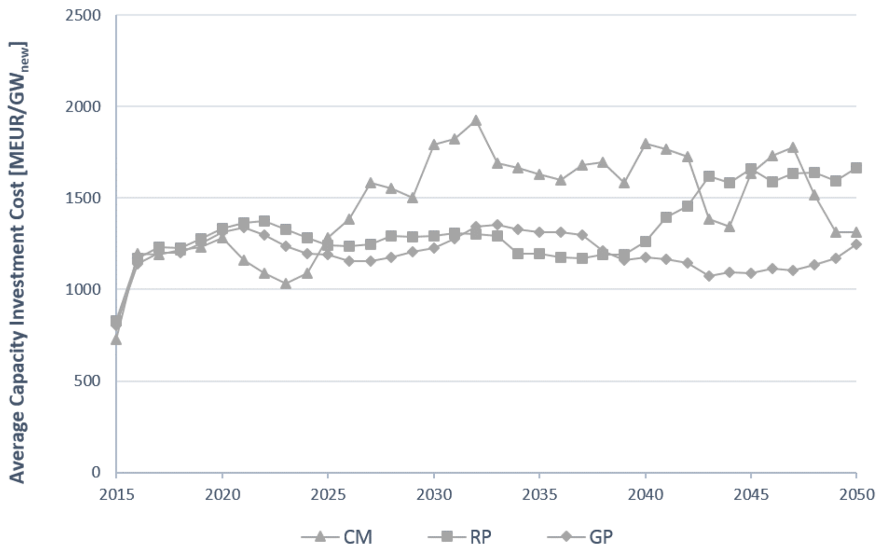


Figure 4.5: *Average capacity investment cost for Europe in all policy scenarios. Data on annual investment cost and capacity increment are presented in Appendix B.*

4.1.4 Capacity Utilization

In Figure 4.6 capacity utilization is presented as CUF (Capacity Utilization Factor) for Europe and the Nordics. It is observed that the Nordic system's starting point in 2015 has a higher CUF than Europe in all scenarios. This is explained by the fact that the present-day Nordic generation mix is nuclear intense. Nuclear contributes to a high average CUF of the system by providing electricity generation at high capacity utilization[1]. In 2015, European electricity mix is far more diverse with a larger share of electricity generated by lower CUF technologies such as wind and gas. Europe also has a lesser influence from hydro power compared to Nordics.

Each scenario implicates characteristic development for both regions respectively. In the CM case both Europe and the Nordics experience the least significant decline in CUF. This is attributed to a scenario setup which precipitates more nuclear and

[1]Typically $CUF_{nuclear} = 0.8$ in the model.

CCS investments, contributing to a higher degree of baseload generation. For the European case a slight increase until 2037 is noted, after which CUF declines. That behaviour is attributed a decline in renewables followed by an expansion of wind and in particular solar starting of in the late 2030's. RP demonstrates slightly different characteristics for both regions. The Nordic case provides a very similar development to CM even though the underlying electricity systems are in fact different. For the European case in RP, the CUF declines until 2050 as the generation mix shifts towards a more wind dominated system where nuclear gives a smaller contribution. With a stagnated demand profile and an increasing capacity volume with greater focus on renewables, CUF declines. In GP both regions experience a significant and consistent decline in CUF. This scenario implicates a substantial build up in renewable energy technologies (primarily wind and solar), which have relatively lower capacity utilization rates in the model.

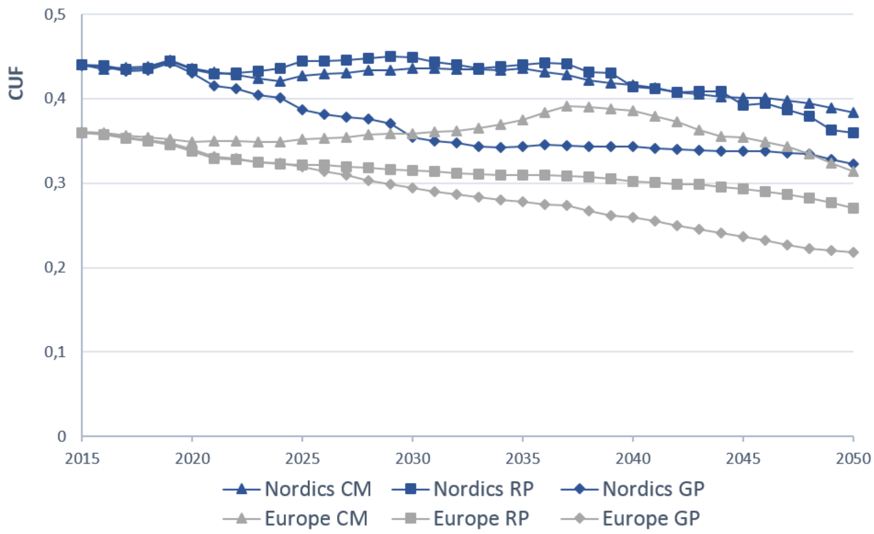


Figure 4.6: *CUF of all generation technologies for the Nordics and Europe. Data on capacity and electricity generation are presented Appendix B.*

4.1.5 Share of RES

This indicator illustrates a system's share of RES on electricity generation basis. In Figure 4.7 a comparison of the Nordics and European share of renewable generation is presented. Key observations include that the Nordics has a significant advantage over Europe, primarily explained by the rich Nordic hydro resources. Another important observation is the distinctly high share in the GP scenario in both regions. This is explained by an intense expansion of RES, in accordance with to the ambitious RES target of the scenario.

For the Nordic region, it is observed that both RP and GP leads to very high levels by 2050. In GP the Nordics achieves above 90% RES already by 2030 as a consequence of nuclear phase-out. The RP scenario takes a less rapid path by retaining nuclear and fossil generation for a longer time period than GP. CM is the least progressive scenario as expected by the policy outline. By 2050 its generation mix is still reliant on nuclear in the Nordics or CCS and nuclear in Europe. The share of RES grows moderately until 2050, 11 percentage point in the Nordics and 20 points in Europe. For Europe this is explained partly due to a build-up of CCS and partly due to a late expansion of wind, solar and bio-waste generation. The Nordic case is explained by a maintained reliance on nuclear and a moderate build-up of wind and bio-waste. Interestingly, the CM scenario features an equally sized RES fleet in 2050 as the RP scenario for both Europe and the Nordics. However, the CM scenario features a significantly steeper demand profile to 2050, allowing an expansion of non-RES generation to 2050.

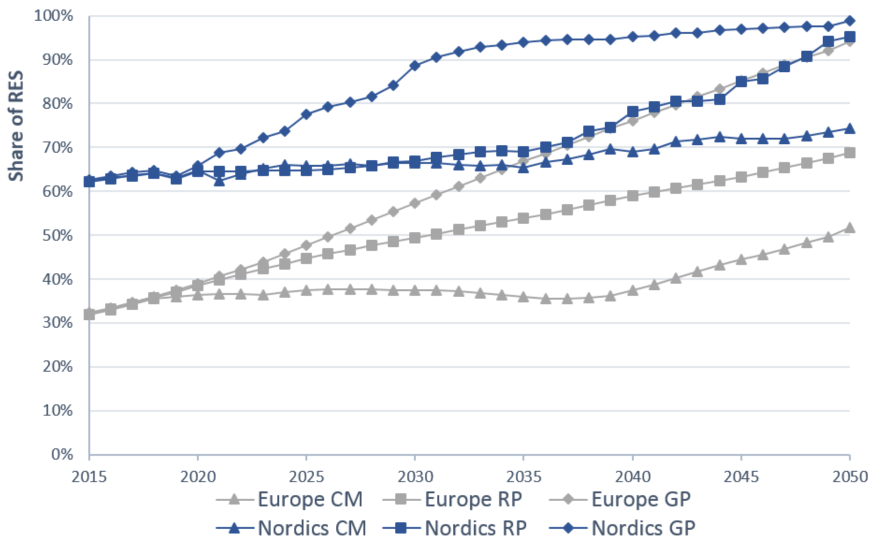


Figure 4.7: *Share of RES in electricity generation for the Nordics and Europe in all policy scenarios. Data on electricity generation is presented in Appendix B.*

4.1.6 CO_2 Emissions

Results for Europe and the Nordics for this indicator are presented in Figure 4.8. All pathway scenarios are controlled by stringent CO_2 emission targets until 2050. This is why the results, regardless of scenario, indicates that emissions in 2050 approaches similar levels. In Europe the development does not differ considerably amidst the scenarios and that is caused by binding contraints on CO_2 emissions. On the other hand, it is possible to observe variations between the scenarios for the Nordics with GP experience the most significant decrease in emissions. This indicates that the Nordics is not constrained by the CO_2 emissions target but instead emit above the European average for all scenarios until just before 2030 for RP and just before 2040 for GP.

A comparison of France and Germany, as given in Figure 4.9a, illustrates an example of the phenomena that two countries with distinct starting points converge into similar levels in 2050 due to CO_2 emission targets. Even though France's initial yearly CO_2 emissions per capita are much lower than Germany's they will more or less end up with similar per capita emissions in 2050. Although, this indicates a positive development for Germany, the country will emit significantly more CO_2 into the atmosphere from 2015 until 2050 in comparison to France. A comparison of France's and Germany's accumulated CO_2 emissions between 2015-2050 is given in Figure 4.9b and it can be observed how Germany's accumulated emissions in the time period increases. It is also observed that their emissions stagnate around year 2040 which coincides with Germany's yearly emissions per capita approaching zero, as observed in Figure 4.9a.

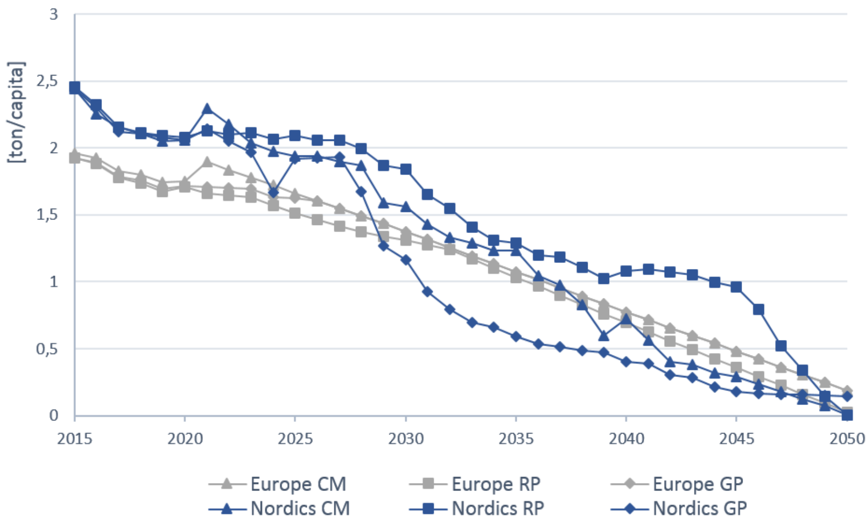
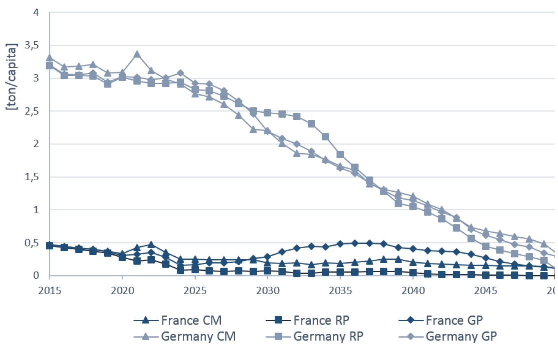
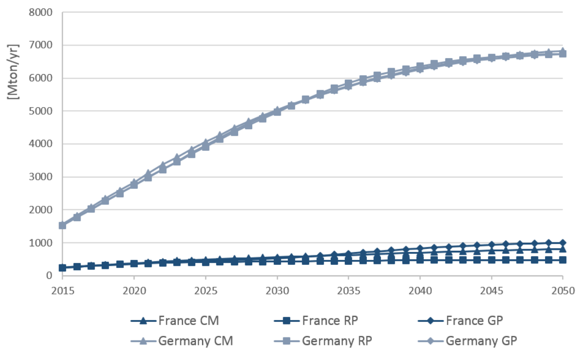


Figure 4.8: *CO_2 emissions per capita for the Nordics and Europe for all policy scenarios. Data on emissions and population are presented in appendices B and C respectively.*



(a) *CO_2 emissions per capita in France and Germany*



(b) *Accumulated CO_2 emissions 2015-2050 in France and Germany*

Figure 4.9: *Comparison of country level CO_2 emissions for all policy scenarios. Data on emissions and population are presented in appendices B and C respectively.*

4.1.7 Import Dependency

The results indicate that aiming at a future development with large shares of RES will result in less import dependency as observed in Figure 4.10 with the sharpest decline in the GP scenario as expected. Figure 4.10 illustrates that before 2020 the scenario developments are similar and the share of import dependent generation indicates a slightly downward trend in all scenarios. However, after 2020 the pathways part. CM has the highest import dependency due to the development of nuclear and CCS which both are technologies with highly import dependant fuels. In contrast it is observed that the GP scenario approaches zero import dependency in 2050 as a result of the RES target that demands 95% RES by 2050.

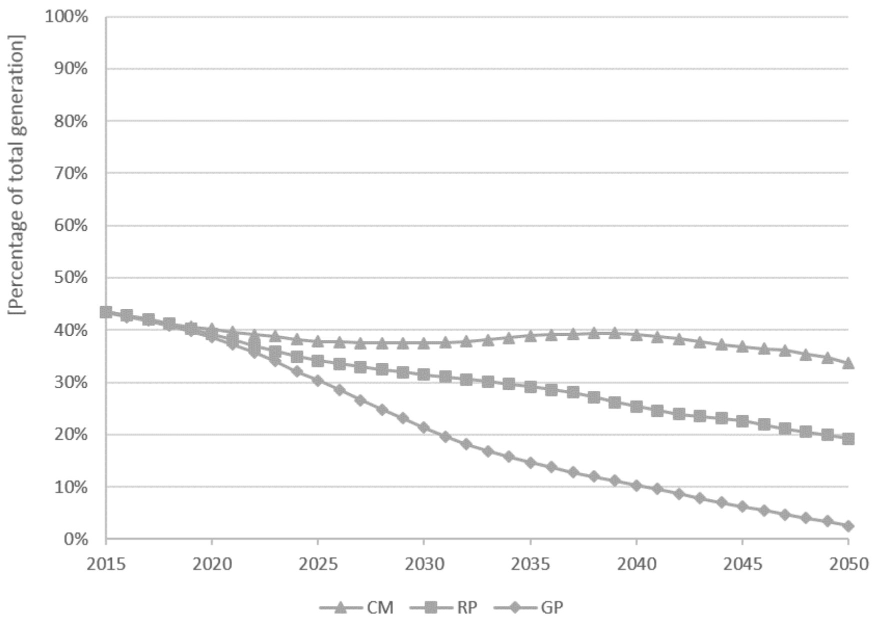


Figure 4.10: *Import dependent generation as share of total generation for Europe for all policy scenarios. Data on electricity generation is presented in Appendix B.*

4.1.8 Unit Price of Electricity as Share of GDP per Capita

In Figure 4.11 the results pertaining to Europe for this indicator are shown. The results for the Nordics are not provided as both systems follow essentially the same trends throughout all the scenarios, but with European levels approximately 1.8 times higher than in the Nordics.

All scenarios provide essentially the same results up until 2020 after which CM diverges. Cost level in CM is at its highest in the middle decades of the time period and decreases slightly towards 2050. This is explained by a growing share of RES generation and declining gas generation, contributing to lower average marginal prices. The CM scenario has consistently the highest levels of all three scenarios. This is explained by a higher level of demand than the other cases. A high annual demand increases prices since more electricity has to be supplied to the system and

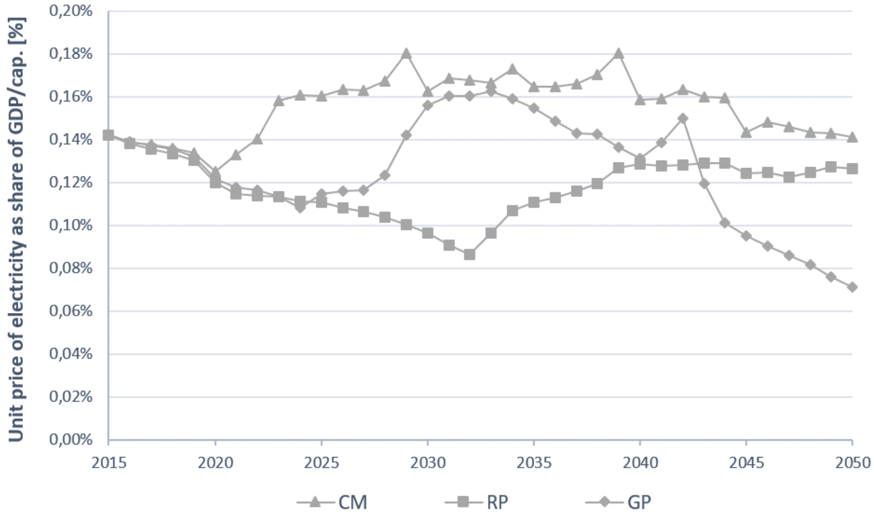


Figure 4.11: *Unit price of electricity (cost of 1 MWh at annual average marginal electricity price) as share of GDP per capita for the Nordics and Europe for all policy scenarios. Data on marginal electricity price is presented in Appendix B and data on GDP and population are presented in Appendix C.*

more costly generation technologies are required. RP and GP trace one another until 2025, where after they too diverge. The RP unit price declines until 2032 after which it increases and in 2050 converges with the CM level. In the GP the cost level diverges from RP after 2025, explained by a shift from nuclear to RES and gas generation. Gas generation has declined up until then but as nuclear is phased out and generation shifts to RES sources, gas generation increases and begins to influence the system price at a greater extent. Towards 2050 the GP system is increasingly dominated by RES generation where gas no longer makes any larger influence on prices. This allows average marginal prices to decrease substantially, leading to a low cost level compared to the other two scenarios.

4.2 Visualizing Sustainable Development

To determine if KPIs can be used to visualize sustainable development over time, in line with the second research question, two instruments of visualization have been generated. Three Pathway Acceptance-matrices are used to give attention to industrial acceptance and public opinions regarding the scenarios' development. Furthermore, a Sustainability Index is conceived as a method for weighting together several quantitative indicators into one single index that visualizes scenario progress towards sustainability over time. The Pathway Acceptance instrument is related to the social dimension of sustainable development and the feasibility of scenario implementation while the Sustainability Index regards every dimension by including all indicators.

Observing the results for Pathway Acceptance, it can be noted that the coal industry experiences a decrease in both capacity and resource use thus resistance to policy implementation can be expected. The gas industry grows in terms of capacity in two out of three scenarios which is assumed to be a positive development for the stakeholders. At the same time natural gas declines in terms of resource use in all scenarios which renders stranded assets. The public acceptance-matrices indicates opposition towards two out of three scenarios since they both entail CCS development. With regard to nuclear development, all scenarios face a significant or moderate resistance from the public.

A key finding for the Sustainability Index is that all scenarios indicates a positive trend towards sustainable development. It is found that GP is the most progressive scenario while CM is the least progressive towards 2050. This result is robust with respect to the weighting of sustainable development dimensions in the index as illustrated by a sensitivity analysis.

4.2.1 Pathway Acceptance

Industry Acceptance and Resistance
Table 4.1 is separated into two parts to regard the coal industry acceptance as well as the gas industry acceptance. The coal industry acceptance towards the CM and RP pathways is estimated to be moderate, neither overwhelmingly positive nor negative. This results in a yellow coloring, due to the fact that both pathways experience a significant reduction in traditional coal-fired capacity which forces stakeholders away from a business-as-usual development. Both scenarios experience quite extensive deployment of CCS-based capacity which can be expected to lessen the impact of lost business opportunities with the retirement of traditional coal-fired plants. Adapting to a new technology can however not be expected to be a smooth transition for the stakeholders. The GP scenario offers no remedies to the industry in terms of CCS deployment and is flagged as red to indicate a critical transformation.

The gas industry's acceptance towards the scenarios is expected to differ. The GP and CM scenarios suggest that the gas industry will have a positive attitude towards

Table 4.1: *Industry acceptance and resistance illustrated as the change in coal and gas capacity from 2015 until 2050. CCS is also regarded and presented as the development of the total amount of traditional coal plus CCS until 2050. Data on capacity is presented in Appendix B.*

	Coal industry acceptance	Gas industry acceptance
Climate market	Traditional coal capacity -64% Total traditional coal and CCS capacity +26%	Traditional gas capacity +20% Total traditional gas and CCS capacity +29%
Regional policy	Traditional coal capacity -55% Total traditional coal and CCS capacity -3%	Traditional gas capacity -24% CCS capacity +0.2 GW
Green policy	Traditional coal -57% No CCS	Traditional gas +23% No CCS

the development since results indicates an increase of gas capacity until 2050 as well as no entry of CCS technology for the GP scenario. This renders both scenarios flagged as green. Oppositely, the RP scenario indicates a decline in traditional gas by 24% and an insignificant growth of CCS. Thus a red flag is raised for RP. CM will experience both negative and positive implications to the industry since the development indicates an increase in gas power but also an increase in CCS gas. However, CCS contributes by about a third so the positive growth of traditional gas is still predominant. Lastly, CCS does not have a significant role in the gas industry development apart from in the CM scenario, where a minor increase is observed.

Stranded Assets in Resources

Table 4.2 illustrates that the use of both coal fuel and natural gas decreases until 2050. Decrease of fuel use can depend on several factors. Primarily it correlates with the reduction of the industry as well as efficiency measures. Coal and natural gas use decrease differently across the scenarios and the largest reductions are in GP for coal and in RP for natural gas. These scenarios are consequently flagged as red. The decrease in GP is due to the stringent renewable energy generation targets while in RP it is explained by energy efficiency measures and a stringent CO_2 targets. For the remaining scenarios it is assumed that the industry is affected but not as critically compared to a 94% (Coal GP) and 98% (Natural gas RP) reduction, giving the scenarios a yellow flag.

Public Acceptance of Controversial Technologies

In none of the scenarios there is an increase in nuclear power as share of the total electricity system. In CM there is construction of new nuclear after 2025. In RP, smaller investments in new nuclear capacity are made after 2038. However, none of these new investments make nuclear power an increasing part of the electricity production system since old nuclear plants are retired simultaneously. The opposition to development of nuclear power is mostly related to the perception that the risk of using nuclear power still outweighs the benefits. The coloring scheme is based on

Table 4.2: *Stranded assets in resources illustrated as the development of coal and natural gas fuel use from 2015 until 2050. Data on fuel use is presented in Appendix B.*

	Stranded assets Coal	Stranded assets Natural Gas
Climate market	Coal use decreased -13%	Natural gas use decreased -52%
Regional policy	Coal use decreased -62%	Natural gas use significant decrease -98%
Green policy	Coal use significant decrease -94%	Natural gas use decreased -72%

the perceptions of nuclear from Eurobarometer 324 which concludes that 56% of the public does not want to see a reduction in nuclear as the total share of electricity supply (EC, 2010). This means that a red coloring indicates a significant decrease of nuclear power as the total share of energy supply while a yellow color indicates a less significant change. However, these statistics are collected before the Fukushima accident and it is therefore important to note that the perception of nuclear technology have likely been altered by this accident.

Opinion polls from the public show that 55% of the public see CO_2 storage as a future risk (EC, 2011). For both CM and RP scenarios the entry of CCS is increasing until 2050 as seen in Table 4.3 while for GP scenario CCS is not entering the market. The development in CM and RP can be assumed to be perceived negatively by the majority of the public and will therefore result in red or yellow coloring while GP result in a green coloring with no CCS.

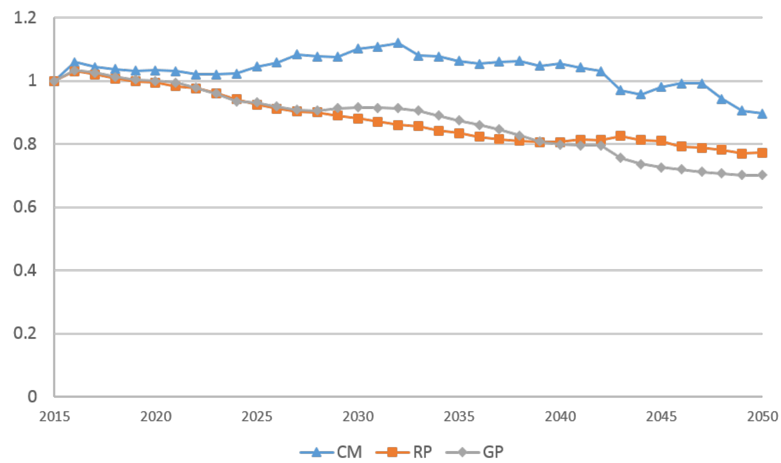
Table 4.3: *Public acceptance of controversial technologies. The table presents the role of nuclear and CCS in the electricity system in 2050 by comparing it to 2015 levels. Nuclear is also presented by nuclear power as share of the total system capacity with 2015 as base year and the development is describes as percentage points (pp.).*

	Public acceptance of Nuclear	Public acceptance of CCS
Climate market	Nuclear increase +42% Decrease as share of total capacity -3 pp.	CCS increase from 0 GW to 145 GW
Regional policy	Nuclear decrease -31% Decrease as share of total capacity -7 pp.	CCS increased from 0 GW to 69 GW
Green policy	Nuclear is not a part of the pathway Decreased -96%	CCS is not a part of the pathway.

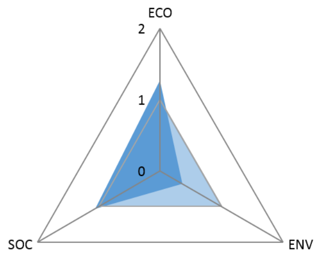
4.2.2 Sustainability Index

The sustainability index is presented in Figure 4.12 as a trend line that visualizes the development towards sustainability over time for all scenarios. This is accompanied by a series of radar charts that illustrates the 2050 state of the index components for each scenario, illustrated in figs. 4.12b to 4.12d. A value less than 1 in the components or in the index implies increasing sustainability. Most notably, the CM scenario has the poorest index performance of all scenarios and the progress of the RP and GP indices coincide but diverge just before 2030. The development of the two latter is characterized by RP being more progressive until the late 2030's after which GP gives the most progressive outcome. Also, all scenarios perform typically poor in the economic dimension as observed in the radar charts.

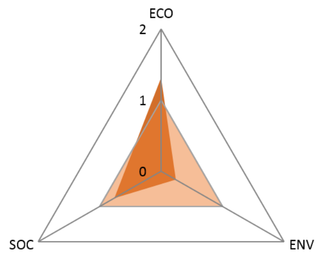
The outcome of CM is explained by relatively poor scenario performance in the three sustainability dimensions by 2050, as illustrated in Figure 4.12b. The overall development from 2015 is heavily influenced by poor performance in the economic and social aspects. The economic performance is diminished by higher electric power production intensity and higher average investment costs than the other scenarios but is somewhat mitigated by a greater capacity utilization. The social performance in CM is traced to high levels of electric power consumption intensity, high average costs of electricity and a greater import dependency compared to the other policies. For the RP and GP scenarios, the generally lower index (thus better performing) is attributed to a few factors. First, both achieve a equivalent performance in the environmental dimension, superseding the environmental performance of CM. This is explained by high RES-shares, GP slightly greater than RP. On the other hand, RP outperforms GP with respect to CO_2 emissions. Both of these aspects are however closely linked to scenario targets. GP has a higher target for RES than RP while RP follows an even more stringent emission target than GP.



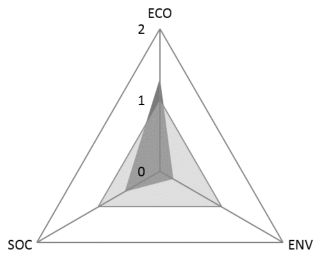
(a) *Sustainability Index over time between 2015-2050 for Europe for all policy scenarios using equal weight for all dimensions*



(b) *Index components in 2050 for CM*



(c) *Index components in 2050 for RP*



(d) *Index components in 2050 for GP*

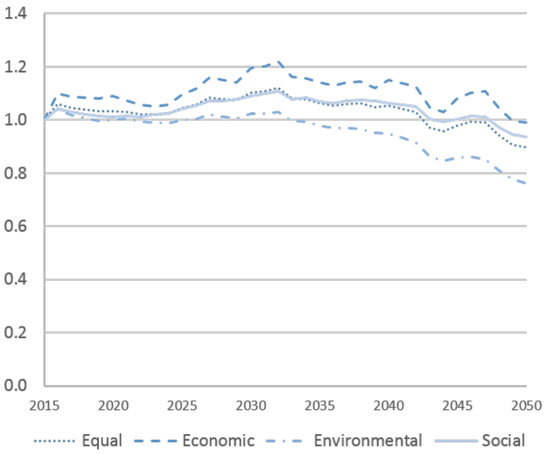
Figure 4.12: *Sustainability Index and its progress over time in **(a)** and the index components (economic, environmental and social) of each policy scenario in **(b)** - **(d)**. Filled area indicates index components in 2050 and pale-hued area in 2015. A 2050 value in the components or in the index implies increasing sustainability compared to 2015.*

Sensitivity Analysis of Sustainability Dimension Weighting

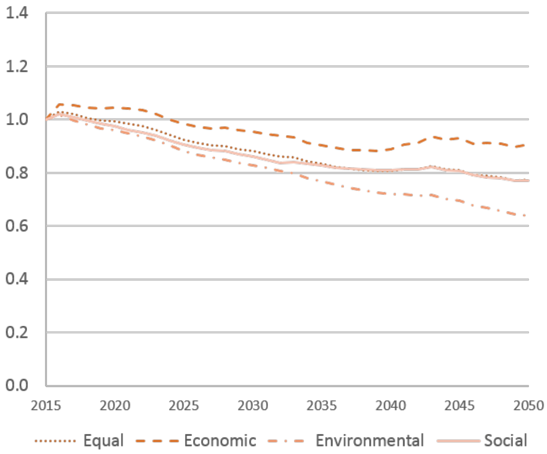
Using the sensitivity analysis described in the method, the Sustainability Index was evaluated using three additional weightings of the sustainability dimensions. Here, each pathway scenario is analyzed in the sustainability index using three additional weights representing different stakeholder perspective and the equal weighting used in the previous section for reference. The results of this analysis are presented in Figure 4.13.

Key findings are that *Equal weighting* and *Social focus* render almost identical results for all policy scenarios. Another key observation is that *Environmental focus* will generate a more positive development in all scenarios compared to the *Economic focus*. The latter generates a more pessimistic view where CM turns out as the least favourable case owing to an index greater than 1 during the entire period of time. Only just before 2050 does the CM index return to 2015 levels when applying the *Economic focus* weighting.

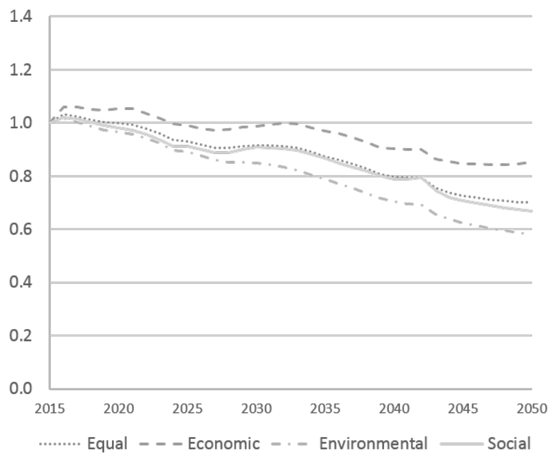
Another key observation from this sensitivity analysis is that no matter what stakeholder weighting is applied the outcome of the index is robust. All weightings examined generate the same result, consistent with the findings in the previous section using equal weighting. That is, GP implies a more sustainable path of development than RP which outperformed by GP in the last decade. CM entails the least favourable path no matter what weighting is applied.



(a) *CM*



(b) *RP*



(c) *GP*

Figure 4.13: *Sensitivity analysis of the Sustainability Index using different stakeholder's weighting on each policy scenario*

5
Discussion

In this chapter the key points for discussion of this thesis are examined and presented. The relevant points for discussion are the topics of answering the research questions, the thesis' method, limitations of the results and recommendations for future work.

A key part of this work focused on generating indicators suited to answer the research questions and to fulfill the aim of this thesis. Therefore, the representation of sustainability was a key criteria in narrowing down the number of indicators used in this work. However, the approach was focused on assessing the relevance to sustainable development in each individual indicator. Since the aim was not to find the most advantageous selection of indicators that could provide a comprehensive sustainable development perspective, it is relevant to discuss what perspectives on sustainability that are accommodated by the indicators selected in this work. For instnace, the environmental dimension is covered by two indicators, CO_2 emissions and share of RES. These indicators do not provide a holistic view of the dimension as they are closely related. An increase in RES-share will correlate with a reduction in CO_2 emissions. This results in double-counting when the indicators are elected to represent the environmental dimension in the Sustainability Index. Furthermore, the social dimension is represented by three indicators, unit price of electricity as share of GDP, electric power consumption intensity and import dependency. As a consequence, this study only contains a very limited perspective of the social dimension. This dimension is challenging to cover since many aspects are not quantitative or directly measurable. To enhance the analysis of sustainability in the future electricity system another selection of KPIs could be suggested to include a wider perspective of sustainable development and in particular for the environmental and social dimensions.

Examining the indicators proposed in this work individually, the insufficiency of single indicators to provide a comprehensive view of the evolution of the electricity system becomes apparent. Without the availability of complementing indicators to provide additional information, a single indicator provides a limited perspective. For instance, a figure such as electric power production intensity correlates only how much electricity is generated for each unit of societal wealth. To achieve a more comprehensive account on the scenario evolution more parameters are typically interesting, e.g. figures pertaining to CO_2 emissions or what kind of generation technologies that are utilized in the examined scenario. This argument gives weight to the point of establishing instruments to combine and aggregate single indicators to form e.g. a uniform figure or a matrix representing several underlying metrics or indicators. The Sustainability Index and the Pathway Acceptance-matrices that are proposed in this work are two approaches to address this issue.

With respect of the Sustainability Index, the weighting of the indicators is an important contributor to the results observed in this work. The presumptions of this work focuses on a stakeholder perspective that assumes that a stakeholder will either put emphasis on one specific dimension of sustainable development or weight all of them equally, as is examined in a sensitivity analysis of the index. However, the indicators that are included in the index are divided into the three dimensions and the indicators are weighted equally within each dimension. To improve the index this relative weighting between indicators within the same dimension could be reassessed. Criteria for determining the importance and the impact of indicators should be established in this process to ensure objectivity and that the result are not biased by stakeholder views.

Limitations

A limitation to this work is the availability of long-term (running to 2050) projections of GDP and population data. In the context of this study, it would have been relevant to examine the influence of scenario setup on this type of data. Arguably, population figures may not be significantly affected by what policy scenario is implemented but the same argument is not as strong for GDP. Different policies directing the path of development in the electricity system may also influence the general economic development and thus GDP may differ between the scenarios. As a consequence, the outcome of individual indicators and the Sustainability Index can actually differ to a greater extent among the scenarios than what is seen in this work.

Another limitations is that this study only regards the electricity system and not a TPES perspective. Therefore, it is of importance to regard and discuss what causes the scenarios to present certain results. Since the preconditions for each scenario are not the same, this affects the outcome and can provide scenarios with a destined drawback. This is clearly related to the different demand profiles since the electricity demand differs quite significantly between the scenarios. For instance, CM is assumed to be subject to increasing demand caused by electrification of transportation while RP is assumed to experience decreased demand due to efficiency measures. While this directly provides RP an advantage compared to CM for an electricity system analysis, the same assumptions could provide another implication if the analysis was based on TPES with additional sectors included. In that case CM could instead be advantageous by lowering total system emissions by moving them from the transportation sector to the electricity sector. Furthermore, the electricity demand assumed in this work will also influence the entire output of the model, for instance in capacity investments and CO_2 emissions. To achieve a more comprehensive representation of scenario developments than in this study a TPES perspective can be applied.

Recommendations for future work

The social aspect of sustainable development is perhaps the most difficult to capture. The dimension consists of features that are difficult to measure which may be one of the reasons to why that dimension often is overshadowed by the economic and environmental perspectives. This issue is noticed in the Pathway Acceptance-matrices where the difficulty of appropriately representing a negative or positive development becomes apparent. For further work it is advised to enhance the analysis of the social dimension and to represent it in a broader sense by including a wider range of indicators that describes further aspects. Additional suggestions for further work could be to consider the UN Sustainable Development Goals, as defined by UN General Assembly (2015), as a framework for selecting indicators. Not only would it provide understanding of important indicators for sustainable development, it could also provide deeper insight on indicators that are suitable for the social aspect.

To further improve this thesis' method for visualizing sustainability, a more widely encompassing approach can be suggested. In such, the concept of sustainable development can be used as the central starting point for generating KPIs. A renewed approach could originate from an exhaustive analysis of what physical aspects, derived from the three dimensions of sustainable development, that the KPIs should include and represent. Next, suitable indicators representing a larger range of physical aspects could be identified and implemented in a Sustainability Index. Clear identification of key sustainable development aspects and adequate representation through KPIs for each dimension could improve the aggregated index. Possible improvements to the Pathway Acceptance instrument includes method refinement and extension of its scope. The instrument could be expanded by covering further stakeholders, assets and technologies to widen the perspectives included. Most importantly, improved and more up-to-date data on public opinion, especially regarding nuclear, could enhance the analysis in this instrument.

6
Conclusion

The aim of this study was to develop and identify KPIs for visualizing and characterizing the evolution of the future electricity system. The aim was also to develop a method for visualizing the progress of sustainability over time. To accomplish that, this study generated a set of KPIs that was applied to three distinct policy scenarios describing the evolution of the future electricity system as well as developing two instruments for visualizing sustainability.

The results suggest that the KPIs developed in this work can be used as a tool to characterize future developments and can be useful for analyzing scenario pathways and their implications for of future electricity systems. Selected KPIs provides the ability to analyze pathway scenarios over time and allows deepened analysis of challenges and the changes that must be implemented to reach the targets set by EU. It is on the other hand important to underline the fact that any indicator regarded in this work single-handedly represents a limited perspective and only a certain characteristic of the development.

The aim of visualizing and characterizing sustainable development in the future electricity system with the selected KPIs was fulfilled by designing two instruments, the Pathway Acceptance-matrices and the Sustainability Index. Pathway Acceptance illustrates acceptance and resistance issues towards policy implementation, although the number of perspectives represented are limited. In the Sustainability Index several indicators were weighed together to form a uniform figure of sustainability and a sensitivity analysis proved robustness of the outcome. Although the representation of sustainable development by selected indicators was narrow, the instruments designed form useful tools and a suitable method for visualizing sustainable development.

In conclusion, this thesis answers the research questions posed and fulfills the aim of developing KPIs that allows visualization and characterization of the future electricity systems as well as a method for visualizing sustainability.

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A

Gross list of KPIs

Table A.1: *Gross list of indicators*

Gross list of indicators	
Indicator	Unit
Electric Power Production Intensity	[MWh_{el}/MEUR]
Electric Power Consumption Intensity	[kWh_{el}/capita]
Average Capacity Investment Costs	[MEUR/GW_{new}]
Capacity Utilization	*Ratio*
Share of RES	[TWh_{RES}/TWh_{total}]
CO_2 Emissions	[Mton]
Import Dependency	[%]
Unit price of electricity as share of GDP per capita	[%]
Electric Power Production per Capita	[MWh_{el}/capita]
Technology Investment Rate	[GW_{new}/decade]
Fuel Use	[TWh]
Biomass Expansion	[TWh/yr]
Market Volume of CO_2	[MEUR]
Investment Costs	[MEUR/yr]
Mitigation Cost as Share of GDP	[MEUR/MEUR]
Stranded Assets	[-]
ETS Price Trend	[MEUR]
Non-Renewable Fuel Dependency	[%]
CO_2 Captured	[Mton/yr]
Public Policy Acceptance	[-]
Expansion of Peak Gas Plants	[GW/yr]
Fuel Diversification	[-]

B
ELIN model output

Electricity demand

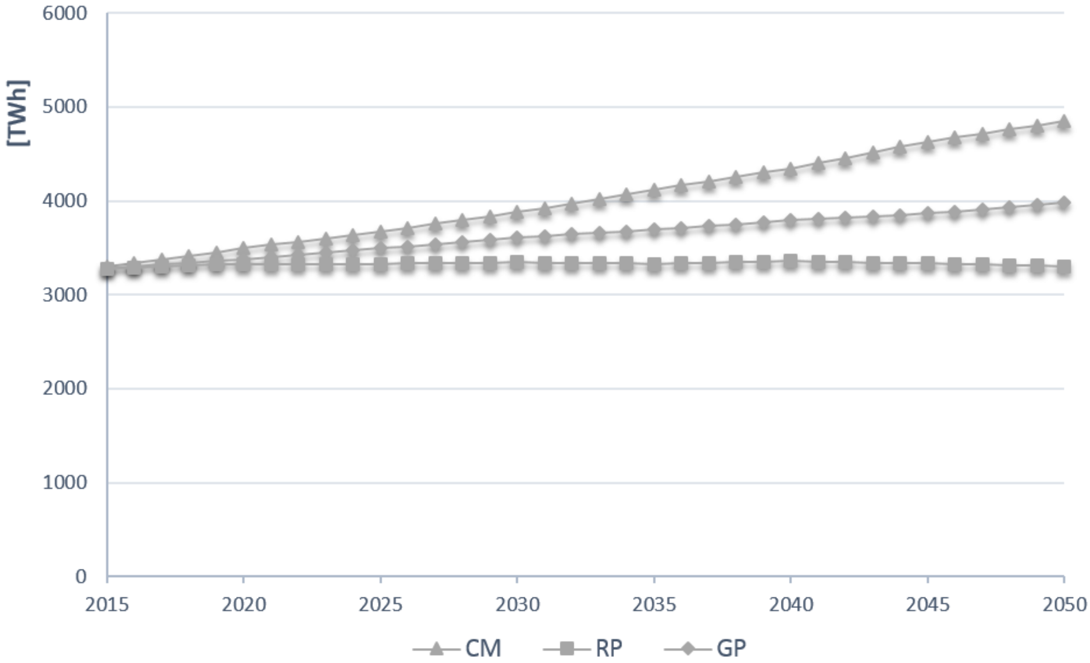

Figure B.1: *Electricity demand in Europe for all policy scenarios*

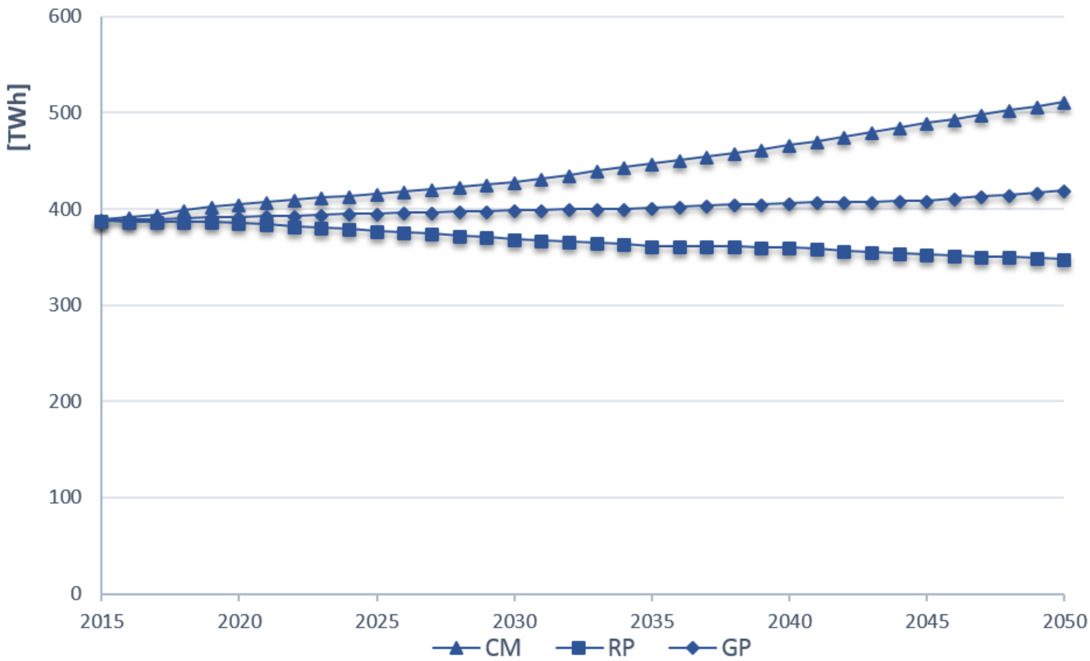

Figure B.2: *Electricity demand in the Nordics for all policy scenarios*

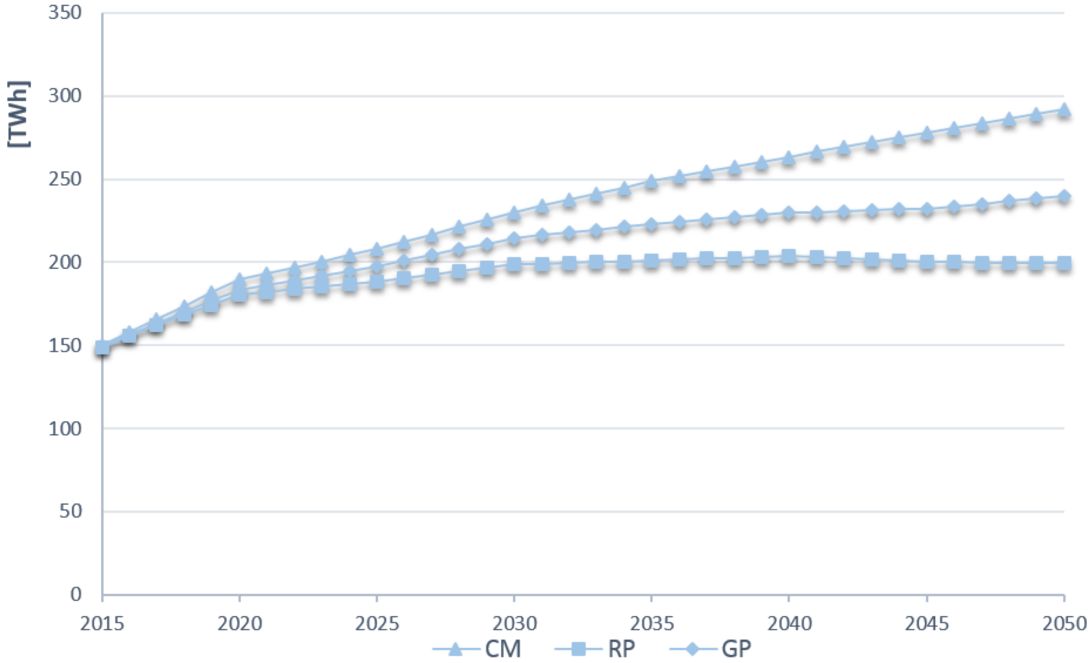

Figure B.3: *Electricity demand in Poland for all policy scenarios*

Installed Capacity

Europe

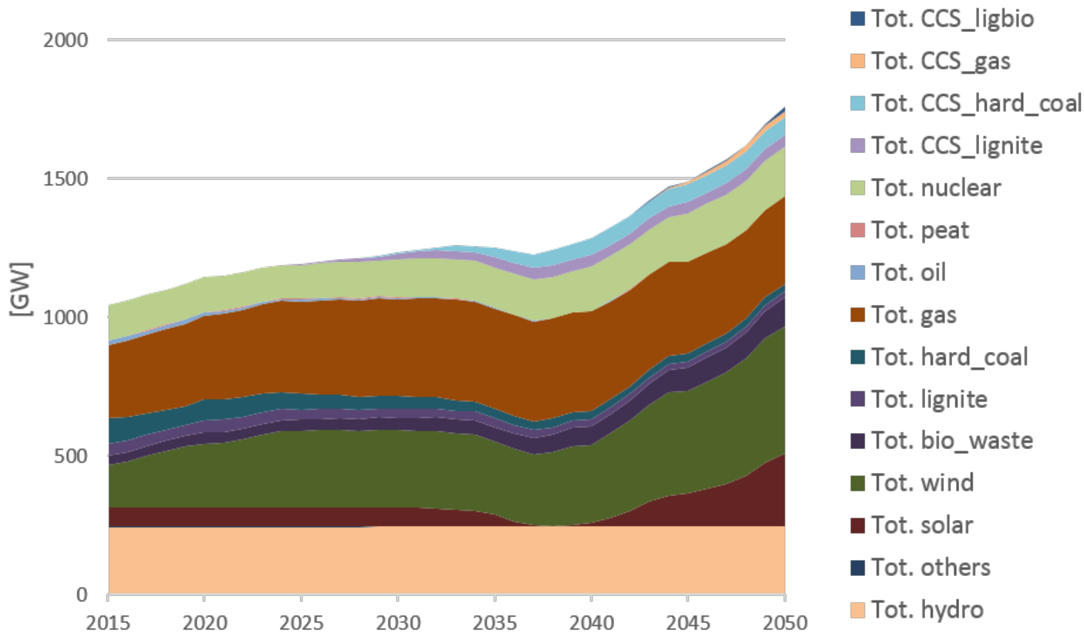

Figure B.4: *Installed capacity in Europe for Climate Market*

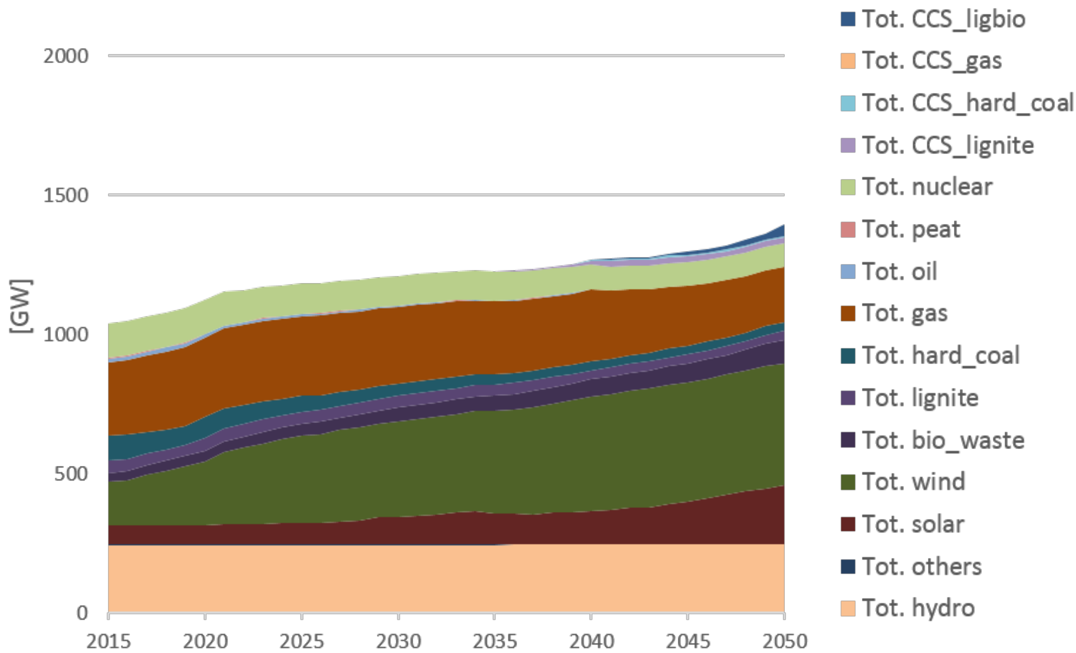

Figure B.5: *Installed capacity in Europe for Regional Policy*

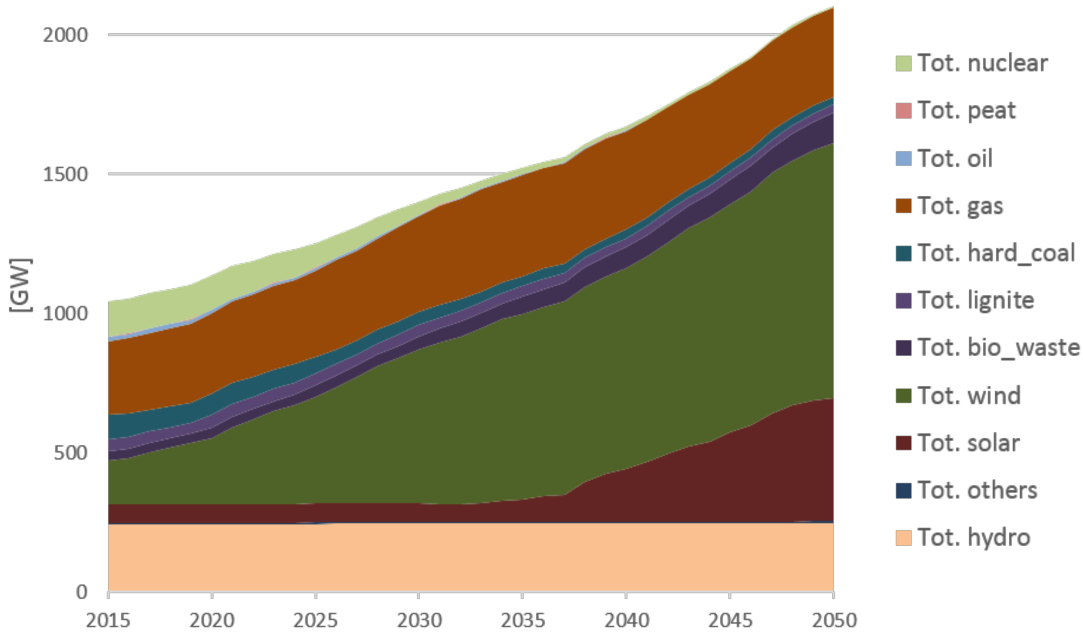

Figure B.6: *Installed capacity in Europe for Green Policy*

The Nordics

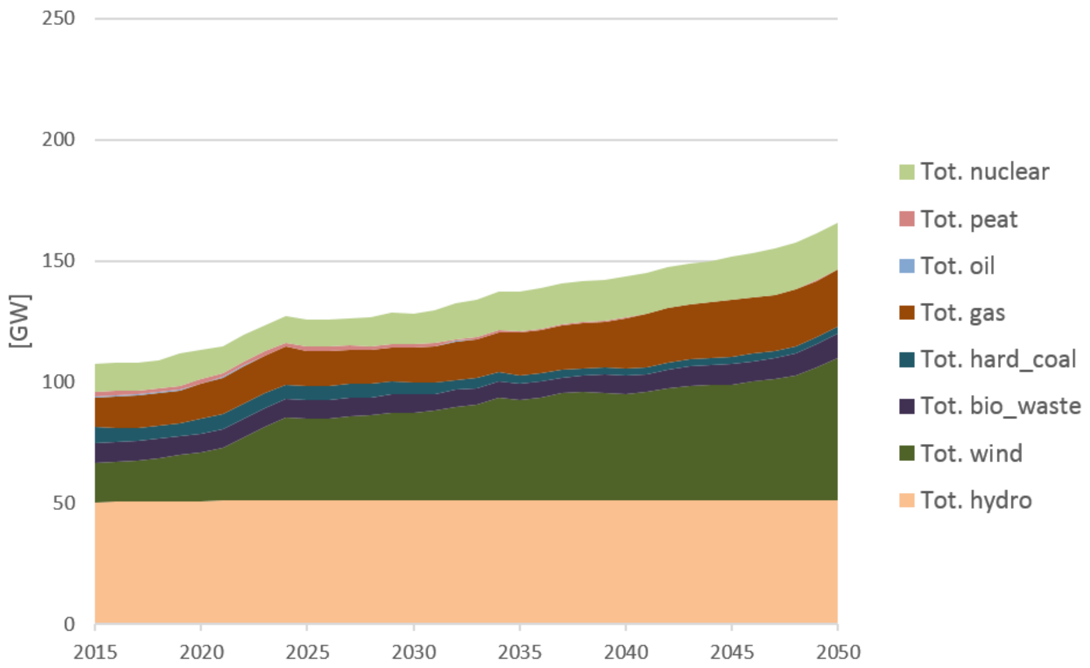

Figure B.7: *Installed capacity in the Nordics for Climate Market*

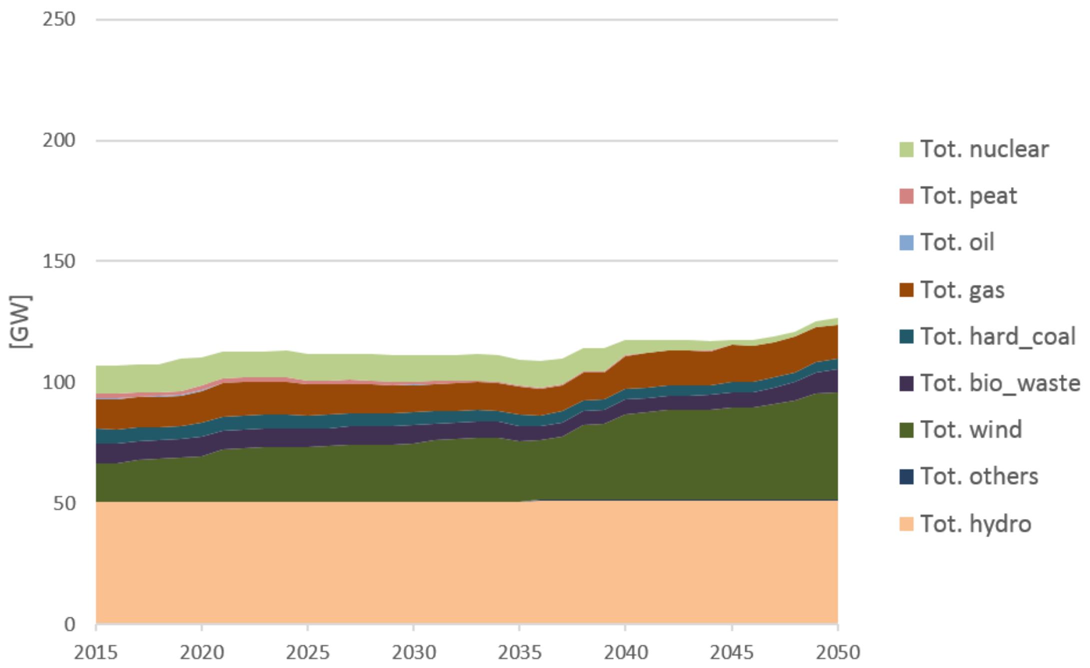

Figure B.8: *Installed capacity in the Nordics for Regional Policy*

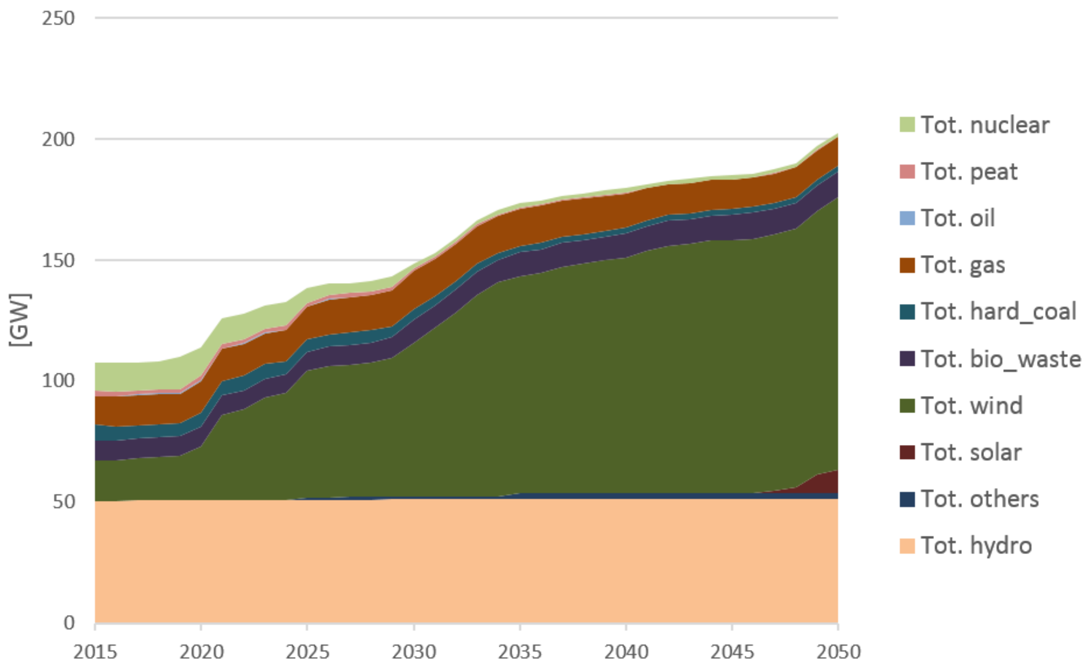

Figure B.9: *Installed capacity in the Nordics for Green Policy*

Fuel use

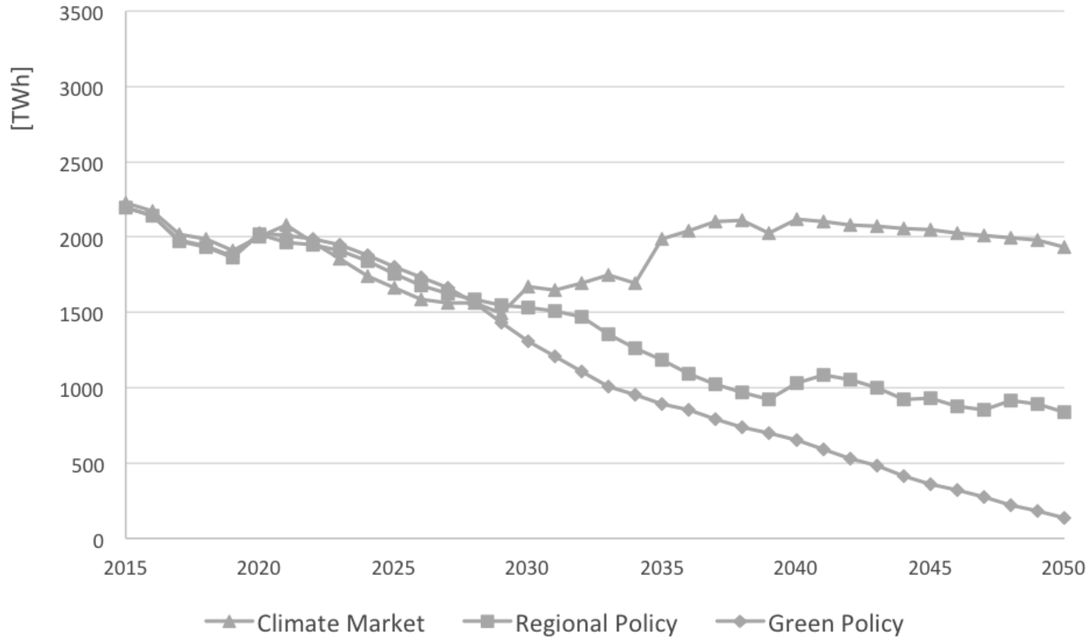

Figure B.10: *Fuel use of coal in Europe for all policy scenarios*

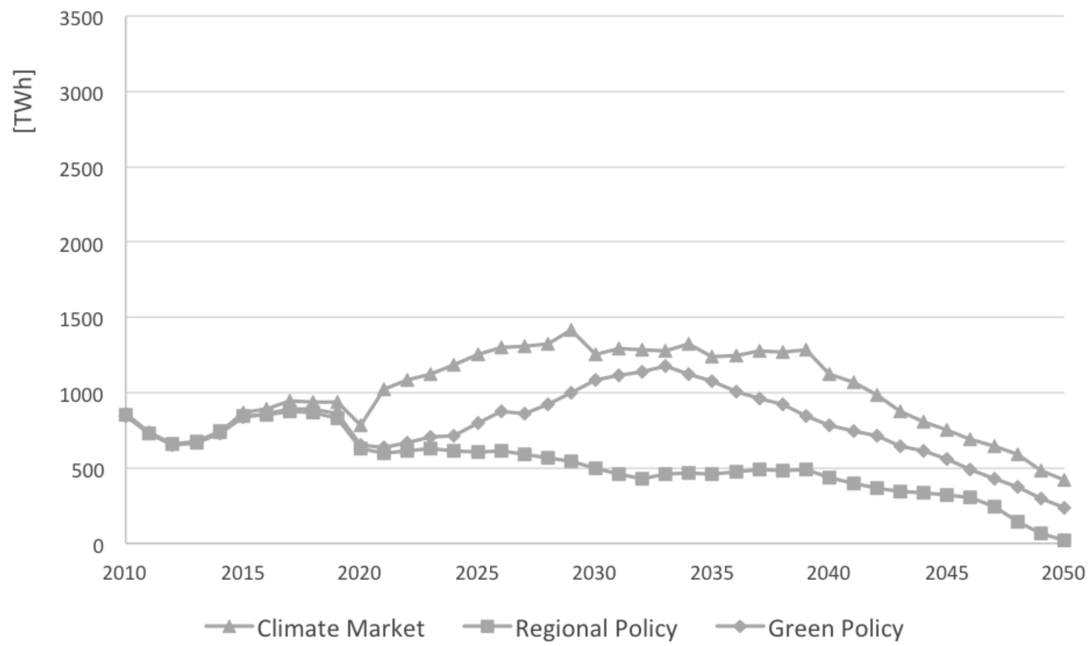

Figure B.11: *Fuel use of gas in Europe for all policy scenarios*

Electric Power Production

Europe

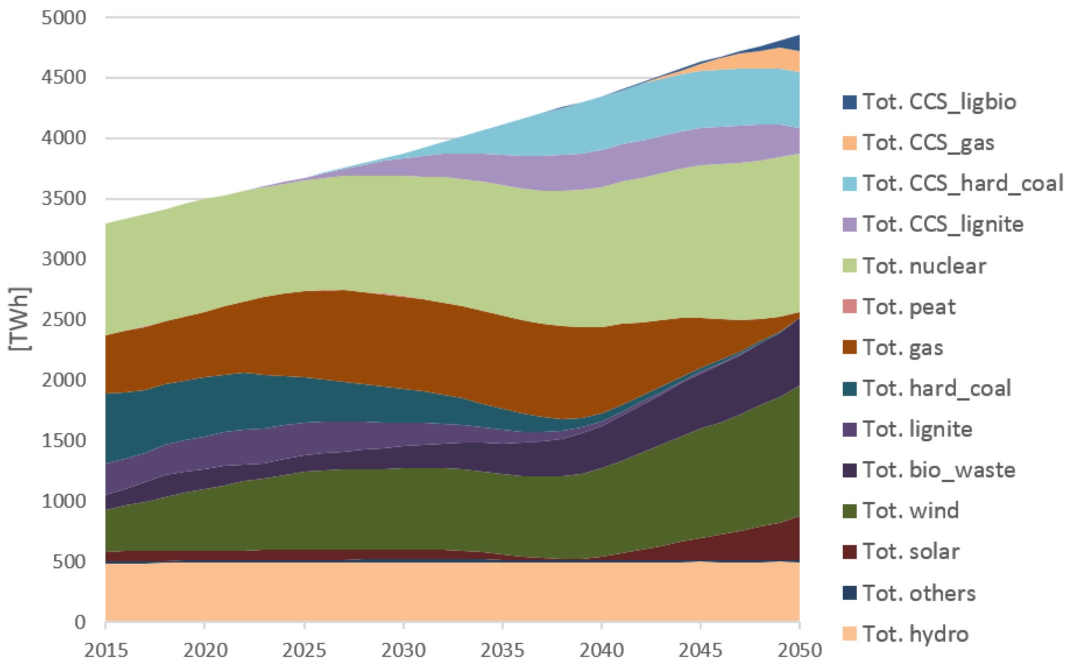

Figure B.12: *Electricity generation in Europe for scenario Climate Market*

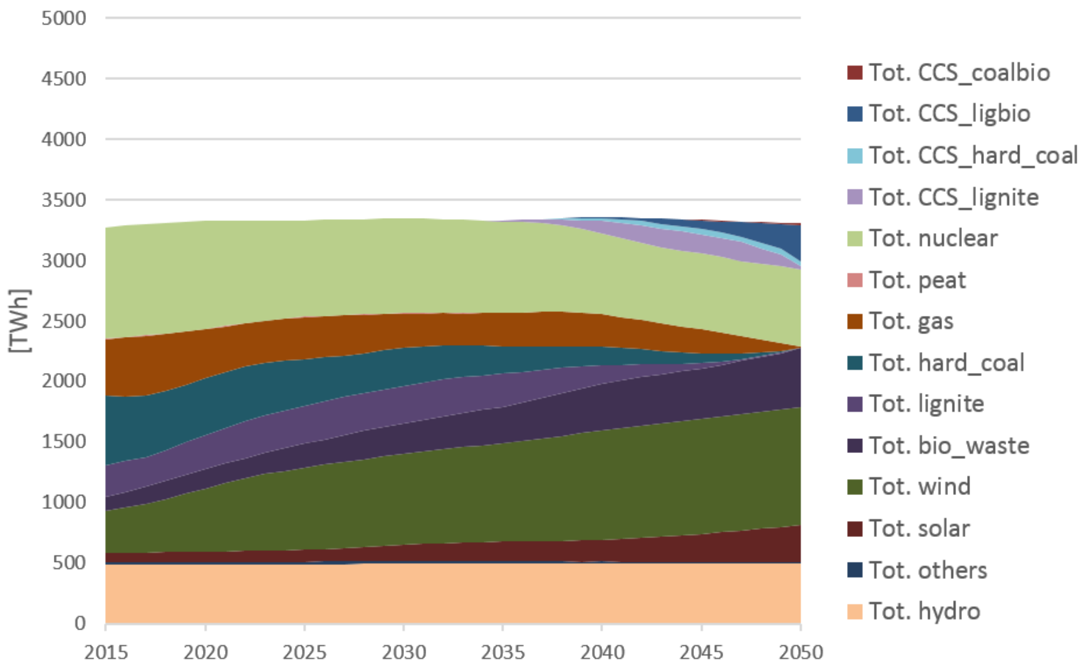

Figure B.13: *Electricity generation in Europe for scenario Regional Policy*

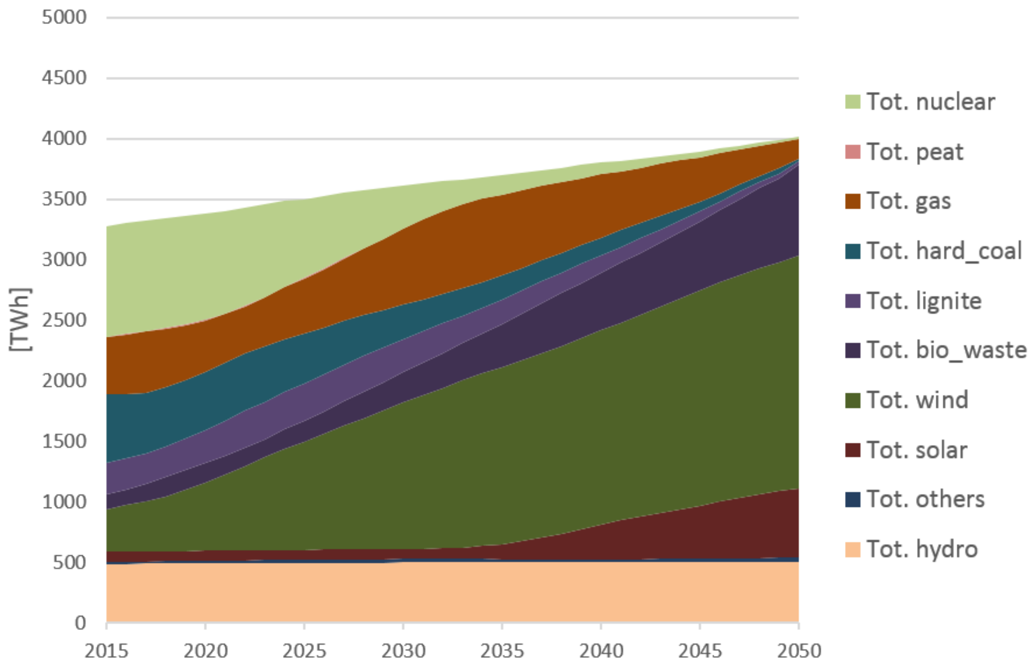

Figure B.14: *Electricity generation in Europe for scenario Green Policy*

The Nordics

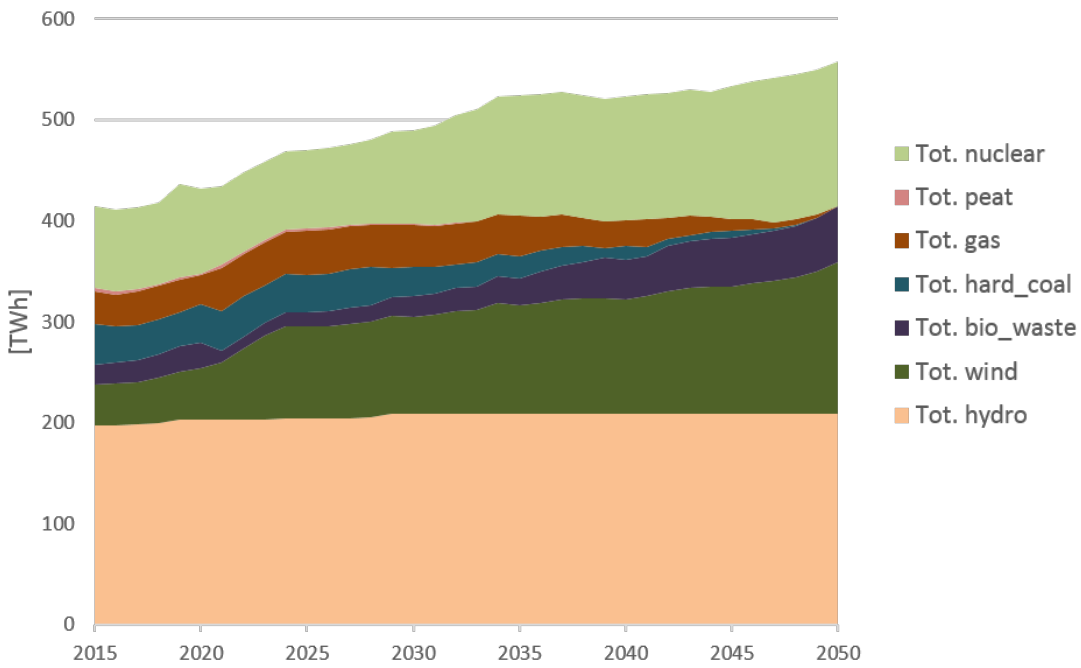

Figure B.15: *Electricity generation in the Nordics for scenario Climate Market*

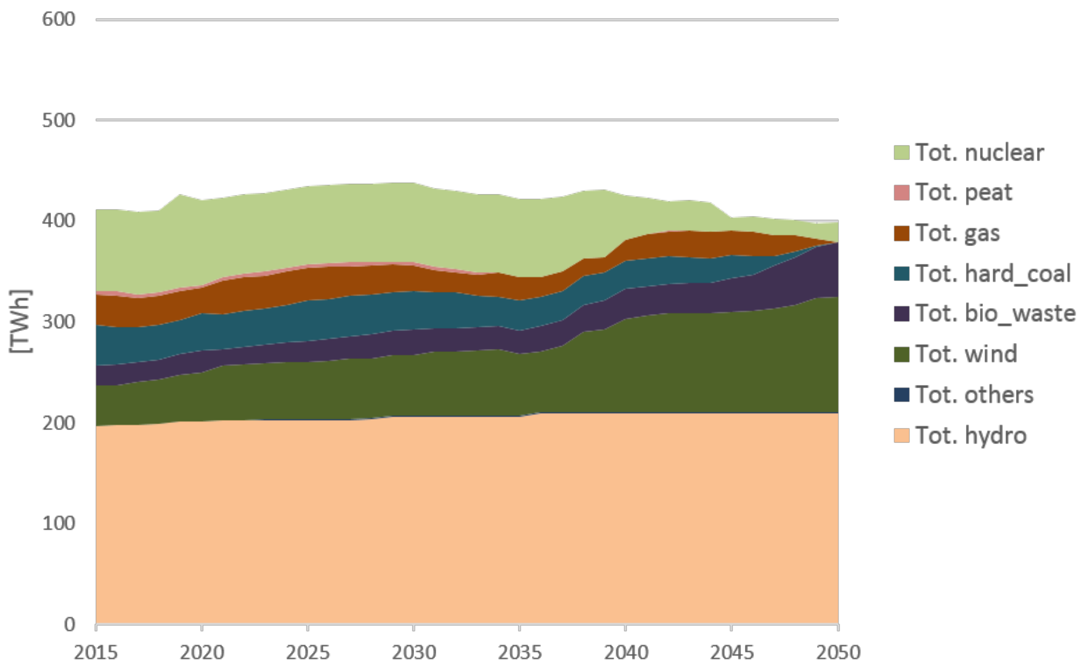

Figure B.16: *Electricity generation in the Nordics for scenario Regional Policy*

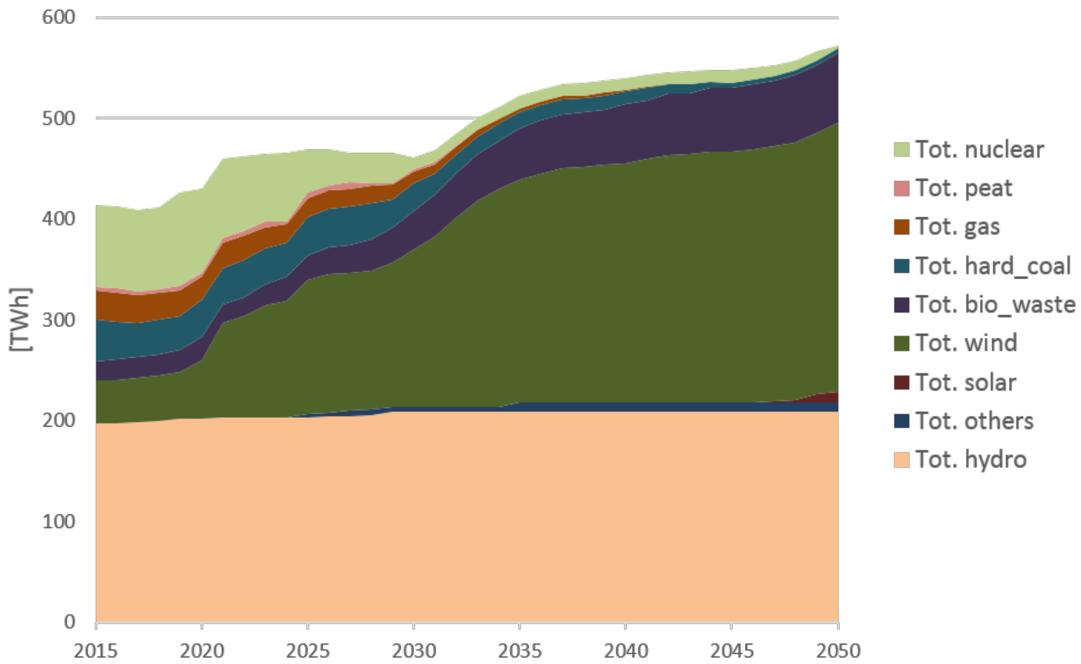

Figure B.17: *Electricity generation in the Nordics for scenario Green Policy*

Sweden

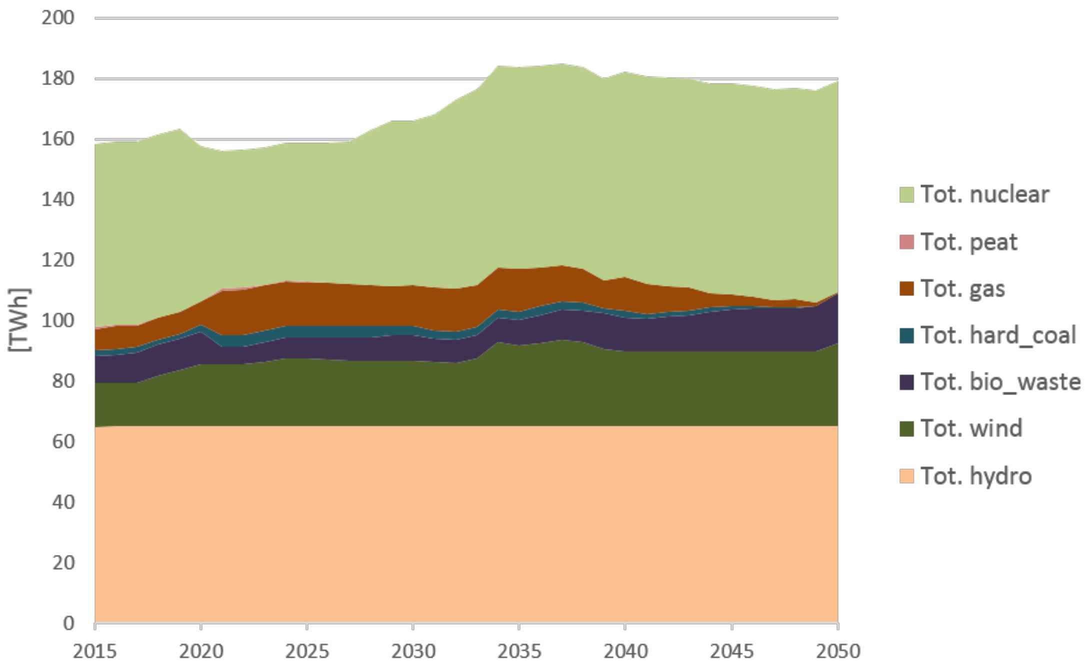

Figure B.18: *Electricity generation in Sweden for scenario Climate Market*

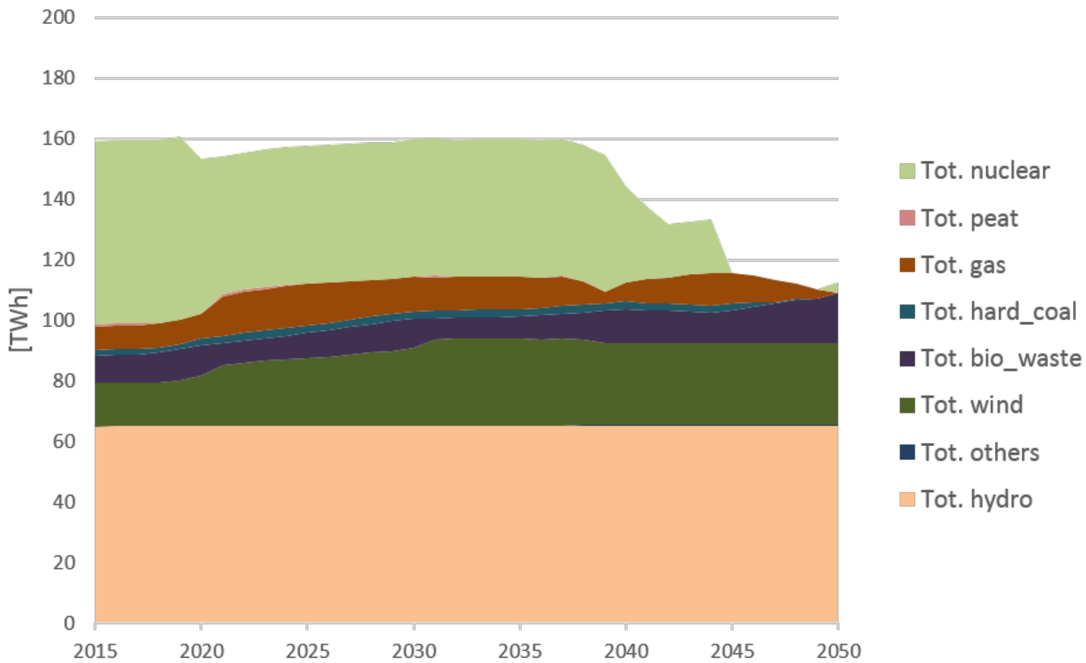

Figure B.19: *Electricity generation in Sweden for scenario Regional Policy*

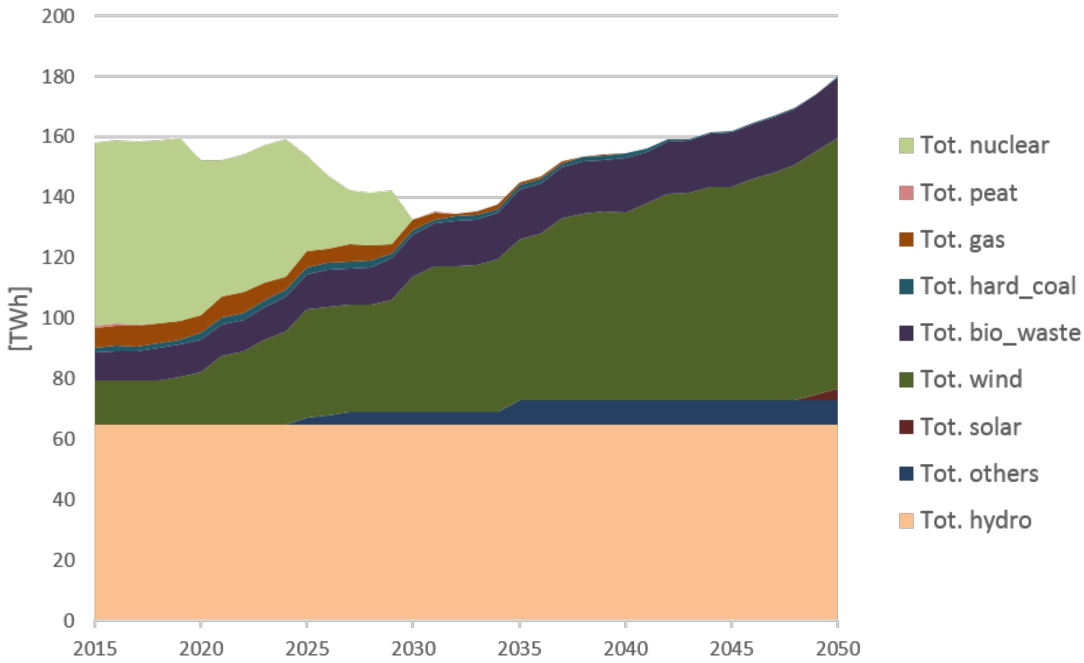

Figure B.20: *Electricity generation in Sweden for scenario Green Policy*

Poland

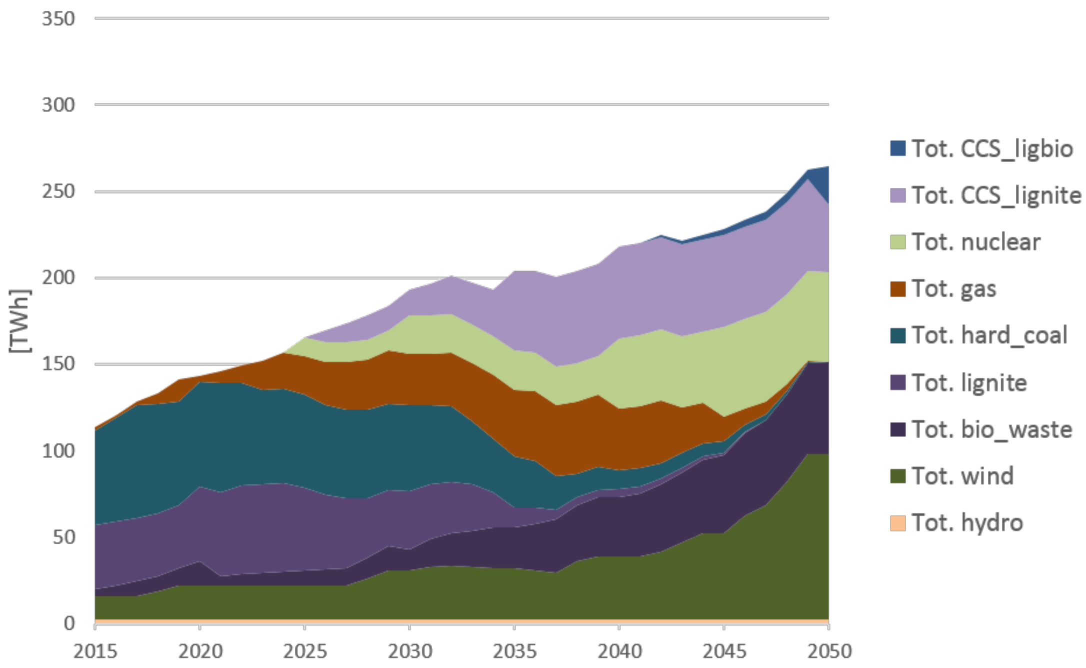

Figure B.21: *Electricity generation in Poland for scenario Climate Market*

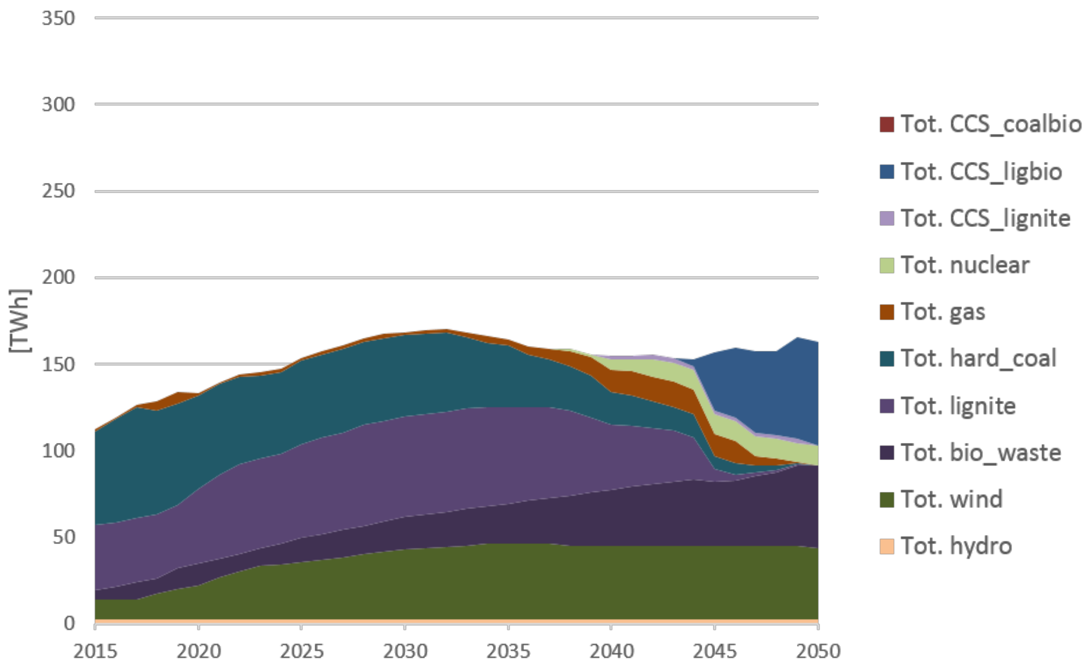

Figure B.22: *Electricity generation in Poland for scenario Regional Policy*

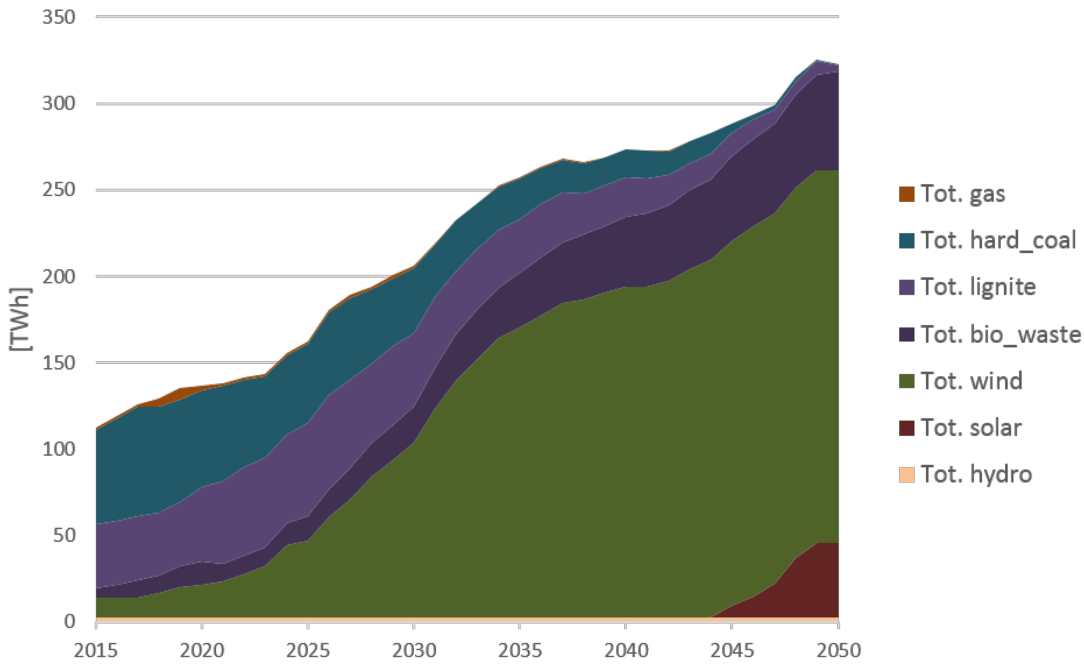

Figure B.23: *Electricity generation in Poland for scenario Green Policy*

Investment Cost

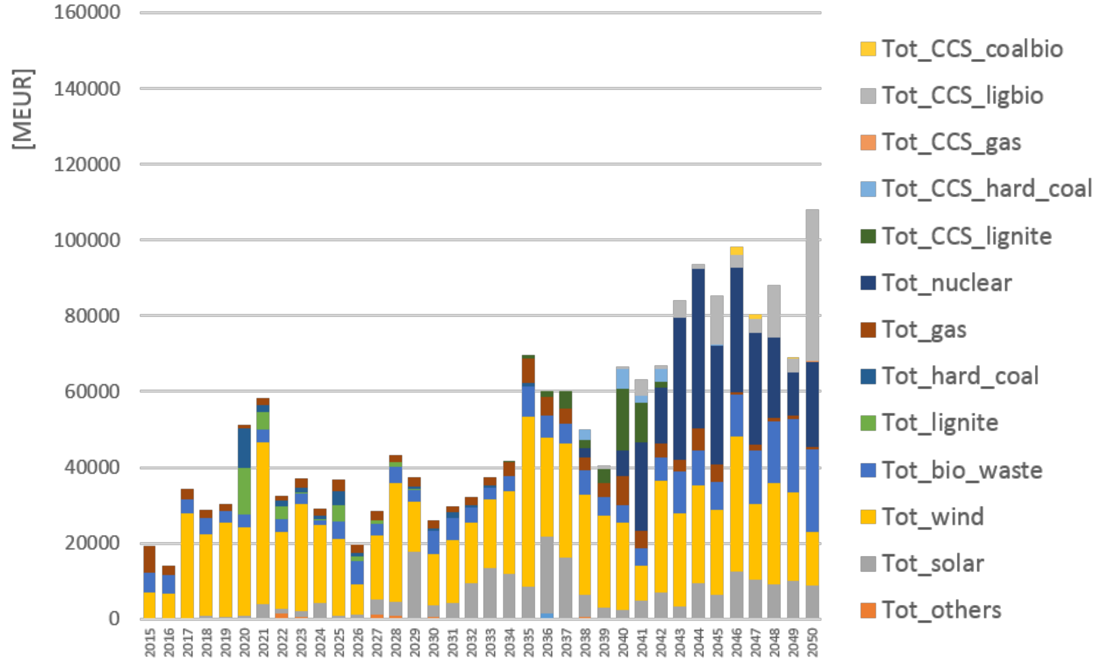

Figure B.24: *Investment cost in Europe for scenario Climate Market*

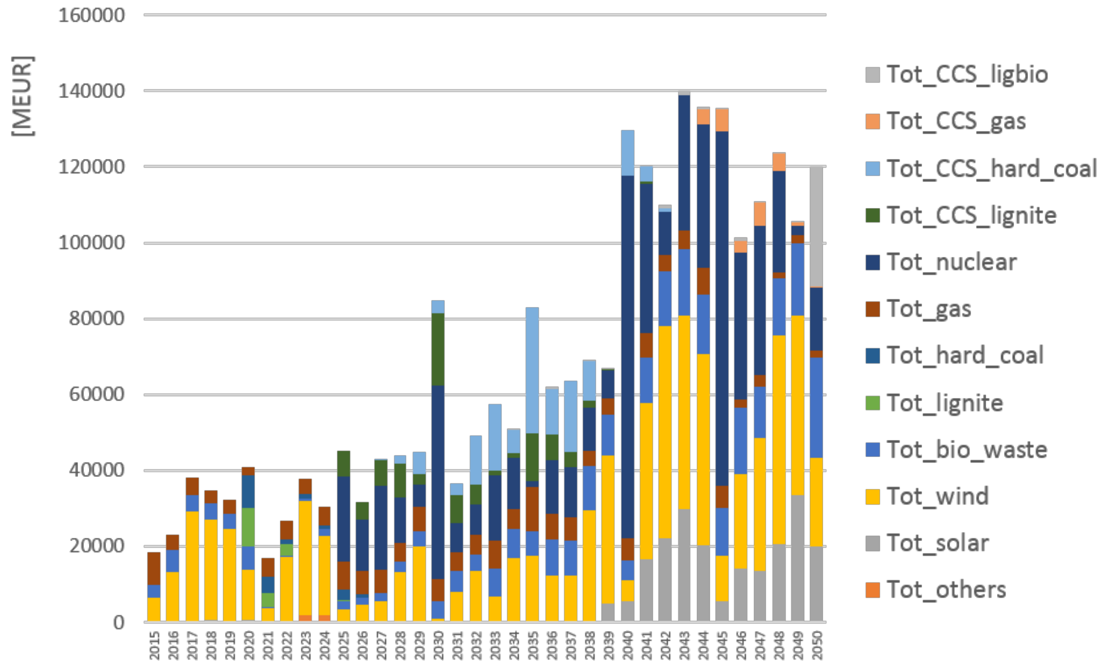

Figure B.25: *Investment cost in Europe for scenario Regional Policy*

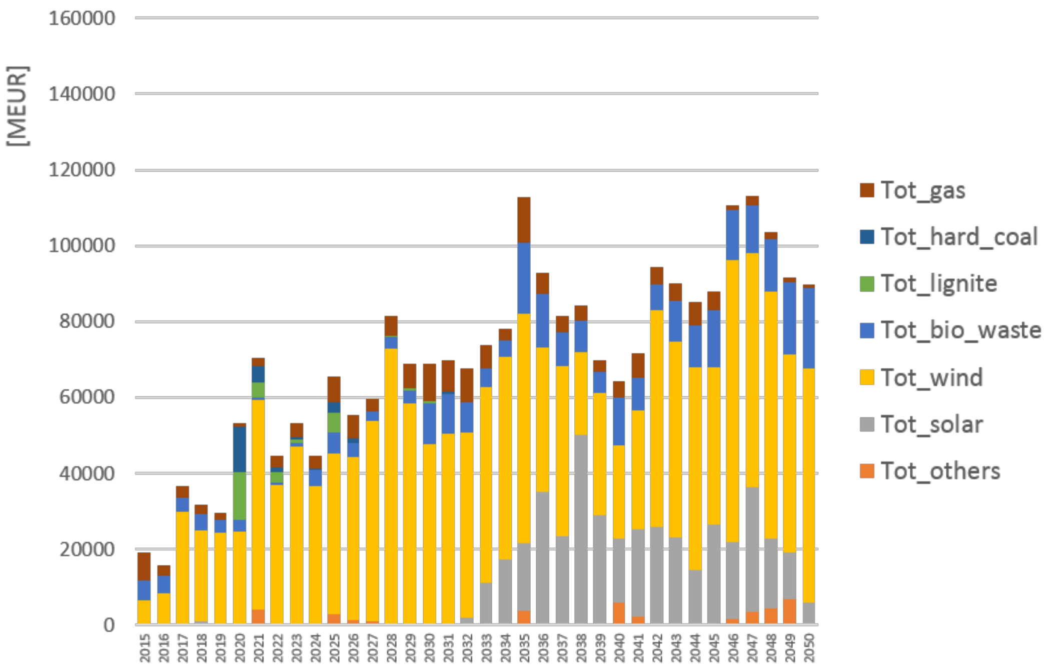

Figure B.26: *Investment cost in Europe for scenario Green Policy*

Capacity Increment

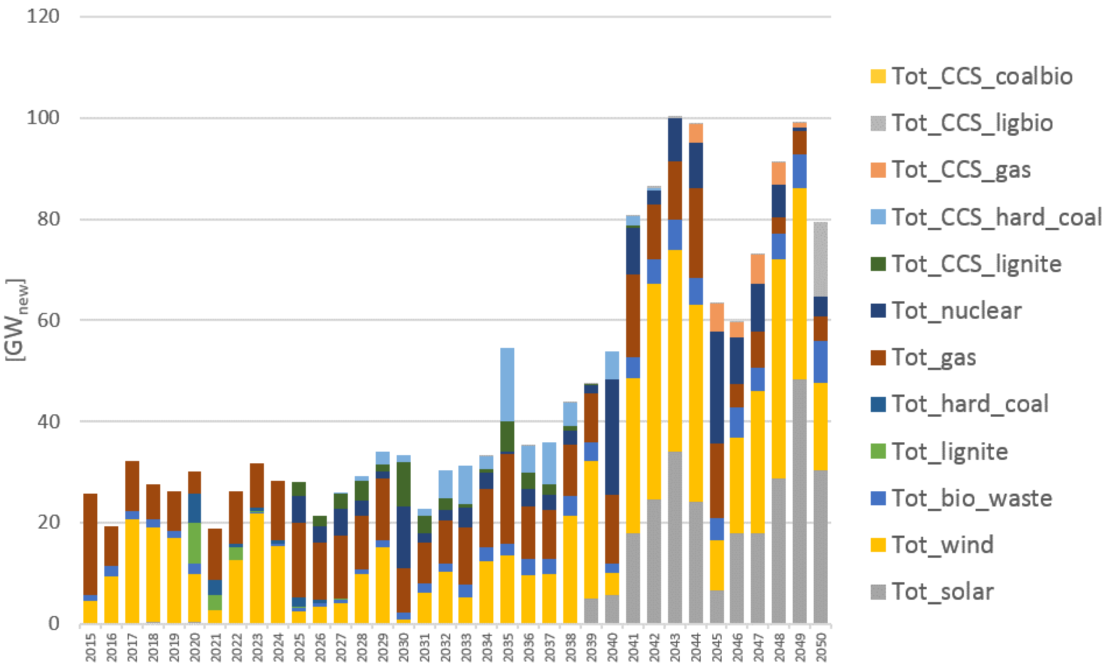

Figure B.27: *Capacity increment in Europe for scenario Climate Market*

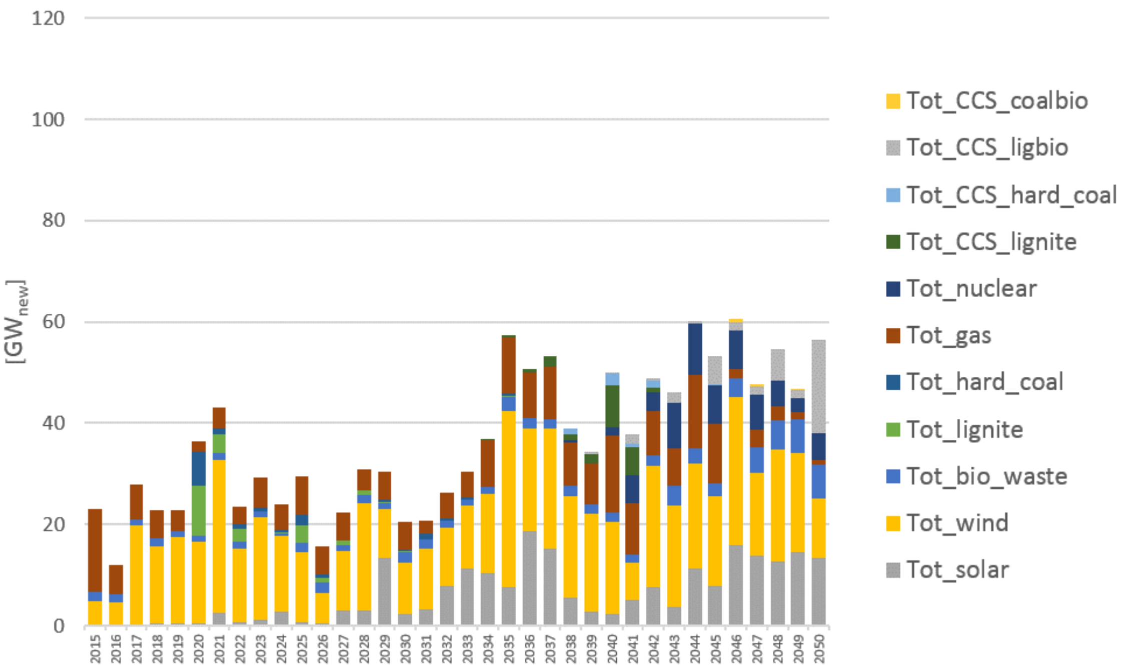

Figure B.28: *Capacity increment in Europe for scenario Regional Policy*

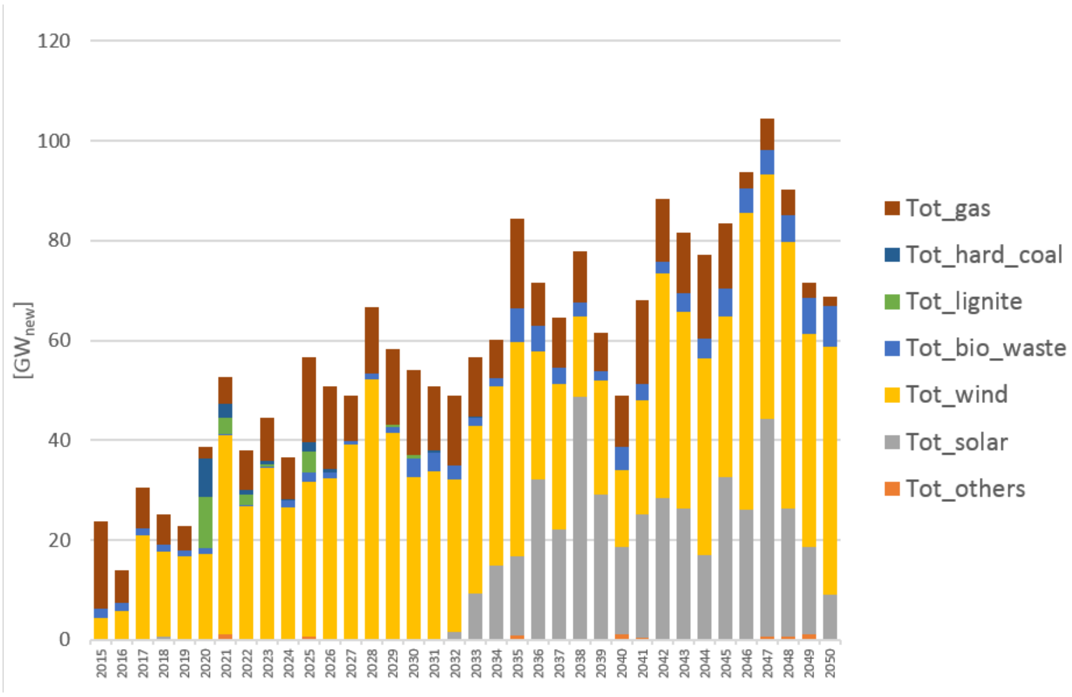

Figure B.29: *Capacity increment in Europe for scenario Green Policy*

CO_2 Emissions

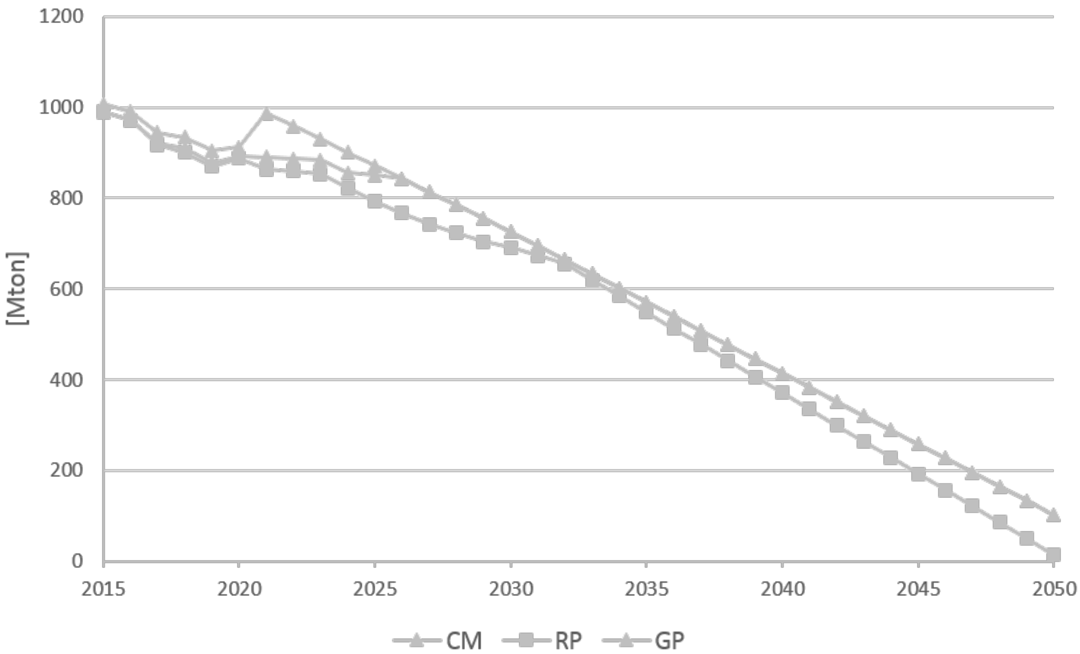

Figure B.30: *CO_2 emissions in Europe for all policy scenarios*

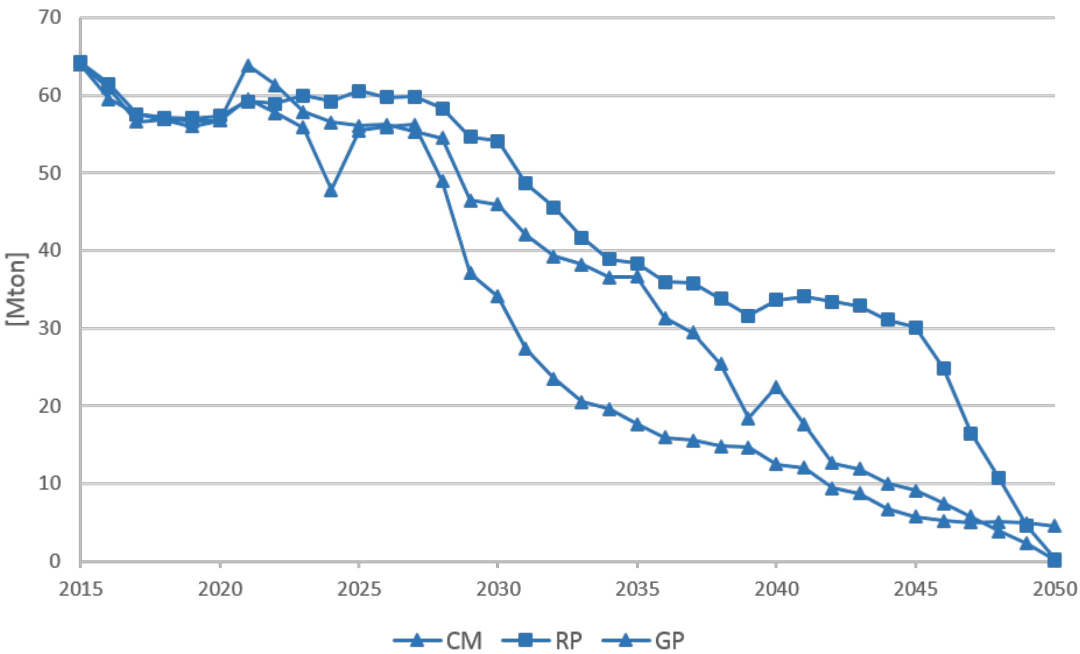

Figure B.31: *CO_2 emissions in the Nordics for all policy scenarios*

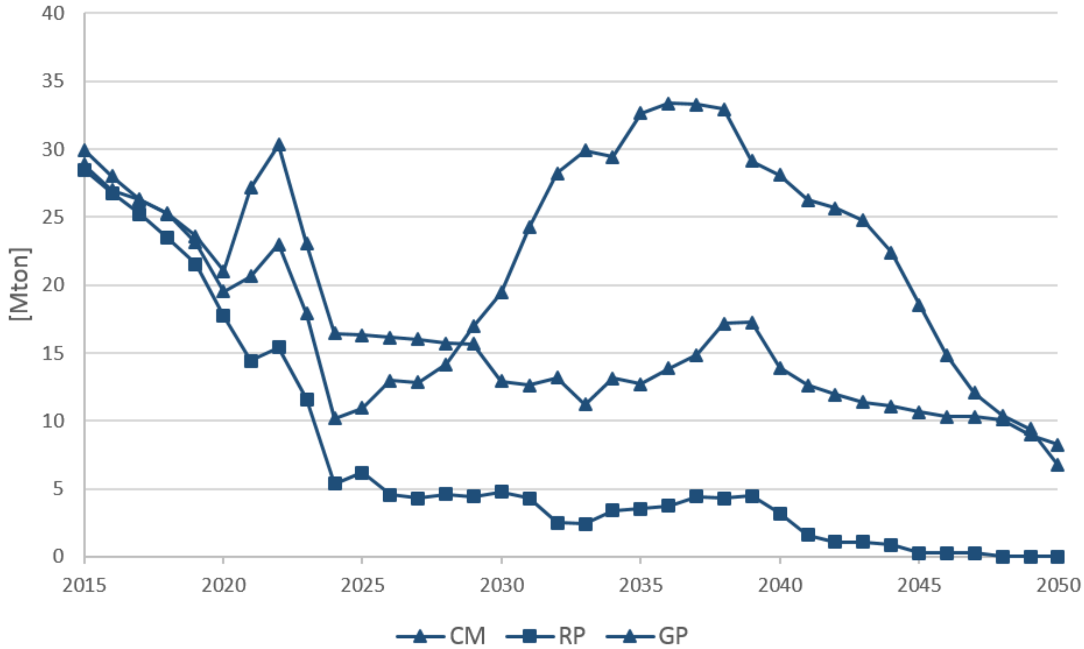

Figure B.32: *CO_2 emissions in France for all policy scenarios*

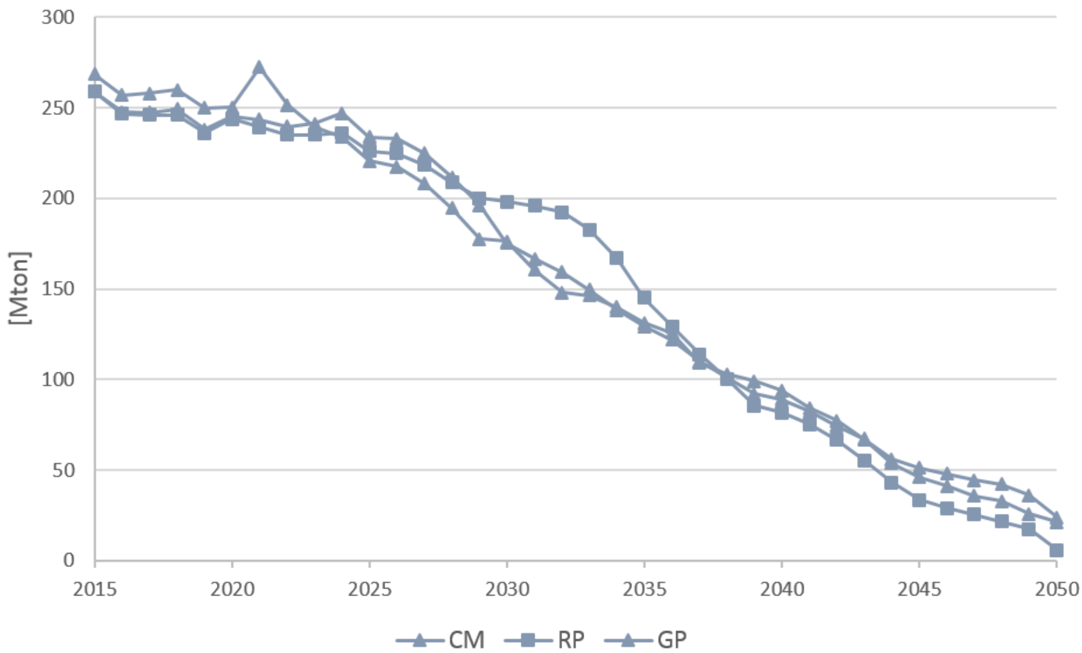

Figure B.33: *CO_2 emissions in Germany for all policy scenarios*

Marginal Electricity Price

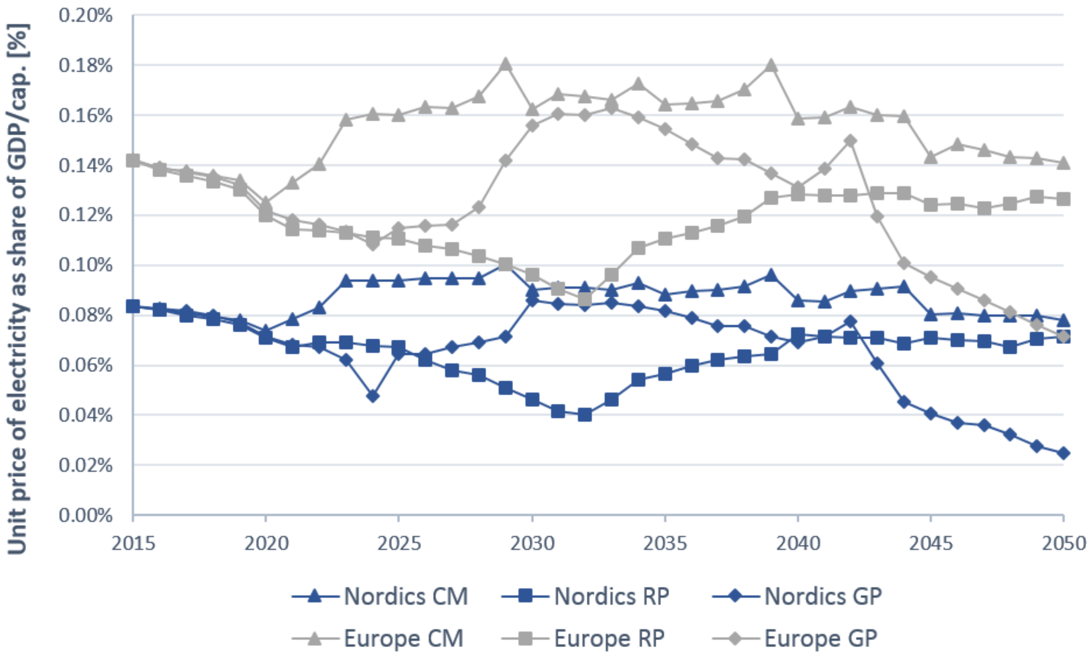

Figure B.34: *Annual average marginal electricity prices in Europe and the Nordics*

C

Projections of GDP and population

Gross Domestic Product

Table C.1: *Long-term Gross Domestic Product projection (EC, 2016). Long-term Gross Domestic Product projections for Norway and Switzerland are retrieved from OECD (2017).*

Gross Domestic Product from 2015 to 2050 (in 000 million €)					
	2015	2020	2030	2040	2050
Poland	425	492	623	726	793
Sweden	404	448	552	684	841
The Nordics	1 242	1 393	1 689	2 037	2 443
Europe	14 222	15 458	17 802	20 771	24 101

Population

Table C.2: *Population projection (EC, 2016).*

Population in 2015 to 2050 (in millions)					
	2015	2020	2030	2040	2050
France	63	64	67	69	71
Germany	81	81	80	78	75
Poland	38	38	37	36	35
The Nordics	26	28	29	31	32
Europe	514	520	528	534	537

GDP per capita

Table C.3: *GDP per capita as constructed from tables C.1 and C.2*

GDP per capita in 2015 to 2050 (in EUR/capita)					
	2015	2020	2030	2040	2050
The Nordics	47 430	50 585	57 531	65 506	77 082
Europe	27 648	29 715	33 720	38 867	44 916