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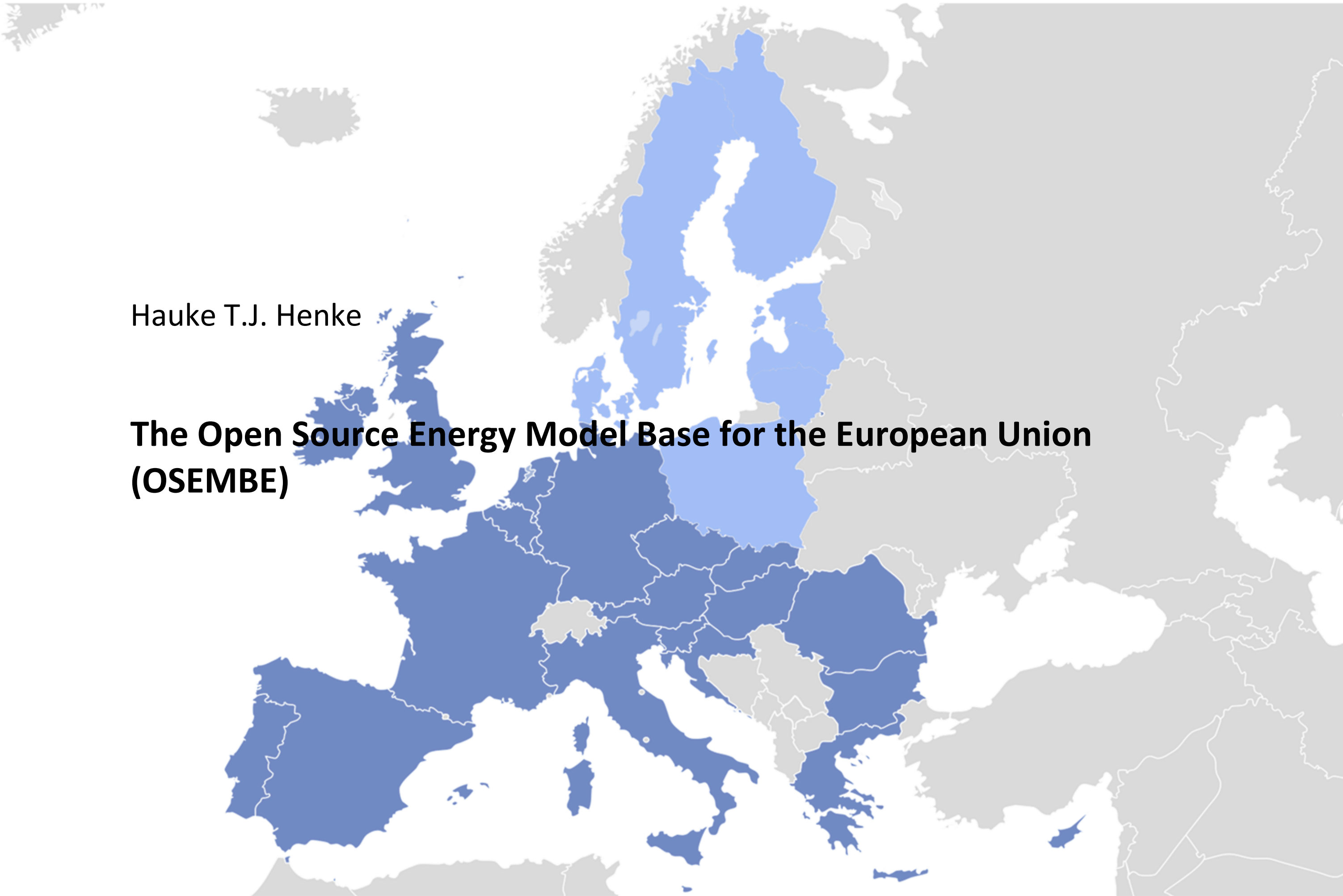

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The Open Source Energy Model Base for the European Union (OSEMBE)

Master's thesis

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Abstract of master's thesis

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Abstract

In this thesis, the Open Source Energy Model Base (OSEMBE) for the European Union was developed. Thus far the model covers seven countries around the Baltic sea, though preparatory work was done for adding the other countries of the union soon. OSEMBE, and hence this thesis, aims to provide an open-access, comprehensive and easy to understand long-term model for Europe. By doing so, it aims to lower the threshold to join and contribute to the discussion about the future of European energy supply. This shall widen the circle of researchers dealing with energy systems modelling and make the energy discussion more transparent. OSEMBE is built using the Open Source Energy Modelling System (OSeMOSYS). As such, OSEMBE calculates the lowest net present value for the modelled system and period by using linear optimization. The modelling period covers the years from 2015 till 2050. Existing trans-border transmission capacity between the included countries – Denmark, Sweden, Finland, Estonia, Latvia, Lithuania and Poland – is considered in the model. New trans-border transmission capacities, currently under construction or in the planning phase, are considered from the expected starting date of operation. The connections to countries not covered by the model are not modelled as of yet. Ten fuels are used by the technologies defined in the model, namely biomass, coal, geothermal, heavy fuel oil, hydro, natural gas, nuclear, wind and waste. Each fuel can be used by several technologies. In addition to technology parameters like investment cost, fuel cost, and fixed and variable operation and maintenance cost, an increasing emission penalty for carbon dioxide is defined, which represents the cost related to the emission of greenhouse gases (similar to the European emission trading system). Domestically produced fuels are assumed to be cheaper than imported ones, but domestic production is limited depending on the countries' resources. The thesis is divided into five chapters. In the first chapter the motivation for the thesis is explained. The second chapter sets the objective of the work, before the creation of the model is described in chapter three. General results and the results of a sensitivity analysis of the influence of the reserve margin are shown and discussed in the fourth chapter. In the last chapter conclusions are drawn and a guideline is laid out on how the development of OSEMBE could be continued, e.g. through improvement of the transmission, implementation of heat, storage and traffic.

Keywords Energy system, open source, Europe, electricity, long-term, OSeMOSYS

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List of abbreviations

Abbreviation	Full word
BM	Biomass
CHP	Combined Heat and Power
CO	Coal
CSP	Concentrated Solar Power
DI	Distributed solar PV
EC	External Combustion Engine
EU	European Union
EWEA	European Wind Energy Association
ETRI	Energy Technology Reference Indicator projections for 2010-2050
ETSAP	Energy Technology Systems Analysis Program
FC	Fuel Cell
FOM	Fixed Operation and Maintenance cost
G2	Second generation of nuclear power plants
G3	Third generation of nuclear power plants
GC	Gas Cycle
GHG	Greenhouse gases
GO	Geothermal
GW	Giga Watt
HF	Heavy Fuel oil
HY	Hydro power
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IRENA	International Renewable Energy Agency
KTH	Kungliga Tekniska Högskolan
LCOE	Levelised cost of electricity
LWR	Light Water Reactor
NG	Natural gas
NTUA	National Technical University of Athens
NU	Nuclear Power
O&M	Operation and maintenance
OSEMBE	Open Source Energy Model Base for the European Union
PJ	Peta Joule

PV	Photovoltaic
RC	Reciprocating Engine
RE	Renewable energies
RES	Reference Energy System
RM	Reserve Margin
SAMBA	South American Model Base
SO	Solar power
ST	Steam cycle
TEMBA	The Electricity Model Base for Africa
TIMES	The Integrated MARKAL-EFOM System
US	United States of America
UT	Utility solar PV
VOM	Variable Operation and Maintenance cost
WEIO	World Energy Investment Outlook
WI	Wind power
WS	Waste

1 A contribution to a transparent discussion about the future of the European energy supply

The analysis of the energy supply of modern societies, now and in the future, is probably more interesting than ever, due to a combination of reasons. First of all, the overall energy demand on earth is still strongly rising. Second, the anthropogenic greenhouse-effect makes a reduction of greenhouse gas emissions necessary. Last but not least the depletion of fossil fuel sources will cause higher extraction costs in the future (IPCC 2007).

Against this background, it is of high relevance for governments, energy intensive companies, investment organizations like pension funds or insurance companies, but also private investors to get an idea of how the energy system could develop in the coming decades.

To make predictions on the development of the energy system, several models - or rather modelling tools – have been developed since the 1980s by different organizations. A relatively well-known one is the PRIMES model, created by the National Technical University of Athens (NTUA). It has been used to generate energy projections for many European countries and also for the EU as a whole entity (E^3M - Lab 2016). In the context of the development of the "Energy Roadmap to 2050" for the EU, the European Commission was criticised for using a model that is not entirely open to the public. The criticism was that without access to the whole model, it isn't possible to retrace its results or reproduce them. Such a possibility to reconstruct the model would be important, especially for a topic with such a high relevance. Reacting to the criticism, Professor Pantelis Capros, who built up the model, declared that he agrees that transparency is of high importance in the context of such a sensitive topic, but that software itself should not be published (Clark 2011). Another modelling framework used in energy system analysis was developed by the International Institute for Applied Systems Analysis (IIASA), and is called MESSAGE. MESSAGE is free for academic use, but due to its complexity it is recommended to attend a course on how to use it before working with it (IIASA 2016). A third internationally-known model generator is "The Integrated MARKAL-EFOM System" (TIMES), which was developed by the IEA – Energy Technology Systems Analysis Program (ETSAP) (IEA ETSAP 2016). TIMES is commonly managed by a shell or rather a data handling software, e.g. ANSWER or VEDA. Unfortunately, these shell software entail license costs (Department of Development and Planning, Aalborg University 2016).

The limitations of the existing models, or rather modelling systems, mentioned above forged the motivation to create a new model of the European energy system while using a free and relatively simple modelling system. A model built this way will be accessible and usable by a broader group of people than the currently existing ones. As a result it will be possible to support an open and transparent public discussion.

Table 1.1: Modelling tools used for existing energy models of Europe

Modelling tool	Owner/Developer	Critical issue
TIMES	IEA ETSAP	License cost
MESSAGE	IIASA, IAEA	Complex
PRIMES	NTUA	Code is not open

2 Development of an Open Source Energy Model Base for the EU (OSEMBE)

The aim of this thesis is to develop the core part of an energy model for the EU that is open source, and thereby provide a contribution to the discussion around where the EU will source its energy in the future.

When planning a model that shall be extended in the future, the central questions are: What has to be considered from the beginning, and what can be left for later? Where is it important to include details, and where is it possible to make simplifications that can be improved by follow up projects?

In this work the focus is to develop a model, where power-generating technologies are differentiated by fuel, size and conversion type. By using these three categories, the technological differentiation will be relatively detailed. A differentiated catalogue of technologies has the advantage that fewer generalizations in terms of technology parameter need to be done. A quoted target is to develop an Energy Model Base for the whole EU, but as it is very time-consuming to gather and prepare the data for all the 28 member countries, this thesis is a first step in which just a group of countries out of the 28 EU members will be included. However, the aim of this thesis is also to ease the extension of the model from a selected group to the whole union. Therefore, when defining parameter such as the day split – the length of one part of one specific day as a fraction of the year – the whole Union shall be considered as the reference and not the group of countries that will be finally included in the model created in this work (Mosknes et al. 2015). In the transition to renewable energy sources, the interrelation of different forms of energy gains more and more importance, starting with combined heat and power plants and pumped hydropower to electricity to heat and electric mobility. Looking at these topics, it becomes clear that the final energy demands, like electricity, heat, and transport, are interrelated. Nevertheless, in this core of an energy-model for the EU, the focus shall be put on the final electricity demand, and how it is satisfied in the present and how it could be satisfied in the future. Due to this limitation, the model will be incomplete, as electricity and heat generation are often very interrelated, but it simplifies the objective of the thesis. The generation and use of heat are a part of the energy system that should be added in the work following this project.

To sum up, the aim of this thesis is to develop a long-term electricity model of a group of European countries, with the potential to be extended to a model of the EU, and with the possibility to add other categories of energy demand alongside electricity demand.

3 Creation of OSEMBE 1.0

For this thesis the methodology and approach of previous work by KTH dESA (division of Energy Systems Analysis) was used (Taliotis et al. 2016; Moura and Howells 2015). In the following subchapters, the methodology used to develop the base of an electricity model for the EU is described. More specifically, the structure of the model, the modelling tool used and the central assumptions are described. The model itself is open source and can be accessed from source code to data. This ensures repeatability and access.

3.1 OSeMOSYS

OSEMBE was developed using OSeMOSYS – the open source energy modelling system. The energy models created in OSeMOSYS are linearly optimized. The models are dynamic, bottom-up, multi-year models. Like other models, OSeMOSYS assumes a perfect market with perfect competition and foresight (Taliotis et al. 2016). The results of an OSeMOSYS model indicate a cost-optimal solution to satisfy an externally defined set of demands. By using different demand projections, it is possible to evaluate investment strategies, with the background of possible developments. OSeMOSYS was developed with a special focus on people who have difficulties to get access to current energy models or their software, due to license cost or closed codes. The aim was to enable students, business analysts, researchers and developing country governments to investigate and work on energy models (Howells et al. 2011). Therefore, the model is open source, and usable with open source software. Furthermore, the model is designed in a straightforward way, so that it is easy to understand and use in comparison to other models. The model consists of seven ‘blocks’ of functionality and has three levels of abstraction. The blocks are interrelated and connected, but the single blocks can be updated or replaced by a new block with new functionality. The seven blocks of the current OSeMOSYS version specify the objective (1), costs (2), storage (3), capacity adequacy (4), energy balance (5), constraints (6), and emissions (7). Each block consists, as already mentioned, out of three layers of abstraction, which are: plain English description (1), an algebraic formulation of the English description (2), and the implementation of the model in a programming language (3) (Howells et al. 2011). These levels of abstraction of OSeMOSYS are also shown in Figure 3.1 below.

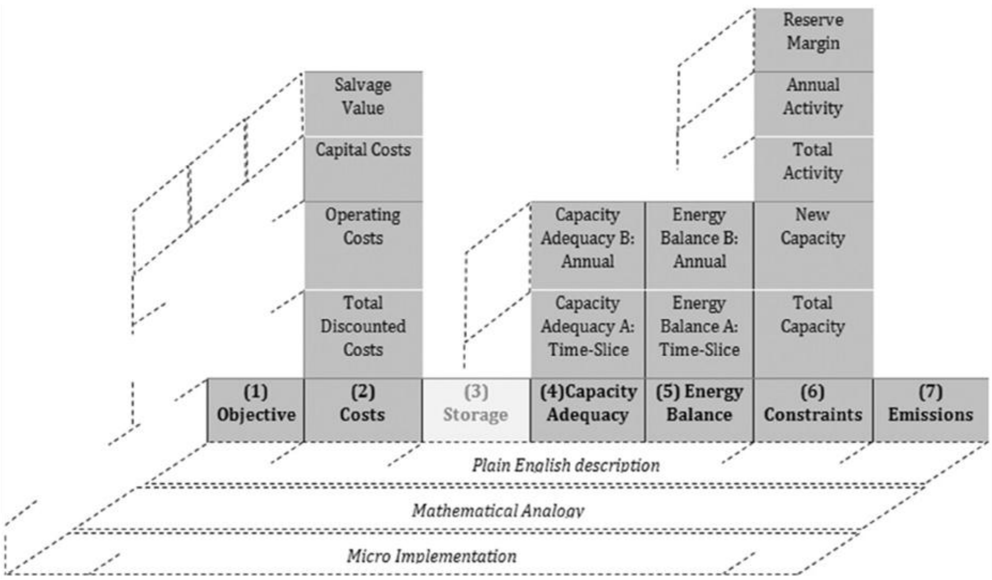


Figure 3.1: OSeMOSYS levels of abstraction

The description in plain English might be the starting point of the OSeMOSYS model itself, but there must exist something to describe. This is usually a reference energy system (RES), representing the energy system that is going to be modelled. The function and the characteristics of RESs are described in the following subchapter.

3.2 Design of the Model Structure

The design of OSEMBE is very similar to the design of "The Electricity Model Base for Africa" (TEMBA) and the structure of the "South American Model Base" (SAMBA) (Taliotis et al. 2016; Moura and Howells 2015). Like in these two model bases, OSEMBE contains a group of countries that is interconnected by electricity transmission capacities. An initial stage in the development of the model was the creation of single country models, that work independently and stably. In the next step, the independent countries were connected by implementing the existing and planned transmission lines.

In the final step a sensitivity analysis was done, evaluating the effect of the reserve margin (RM). Three scenarios were generated: The base case was a scenario with a RM of 20%, a high RM scenario was created with a RM of 25% and a low RM case with a RM of 15%. These three scenarios were compared to analyse the effect of the RM on the levelised cost of electricity (LCOE), the share of renewable energy technologies in the installed capacity and in produced electricity.

An important element of this first part of OSEMBE is the typology of technologies that are included in the model base. The goal was to have a broad set of technologies, that is differentiated by their size, their fuel, their way of energy conversion and their age. In this context the "Energy Technology Reference Indicator Projections for 2010-2050" by the European Commission were an important source and guideline when defining the set of technologies implemented in the model base (EC 2014a). As already indicated, the two main factors for defining the set of technologies available are fuel and the form of energy conversion. The fuels, or rather the fuel groups, that are defined are: Biomass (BM), coal (CO), crude oil (OI), heavy fuel oil (HF), hydro (HY), natural gas (NG), nuclear (NU), solar (SO), wind (WI) and waste (WS). For the energy conversion, or rather the technology, the following types were defined and implemented: Concentrated solar power (CSP) - generic (C1), CSP – cogeneration (C2), CSP with gas co-firing (C3), combined cycle (CC), combined heat and power (CHP), distributed solar photovoltaic (PV) (DI), hydro power dam (DM), dam with pumped storage (DS), external combustion engines (EC), fuel cells (FC), gas turbine cycle (GC), internal combustion engines with heat recovery (HP), wind power offshore (OF), wind power onshore (ON), reciprocating engines (RC), steam turbine (ST), utility scale PV (UT) and wave power (WV). Some of the technologies are specifically related to one fuel, e.g. wind power or solar PV, but other technologies like CHP or ST are more flexible and can be used with different types of fuels.

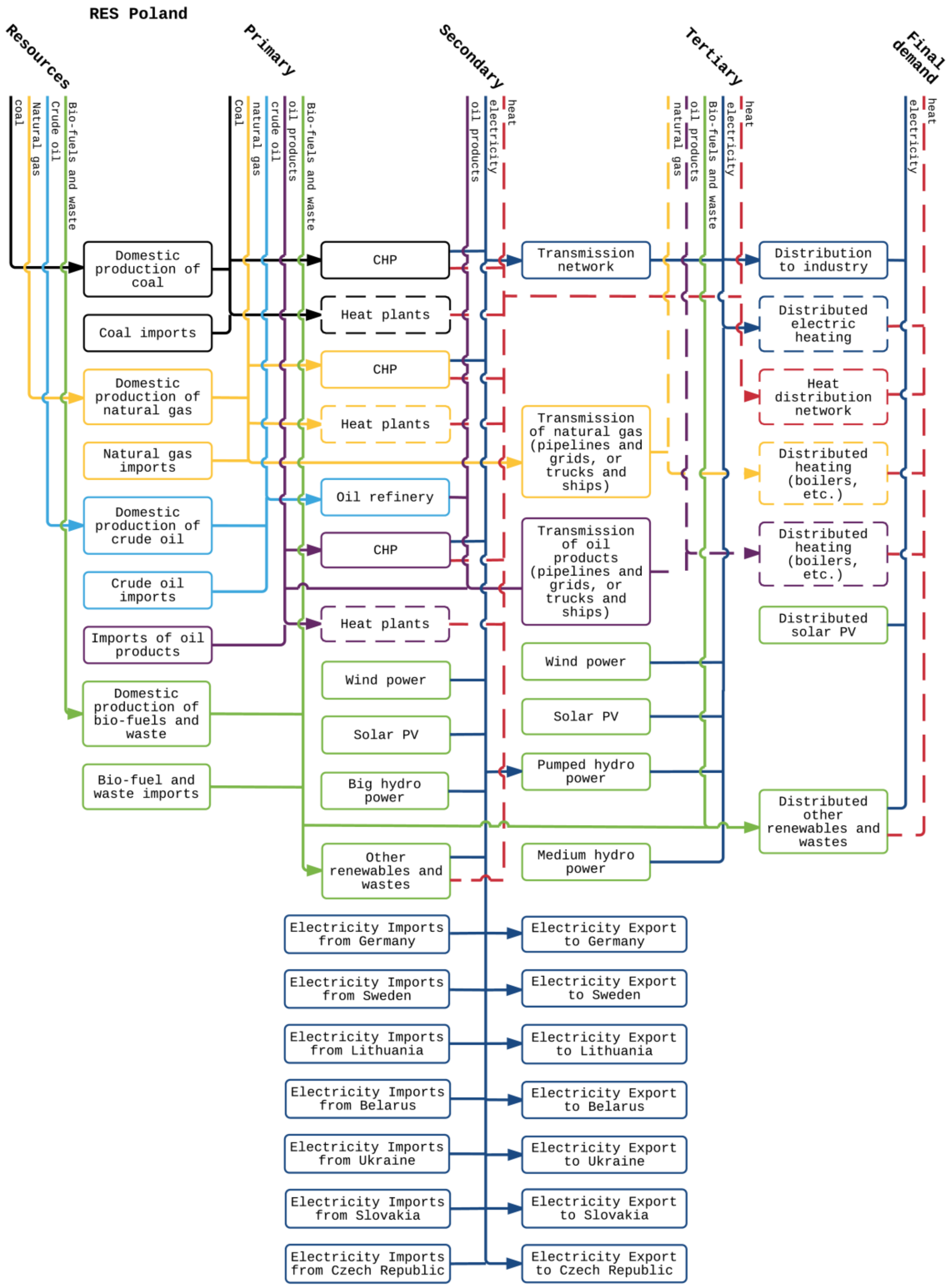
Of similar importance to the typology of technologies is the definition of the time slices for the model base. Time slices are defined parts of the year with a characteristic level of energy consumption, i.e. that the day is divided into pieces of different energy consumption levels like day and night. But the energy, or rather the electricity consumption, does not just vary over the day, but also within longer periods of time like months or seasons. Therefore, the time slices are defined as a part of a day and as a fraction of a year, e.g. if a time slice is defined as daytime in June, the fraction of the year is calculated that is daytime in June ((12hx30d)/(24hx365d)) (Mosknes et al. 2015). By defining more time slices, a model can become more accurate and reproduce the consumption pattern in a more detailed way. When defining fewer time slices, the focus is more on the overall trend of energy consumption and the calculation time decreases. In OSEMBE, one aspect of interest is the integration of renewable energy technologies. Taking this under consideration, it is important to define the time resolution high enough to be able to portray the characteristics of the renewable energy technologies, like the cyclic variation in production of solar technologies. To be able to represent the fluctuations in energy consumption over the day and to keep calculation times as low as possible, the days are mostly split into three time slices. Seasonal variations are considered by defining time slices for each month of the year. The method that was applied to define the time slices is described in chapter 3.4.

Reference Energy Systems

After the decision about what is going to be modelled, the first step is often the generation of a RES (Howells et al. 2011; IAEA 2012). The process of creating a RES is helpful to get an overview of the energy system to be modelled, and indicates what is going to be included in the model. The development of OSEMBE for the European Union (EU) was started by generating RES's. At this point, it is important to mention that one RES for every single member country of the EU was created, rather than one single RES for the EU as a whole. There are two main reasons for this approach. First fact is that the national energy systems in the EU are connected but not (yet) joined to one single system with same regulations, subsidies and one market. The second reason is that the focus of this work is also to investigate the electricity exchange between the countries, and this is easier to do when the countries are clearly divided into separate but connected systems.

The RESs have, as mentioned previously, the purpose of recording the characteristics of the current energy systems in the selected countries, i.e. to indicate the fuels used, where they originate from, the technologies used for energy conversion and the existing demands. A RES indicates what technologies are used, what demands exist, and how they are satisfied. However, a RES does not contain any numerical values, and there is no quantification of the presented energy system. On the following page an example of the RES of Poland is shown.

On the right of the RES, see Figure 3.2, the resources of the country are indicated, on the left the demands. In between are the primary, secondary and tertiary energy levels, which can be considered as stages in the energy conversion from resource to final energy. The final energy is used to satisfy a demand. Interesting country-specific characteristics are e.g. the number of domestic resources, technologies used to generate electricity, and the number of connected neighbouring countries (lower part, secondary energy). A RES is a qualitative description of an energy system.



Sources: http://www.iea.org/statistics/statisticssearch/report/?year=2013&country=GREECE&product=RenewablesandWaste,

Figure 3.2: Reference energy system of Poland

The RESs of the other six modelled countries can be found in Appendix A - Reference Energy Systems.

3.3 Assumptions

In the process of building a model, it is necessary to make fundamental assumptions that have a big influence on the model and its results. In this chapter the most important assumptions shall be explained.

3.3.1 Units

The time horizon of the model, or the *modelling period*, is 2015 to 2050. The end of the modelling period can affect the results, as the attractiveness of short-term solutions might increase. Such changes in the results are called ‘edge-effects’. To prevent these so called ‘edge-effects’ from influencing the results of the model, the modelling period is extended till 2060.

The *default unit* in OSeMOSYS is petajoule (PJ). That means that energy flows, demands etc. are measured in PJ and when entered they need to be converted to PJ.

Capacities, like residual capacity or the installed capacity during the modelling period, are measured in gigawatt (GW).

The *monetary unit* for the whole modelling period within OSEMBE is 2015 US Dollar (US$).

All *costs* in the model are in million US$ per GW (MUS$/GW), this is equivalent to US$/kW. Only *variable costs* are in MUS$/GWh.

An important parameter, in the context of including the overall cost of fossil fuel based technologies, is the *EmissionActivityRatio*. It indicates how much greenhouse gas is emitted while using the technology. The *EmissionActivityRatio* is measured in kilotons per PJ (kton/PJ).

Related to the emissions is the *EmissionPenalty*, which is implemented for the CO_2-emissions and CO2-equivalent emissions of fossil fuel using technologies. The *EmissionPenalty* is given in M$/kton CO_2.

3.3.2 Parameters

The *discount rate* is kept constant at 5% during the entire modelling period.

The forecast used for the electricity demand is by the European Commission, and ends in 2050 (EC 2014b). Therefore, it was necessary to extrapolate how the demand develops in the period from 2050 to 2060. It was assumed that the trend of the previous years will continue. To extend the demand projection, the growth rate of the electricity demand for the years 2049 and 2050 was calculated. If it was constant it was assumed to stay constant. In several cases the growth rate was slightly decreasing, and this trend was continued if found.

Figure 3.3: Defining the time slices

As already described above and shown in Figure 3.3, in OSEMBE the year is presented by 36 characteristic time periods (12 months and day, peak, and night), but to be precise one period is set to zero (peak July) so the model consists of 35 times periods. By this the seasonal, but also the changes within a day of consumption and availability of RE-sources, are considered.

3.4 Analysis of the consumption patterns of the included countries

To model an energy system, it is important to analyse demand pattern(s), as the energy demand is varying over time. For different periods of time, e.g. day, week, season, there are typical patterns and characteristic heights of demand. Furthermore, the pattern varies for different levels of an energy system, i.e. household, city, country and region. Each country has its own characteristic consumption pattern, in addition to the influence of seasons and geographic location. This depends on many other factors, e.g. the shares of industry, service, and residential sector in the consumption, cultural habits like sauna or construction standards. Considering this, and the fact that the model is consisting of the models of the single countries that are interrelated, the consumption pattern of every country was investigated individually. In this context, we are only talking about electricity, as no other final energy demands will be included in the model at this stage of development. The consumption patterns were analysed based on hourly load data of ENTSO-E – the European Network of Transmission System Operators of Electricity (ENTSO-E 2016). The aim was to divide the average daily consumption pattern for each month into several time slices of relatively constant load level. After creating average daily load curves for each month, it turned out that the best way to split the load pattern was to divide it into three time periods, sometimes just into two. In Figure 3.4 the average consumption curves for each weekday in January 2015 in Sweden are shown. Based on the curves, the days in January are split into the time periods 8 a.m. till 3 p.m., 3 p.m. till 12 a.m., and 12 a.m. till 8 a.m.. The first time slice could be named January day, the second January peak, and the last January night, but to have short codes for them they are called: S1B1, S1B2 and S1B3. S stands for season and B for break. The number behind the letter indicates which season (month) or rather which part of day (day, peak or night) it is.

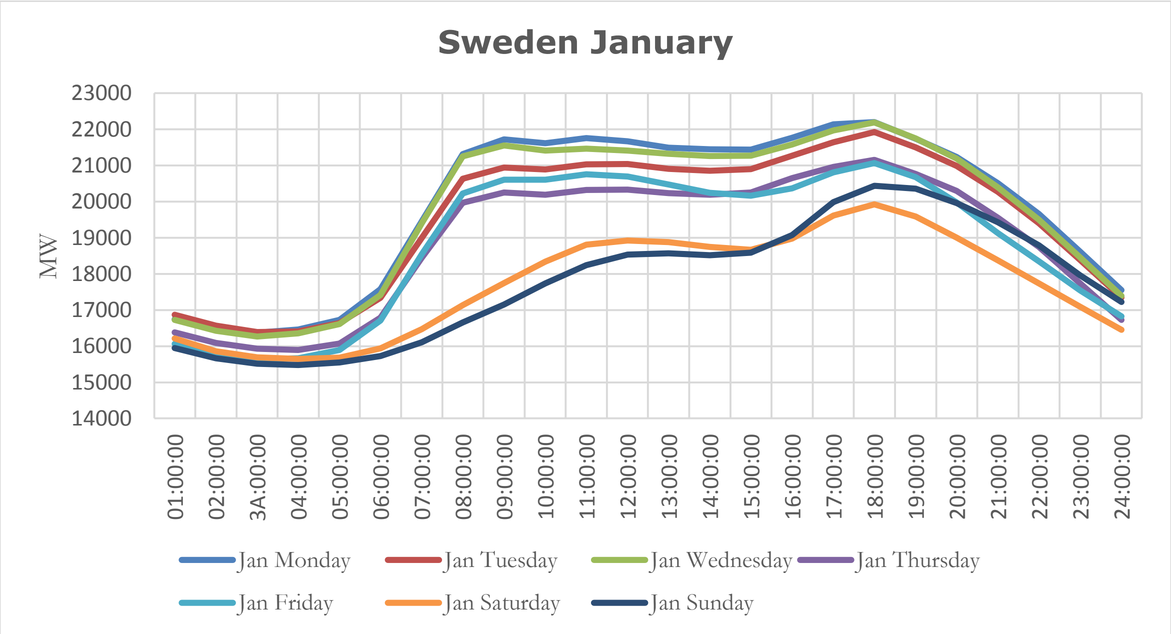


Figure 3.4: Load curves January, Sweden

With this approach, all months for all EU28 countries, except Malta, were analysed and characterised. Malta was not analysed due to the reason that there was no data found. Till 2015 the electricity system of Malta was not connected to the continent and the transmission grid operator was not member of ENTSO-E (ENTSO-E 2015). Based on the monthly day splits, the 'SpecifiedDemandProfile' was calculated, i.e. the share for each time slice in the overall annual electricity consumption was calculated. This was necessary as the 'SpecifiedDemandProfile' is an input to every OSeMOSYS model.

Generation of an average year split

OSEMBE focuses on the region of the EU, and to model this region, it is necessary to define a common year split, i.e. out of the 27 previously created country-specific year splits, one common set of time slices had to be generated. This was done by calculating the weighted average of the day split times. Every country was weighted by its share in the overall EU electricity consumption. This means that countries with a higher consumption of electricity have a bigger influence on the times of the common EU year split than countries with a lower consumption. The final day split and their share of the time of the year are shown in Table 3.1 on the following page. In Appendix A. - Specified Demand Profiles the split of the load can be found.

The year split is an important characteristic of an energy system, but it is possible that it changes over the years, e.g. when specific users in the industrial sector grow or shrink (Howells et al. 2011). However, in this work it shall be assumed that the year split stays constant over the whole modelling period. In a follow-up work, the final demand could be divided into final demands by sectors, e.g. industrial, residential, and commercial. By considering the development of the sectors independently, a change of the year split could be forecasted.

Table 3.1: Weighted day split

Month	Day Split	Start hour	End hour	Year Split
January	Day	08:00	15:00	0.0282
	Peak	16:00	23:00	0.0282
	Night	24:00	07:00	0.0282
February	Day	08:00	16:00	0.0297
	Peak	17:00	23:00	0.0231
	Night	24:00	07:00	0.0264
March	Day	08:00	16:00	0.0318
	Peak	17:00	23:00	0.0247
	Night	24:00	07:00	0.0282
April	Day	08:00	18:00	0.0376
	Peak	19:00	23:00	0.0171
	Night	24:00	07:00	0.0273
May	Day	08:00	18:00	0.0388
	Peak	19:00	23:00	0.0176
	Night	24:00	07:00	0.0282
June	Day	08:00	19:00	0.041
	Peak	20:00	23:00	0.0137
	Night	24:00	07:00	0.0273
July	Day	09:00	21:00	0.459
	Peak	-	-	-
	Night	22:00	08:00	0.0388
August	Day	09:00	18:00	0.0353
	Peak	19:00	23:00	0.0176
	Night	24:00	08:00	0.0318
September	Day	08:00	18:00	0.0376
	Peak	19:00	23:00	0.0171
	Night	24:00	07:00	0.0273
October	Day	08:00	16:00	0.0318
	Peak	17:00	23:00	0.0247
	Night	24:00	07:00	0.0282
November	Day	08:00	15:00	0.0273
	Peak	16:00	23:00	0.0273
	Night	24:00	07:00	0.0273
December	Day	08:00	15:00	0.0282
	Peak	16:00	23:00	0.0282
	Night	24:00	07:00	0.0282

3.5 Typology of technologies

As already mentioned above, the fundamental differentiation of power plants in this model is made by fuel and by technology. This is a relatively simple approach as many fossil fuel – and also biomass – technologies are basically using the same technology but a different fuel. In Table 3.2 all technology-fuel combinations considered in OSEMBE are indicated. However, even though some technologies might use the same working principle, the cost parameter are not necessarily the same. But every fuel type has always the same costs, independently in which technology it is used.

Table 3.2: Fuels and energy conversion technologies

	BM	CO	GO	HF	HY	NG	NU	SO	WI	WS
C1								X		
C2								X		
C3								X		
CC	X	X		X		X				
CH	X	X		X		X				X
CV			X							
DI								X		
DM					X					
DS					X					
EC	X					X				
FC	X					X				
G1							X			
G2							X			
G3							X			
GC	X			X		X				
HP	X	X		X		X				X
OF									X	
ON									X	
RC	X			X		X				X
SC	X	X								
ST	X	X	X	X		X				X
UT								X		
WV					X					

Each fuel-technology combination has its own set of economic and technical parameters. More information about the technology parameter follows in chapter 3.5.1. In addition to the categorization by conversion type and fuel, the energy conversion technologies are also classified by size. The aim was to differentiate by the energy level into which the electricity is fed in. For some technologies it was easy to find technology data for different sizes, but for others it was not. As a result, not all technologies implemented have size-dependant cost parameters, but have the same characteristics independent on which level they feed in their electricity. This is an aspect of the model that should be improved in the future. See as well the section concerning Scale effects in chapter 5.1.

3.5.1 Technology parameter

All available technologies in OSEMBE are defined by a set of parameters that are required to build a model in OSeMOSYS. Not every technology requires, or rather has, every parameter, e.g. solar PV has no variable cost as there are no fuel costs, and all other cost are not related to its operation or predictable with high accuracy.

The parameters in this first version of OSEMBE are from a small set of sources. First to mention are the Energy Technology Reference Indicator projections 2014 (ETRI), published by the Joint Research Centre of the European Commission. Due to two reasons ETRI was the first choice if it had required technologies included. First, it has its scope on Europe, therefore the parameters represent the estimated technology development in Europe. Second, the technologies included are described with sufficient detail and include a projection of the development of the parameter, if any change is expected (EC 2014a). Another source frequently used is the IEA World Energy Investment Outlook 2014 (WEIO). The outlook also covers a broad range of technologies and makes assumptions for the technology development till 2035, but it is slightly limited by the fact that technologies running on conventional fuels are just described by capital cost, yearly O&M cost and the efficiency, with no information on average capacity factor, construction time or the ratio of fixed to variable O&M cost given. Only for renewable energy technologies the capacity factor and the construction time are given (IEA 2014). A third source for data on power technology was the Catalog of CHP Technologies by the US Environmental Protection Agency. As the title says, the catalogue deals only with combined heat and power technologies, and due to the fact that the information in the catalogue is very detailed, more processing would have been necessary than when using data from the other reports mentioned previously. For this reason the catalogue was only used when the other two sources were not providing the required information (Darrow et al. 2015).

As mentioned above the WEIO document provides forecast values for the development of technology parameter till 2035. The ETRI projections reach till 2050. As the model reaches till 2060 those forecasts had to be extrapolated. The easiest cases were those where the parameter are assumed to stay constant. For those it was assumed that they will also stay constant after 2050. For all other cases the aim was to continue the trend of the previous years. A constant growth or decline is kept constant. If a growth rate was predicted to increase or decrease this trend is continued.

The values for the technology parameter and their development can be found in the Appendix A. – Generation technology parameter.

Availability Factor

The AvailabilityFactor is defined for each technology, except those powered by water, wind, or sun light. It defines the time per year in which the technology is available, i.e. by this factor outages and maintenance times are considered. The model allocates the time in which the technology is not operating by itself within the year (Mosknes et al. 2015). In OSEMBE the availability factors applied are the same for all countries. Some are changing or rather increasing over the time as technologies are expected to improve.

Capacity Factor

The term capacity factor might cause some confusion, because in the context of OSeMOSYS it is used in a slightly different way than normal. A brief explanation of the term capacity factor in OSeMOSYS shall clarify what the term refers to in this context. The capacity factor is the availability factor of renewable energy technologies that are depending on a resource that is not constantly available, like for example wind or sun light. In comparison to the availability factor the capacity factor is defined for every time slice in the model. Due to that, it is possible to model the characteristic production pattern of technologies like solar PV. As there is no sunlight during the night the capacity factor during the night is zero, whereas in the time slice covering noon the capacity factor is highest of the day. In addition to the variation of resource availability among days, the variation between seasons is also reflected. As mentioned previously OSEMBE contains twelve seasons, or rather twelve months. In contrast to the availability factors the capacity factors are not the same for all the modelled countries, but country specific. The capacity factors for solar technologies and wind power were generated by using the webpage *renewables.ninja*. This page provides site-specific capacity factors for wind power and solar power based on "*Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data"* and "*Using Bias-Corrected Reanalysis to Simulate Current and Future Wind Power Output".* The necessary weather data for *renewables.ninja* is taken from three sources: "*NASA's Modern-Era Retrospective Analysis for Research and Applications", "Digging the METEOSAT Treasure—3 Decades of Solar Surface Radiation"* and the *"SARAH dataset"* (Pfenninger and Staffell 2016; Staffell and Pfenninger 2016; Rienecker et al. 2011; Müller, Pfeifroth, Träger-Chatterjee, Trentmann, et al. 2015; Müller, Pfeifroth, Träger-Chatterjee, Cremer, et al. 2015).

Up till now, *Renewables.ninja* is only a beta version, and due to that it is just possible to generate capacity factors for the year 2014. However, those values are hourly for the whole year. For each country, values for several locations were generated. For onshore wind and solar the same locations were used. From the data for the different locations, average values for the whole country were calculated. The hourly values are transformed to averages of each time slice, e.g. average of all values in January between 8 a.m. and 4 p.m. The country averages are used as initial values. The future development of the capacity factors – for onshore wind, offshore wind and solar – was estimated by applying the predicted annual growth rate from ETRI (EC 2014a). By applying the growth rate of the annual average capacity factor from ETRI on the time slice specific values, some of the wind power values grew too strong, e.g. capacity factors that are already high are not going to increase as strong as those below the average. To keep the annual average of the capacity factors equal or smaller than the expected maximum annual capacity factor, the growth is limited. A maximum of 0.8 kept the average values below the expected maximum.

Fuel cost

A good prediction of future fuel prices is probably one of the most complicated things to be forecasted. For biofuels some influences on the future price are relatively obvious, e.g. increase in demand and evolution of technologies. However, this does not mean that it becomes a lot easier to predict the development of the price. For example the demand depends on how the price difference to fossil fuels develops. For this work the price of biofuels was derived from two reports by IRENA. Based on information from the report

Renewable power generation costs in 2014, an average price was calculated. The average price development was estimated by data on biofuels from *Production of Liquid Biofuels – Technology Brief* (IRENA 2015a, 128; IEA-ETSAP and IRENA 2013, 16). According to this data, the average price of biofuels will decrease till 2020. Afterwards it is still decreasing but so slightly that it is almost not notable.

Price projections for coal, gas, and oil were taken from the *DECC 2015 Fossil Fuel Price Assumptions* by the British Department of Energy & Climate Change (DECC 2015). From their scenarios, the central scenario was selected. The forecasts from that report are up till 2040. Since all of them are constant for the last years of the forecast period, the period 2040 till 2060 was assumed to be constant as well.

The price for heavy fuel oil was connected to the price of crude oil, as it is usually strongly related (IEA 2016). Currently the price of crude oil is extremely low. This was taken into account, as it affects the ratio of crude oil price to fuel oil price. Based on the historical data, it was assumed that the price for fuel oil will be in average equal to the price of crude oil till 2020. Afterwards, when the crude oil price is assumed to be on a higher level than currently, the historical ratio of 0.8726, which was relatively stable till summer 2014, will be re-established (IEA 2016).

Gaining reliable average prices for uranium is not easy, as many countries with nuclear power capacities do not publish numbers on the fuel cost. However, numbers on the operating cost of nuclear power plants are published on the webpage of the World Nuclear Association, including fuel cost (World Nuclear Association 2016). Due to the lack of predictions on the price development, the assumption was made that the price will stay constant.

For all fuels it is assumed that domestic production is 10% cheaper than imports. By this measure domestic fuels are favoured over imported ones. However, the domestic production of fuels is limited by numbers of the European Commission (EC 2014b).

The fuel prices used in the model are also listed in Table 2 in Appendix 1.

Fixed cost

The fixed costs are the annual costs of a technology per capacity, i.e. the fixed costs occur for every installed unit independently if it is used or not. There are technologies that do not have fixed costs (Mosknes et al. 2015).

In the ETRI projections by the EC it is indicated that some technologies have higher fixed costs during the second half of their lifetime due to aging effects (EC 2014a). However, in OSeMOSYS it is not possible to implement these so-called refurbishment costs directly, because in OSeMOSYS the technology costs are not considered independently for single power plants, but for technologies, i.e. in the installed capacity of one technology there are usually older and newer parts/power plants. In ETRI the refurbishment costs occur in the second half of the lifetime of a power plant. To be able to consider them in OSEMBE they are divided by two and applied constantly as the capacity of one technology consists usually of parts that are installed at different times. The only occasion where the refurbishment costs are not applied is for new technologies in a period that is equal to half of their expected lifetime, counted from the beginning of installing the technology. After this period half of the refurbishment costs are added to the fixed costs as for all other technologies.

Emission Activity Ratio

The EmissionActivityRatio relates a technology to the generation of emissions. It defines how many kilo tonnes of emissions are produced while generating one PJ of output (Mosknes et al. 2015). In the current version of OSEMBE, the EmissionActivityRatio's are defined for all extraction and import technologies of coal, crude oil, heavy fuel oil and natural gas. The values are shown in Table 3.3.

Table 3.3: Emission Activity Ratios

Coal	Oil and oil products	Natural gas
[kt/PJ]	[kt/PJ]	[kt/PJ]
90.53	70.08	50.29

Emission penalty

The use of fossil fuels and the emission of greenhouse gases (GHG) is, or can be, penalized with a wide range of measures. A widely known, but also criticized system is the emission trading system (ETS) of the EU. By setting a cap, it aims to reduce the GHG-emissions. Since 2013 most emission generators have to buy certificates within an EU wide auctioning system to be allowed to emit GHGs (EC 2016). In addition to this emission trading system, most national states also have regulations and laws that are effecting the prices of fossil fuels, e.g. environmental fees, energy taxes, electricity taxes and fossil fuel taxes, but also subsidies.

To create a model that is very close to reality it would be necessary to investigate every country individually and implement the national penalty and support measures for different sources of energy and technologies. In this work the simplification was made that no national tax or penalty systems are considered outside the ETS of the EU. To compensate the missing taxes, fees, and subsidies, the price for each ton of CO_2 is put on a level that is significantly higher than in reality. The ETS is not modelled in all its details, but a cost is assigned to each ton of CO_2 emitted. It was aimed to keep as many of the modelled countries in a group with the same cost and the same cost development. However, Poland had to be taken out of the group, as its energy system characteristics and their national tax and subsidy system is so different that higher costs for GHG emissions lead to a hasty change in the power generation mix and investment patterns that are relatively unlikely to occur. In Poland, a fast increase of emission costs leads to an immediate shut down of the large existing coal power capacities. Therefore, the initial price for CO2 emissions in Poland in the year 2015 is set to a third of the price in the other countries. But by 2050 the penalty level is brought in line with the level in the other countries.

Annual Emission Limit

The parameter AnnualEmissionLimit is relatively self-explanatory – its definition limits the related emission allowed. The limit is defined on an annual basis, therefore it can be changed over the time. The CO_2-emissions in this model are not limited, but to limit the production of wind power an emission by wind power is implemented to control its application. A more detailed description of this aspect of the model can be found in the section on *Limiting Wind Power*.

Phasing out of technologies

On the one side, new technologies are constantly developed and existing ones improved. But on the other hand, there are also technologies that are no longer used or rather no longer newly installed. Technologies that are considered to phase out, e.g. based on the information from the ETRI report, are implemented in OSEMBE with a phase-out period. In the phase-out period the capacity that can be installed is first limited to 1 GW and then linearly reduced over ten years to zero.

Reserve Margin

The RM defines the reserve in installed capacity over the peak demand. The RM is defined as a factor, e.g. a RM of 1.2 indicates that the system needs to be able to provide 20% more capacity than required to satisfy the highest peak in the modelled demand. To provide the RM, only the technologies that are tagged as RM technologies are available. This means that the installed capacities of those tagged technologies have to be sufficient to satisfy a demand equal to the highest peak in the year plus the reserve, in the example above 20% (Mosknes et al. 2015). In OSEMBE all technologies using CO, HF, NG, NU and WS[1] are tagged as RM technology, and furthermore all HY[1] technologies except wave power. These technologies are tagged because they rely on storable fuels, which means that they are able to provide their reserve capacity at all times. For countries with dryer climates it might be necessary to exclude HY, as there are probably times when there is not enough water available.

Total Annual Max Capacity

With the TotalAnnualMaxCapactiy, the use of a technology or fuel can be limited. In OSEMBE this parameter is used to limit the use of domestically produced fuels. Due to their lower price, domestically produced fuels are favoured over imports. The values for the maximum available fuel of domestic origin are taken from the EU Energy, Transport and GHG Emissions – Trends to 2050 (EC 2014b).

3.5.2 Available Technologies

Multi-fuel technologies

Combined Cycle power plants

A combined cycle (CC) is adding a gas turbine and a steam turbine to increase the efficiency of the whole power plant. In the first stage, electricity is generated in a gas cycle. The exhaust heat from the gas cycle is used to produce steam, that is then used to run a steam turbine. A CC can be operated in different ways, both for base load electricity generation and for load following production. In OSEMBE four types of CC power plants are implemented, using BM, HF and NG[1] as fuel. The technology parameters are all derived from ETRI (EC 2014a).

Combined Heat and power

The main characteristic of Combined Heat and power (CH) technologies is that they produce electricity and heat at the same time. In this work a CH technology can consist of different sets of technologies, e.g. a boiler and a steam turbine, with the boiler generating steam and the turbine generating electricity. The rest of the heat is then used for other purposes. CH technologies are used with a wide range of fuels. In OSEMBE with: BM, CO, HF, NG and

[1] Biomass (BM), Coal (CO), Heavy Fuel oil (HF), Hydro (HY), Natural Gas (NG), Nuclear (NU), Waste (WS)

WS. The characteristics were taken from ETRI and the Catalog of CHP Technologies (EC 2014a; Darrow et al. 2015).

External combustion engines

The potential of external combustion engines (EC) is investigated on several test power plants in Europe, e.g. in Denmark. The fundamental idea of an EC is that the combustion of the fuel is not within the cylinder chamber, but outside of it and that the piston is only moved by the expansion of the heated air in the cylinder. Unfortunately, there was no general data on ECs available, and due to that the technology could not be fully implemented in the model.

Fuel cells

In fuels cells (FC) hydrogen or other gases are electrochemically converted. They produce electricity and heat and have a good scalability, from portable to stationary size. Their electrochemical working method allows for high efficiencies. In OSEMBE FCs are implemented using NG as their fuel or rather gases that are included in the fuel group of NG. The parameters are taken from ETRI (EC 2014a).

Gas cycle

The gas cycle (GC) is a relatively simple power plant layout. Its main component is a gas turbine that is producing electricity. The turbine is driven by the exhaust gases that come from a combustion chamber where the fuel is burned. The gas cycle can be operated relatively flexibly, and power plants of this type are commonly used to cover the peak demand. In OSEMBE GC power plants are included that run on HF and NG. The corresponding data comes from ETRI (EC 2014a)

Internal Combustion engine with heat recovery

A smaller version of the CH power plants is the internal combustion engine with heat recovery (HP). Such units are commonly found in hospitals and hotels. There they serve as heat and electricity providers, but also as back up in case of power outages, especially in hospitals this is of high relevance. Those generators can be designed for a wide variety of fuels. In the model, they can be operated on BM, HF and NG. Their characteristics are derived from WEIO and the Catalog of CHP Technologies (IEA 2014; Darrow et al. 2015).

Reciprocating engines

For standalone power supply or back up power reciprocating engines (RC) or so called gen-sets are common and reliable solution. As there are very few areas in Europe without grid connection, the most common application for RCs in Europe is for backup power in hospitals, hotels, and other institutions, where an unexpected power outage can cause damage. OSEMBE has three types of RCs included. They are differentiated by their fuel and run on BM, HF and NG. Their characteristics were taken from the World Energy Outlook Data and the Catalog of CHP technologies (IEA 2014; Darrow et al. 2015).

Steam cycle

A steam cycle (ST) is one of the most basic power plant designs that exists in the range of fossil fuel based power plants. In the combustion chamber water is vaporized. The generated steam drives a steam turbine that generates electricity. Afterwards, the steam is condensed and led back to the vaporizing unit in the combustion chamber. The required information for steam cycles are either derived from the World Energy Outlook Data or from ETRI (IEA 2014; EC 2014a).

Geothermal technologies

In this first version of OSEMBE just one geothermal technology is implemented. It is simply called conventional geothermal (CV). The operational cycle of geothermal technologies is very similar to a steam cycle, with the difference that no combustion takes place. The steam, required to run the steam turbine and generate electricity, is taken from hydrothermal resources in the ground. In the ground the water is mostly liquid due to a higher pressure, and when extracted it is expanded and changes to the gas phase before it enters the turbine. The characteristics for this technology are taken from ETRI (EC 2014a).

Hydro power technologies

The model includes a collection of hydro power technologies. They can be categorized into the three categories that are presented in the following lines.

Hydro power dam

The working principle of a hydro power dam (DM) is that a dam holds back the water of a river or stream and that the water is led through one or several turbines in the dam when power is demanded. In OSEMBE four sizes of dams are implemented, with data from ETRI. Depending on the size of the dam, or rather the turbine, the plant feeds in its electricity at a different level of the power system. The smallest size feeds into the final level, two medium sizes feed in to the tertiary level, and electricity form large dams is fed into the secondary level (EC 2014a).

Hydro power dam and storage

The difference between hydro power dam and storage (DS) and DMs is the capability to store energy by pumping water on a higher level when there is an excess of electricity, and letting it back down through an electricity generating turbine when there is high demand. DS is implemented with the same size steps as DM. Unfortunately, energy storage is not considered yet in this version of OSEMBE, which means that in this version of OSEMBE DM and DS are similar in their characteristics. As for DM the data was taken from ETRI (EC 2014a).

Wave power

Wave power (WV) technologies are a young technology, that will still require a lot of research to make it competitive. But in several countries, test installations are under operation. By including it in the Energy Technology Reference Indicator projections for 2010-2050, the European Commission is considering it as a technology with the potential to become competitive in the future. The forecasted development of WV power from ETRI is considered in OSEMBE (EC 2014a).

Limiting Hydro power

The use of conventional power plants is related to the cost of fuel. In case of a high demand or low domestic resource availability, imports might be necessary, which are often more expensive than domestic fuel production. The increasing cost with increasing production is a limiting factor for conventional power plants. However, for renewable power plants, using hydro, sun, or wind, the power production is not related to fuel costs. Therefore, it is important to look at their limiting factors when modelling an energy system that includes renewables.

All hydro power technologies available in OSEMBE except wave power were implemented with one common production limit per country. In this way, the potential to build hydro power plants in rivers or lakes in each country was considered.

The production limits are shown in Table 4 in Appendix 1. Only for Estonia and Latvia no data could be found. However, since hydro power is a very mature technology it was assumed that these two countries have already reached their limit with their existing capacity.

Nuclear Power technologies

Generation 2

Among those currently operating, this type of nuclear power plant is the most common one. They were mostly built during the 1980's and are the second generation of nuclear power plants (G2) to be built. Originally they were designed for a lifetime of 40 years, but most of them received or rather will receive a lifetime extension of ten to twenty years. Their characteristics are taken from the IEA ETSAP Technology Brief E03 (IEA ETSAP 2010).

Generation 3

The third generation of nuclear power plants (G3) is the current generation. Nuclear power plants currently constructed in Europe belong to this generation. In OSEMBE two types of power plants are included in G3. First, the Generation 3 Light Water Reactor (LWR), which is already available or rather under construction. It is a further development of the G2 plants. The technology was improved, but most importantly the security was increased. The second type of power plant that is included in G3 is the small and medium sized LWR. They are expected to start commercial operation in the beginning of the 2020's. It is unclear what role they will play in Europe but their main advantage will be their reduced size - it is assumed that they will have a maximum capacity of 700 MW, which will make them more attractive to smaller countries than previous nuclear power plants. Information on cost and technological parameter of G3 plants are taken from ETRI (EC 2014a).

Solar Power technologies

The group of countries that was chosen as initial region in OSEMBE is not very well-suited for solar power. Due to that, not all the technologies that should be available for a model of the entire EU are implemented yet. Only the very common solar photovoltaic is implemented in two sizes. The smaller size includes solar panels up to 100 kW. This category would also represent distributed (DI) solar PV capacity on rooftops, in gardens, or similar. The other type of solar PV that is implemented is called utility (UT) solar PV. It includes all solar PV capacities that are bigger than 100 kW. Data on the characteristics of solar PV was derived from ETRI (EC 2014a).

Limiting Solar Power

Similar to hydro power, solar PV has no fuel cost that would limit its production. An important limiting factor for solar is the availability of suitable space. But as the solar radiation potential is not very good in the modelled countries due to their northern location, not many publications have analysed their overall potential for solar PV. The consideration of solar PV in countries so far north is fostered by the dramatic price drop of solar PV in recent years.

However, with the exception of Poland, no usable numbers were found to support the definition of limits for power production by solar PV. For Poland, numbers based on REmap

Poland by IRENA were used (IRENA 2015b). For the other countries, a maximum share of electricity by solar PV in the final electricity mix in 2050 were assumed. The limit for all previous years was than calculated by allowing a linear growth from the current share to the set share in 2050. For shares in 2050 the following assumptions were made: Denmark 5%, Estonia 5%, Finland 4%, Latvia 5%, Lithuania 5%, Sweden 5%. The absolute values of the limits can be found in Table 4 in Appendix 1.

Wind Power technologies

Wind power technologies are divided into offshore wind power (OF) and onshore wind power (ON). For both technologies, different feed in levels are implemented, which reflects that wind turbines can be installed as a single unit or in groups of varying sizes. In the sources used, the reduced cost per unit when the turbines are erected in a group are unfortunately not considered, therefore the model is slightly imprecise on this point. The information used on wind power is from ETRI (EC 2014a).

Within the renewable energy technologies wind power is one of the most mature. For that reason, it is already competitive on the electricity market. This makes it necessary to add a limiting factor that reflects how much wind power capacity might be installed in the future (Siyal et al. 2015). The measures used to limit wind power are described in the following subsection.

Limiting Wind Power

As mentioned above, like most other technologies, wind power also has limiting factors. Two very important ones are the availability of space for the turbines, and the capability of the transmission grid to handle the fluctuating production of wind power.

To achieve a reasonable mixture of investments, a limit for the power production by wind is implemented. This is realised by creating an emissions factor for wind power, called wind trace. The wind trace is counted in Peta Joule (PJ) and corresponds 1:1 to the electricity output. By limiting the emission “wind trace”, the power generation by wind is limited.

The maximum allowed capacities had to be calculated individually for each country. Up until 2020 or even till 2030, most countries included in the model have formulated targets of installed wind power capacity. If available, these values were used as the limit. But the data available was different from country to country, and the calculation was therefore different for each case.

Denmark has formulated a goal to achieve 50% of its final electricity demand by 2020 from wind power, and it is more than likely that this goal will be achieved (IEA wind 2015). It is assumed that the share could go up to 75% in 2050 and 80% in 2060. This growth would be realized on the one hand by new added capacity, but also by by the increasing capacity factor till 2050, which permits the production of more electricity with the same amount of capacity.

In Estonia the wind power sector is barely fifteen years old, but its production has reached almost 9% of the final electricity consumption (Tuuleenergia.ee 2015). Based on the development in recent years it is assumed that the share of wind power in the Estonian power mix could rise to 40% in 2040 and increase to almost 50% in 2060.

In 2013, the Finnish government increased the target for the electricity production from wind power. It is now aiming to reach production of 6 TWh in 2020 and 9 TWh in 2025 (IEA wind 2015, 108). The production of 6 TWh requires approximately 2500 MW of installed capacity. For this model the limitation is set in a way that the target can be reached one year ahead of schedule, or rather two years earlier, so the model can have a maximum production by wind power of 9 TWh in 2023. For the years afterwards, the limit is increased with an annual growth rate similar to the years before, of 9% till 2030. After that, the limit is increased with a decreasing growth rate. In that way, the Finnish wind power production is limited to 33% of the final electricity demand in 2060.

In 2014 Latvia had a wind power capacity of 60 MW. The Latvian Renewable Energy Federation assumes that this number will increase to 300 MW in 2020 (Atjaunojam 2014). After 2020 the growth rate of the limit for wind power is decreased to a slower pace. In 2030 the maximum wind power production is assumed to be 28%, in 2040 36%, and in 2050 42% of the final electricity demand.

In comparison to Latvia, Lithuania has a slightly higher share of wind power in the power generation mix. As of 2015, the installed capacity amounted to 350 MW. For 2020 the forecast of the Latvian Renewable Energy Federation is a capacity of 700 MW (Atjaunojam 2014). In the same way as already described for Latvia, the growth rate of the maximum wind power production is slowly reduced after 2020, so that in 2030 Lithuania could cover a maximum 42% of its final electricity demand by wind power, 49% in 2040 and 51% in 2050 .

The wind power numbers and assumptions for Poland are based on the REMAP 2030 – Renewable Energy Prospects for Poland by IRENA. In that report IRENA in cooperation with the Polish government evaluated the current renewable goals and investigated if it would be feasible to achieve more ambitious shares than currently aimed for. The report concluded that it would be possible to do so and proposed a scenario for how that could look. The limit of wind power in Poland till 2030 is defined based on the installation targets in this scenario. According to the report, Poland could have an annual growth of 490 MW in onshore wind and 120 MW in offshore wind over the period between 2015 to 2020. Afterwards, in the 2020’s, the growth would reduce to 20 MW of onshore and 3.7 MW of offshore per year (IRENA 2015b). Based on these numbers Poland could achieve a maximum wind share in production of 26% in 2030, from a limit of 12% in 2015. For the remaining time till 2060 it is assumed that the possible share of wind power will continue growing with a decreasing growth rate. A maximum share of 28% in 2040, and 30% in 2050, is allowed.

The limit for wind power for Sweden in the model is probably the most comprehensive wind power limitation implemented in this first version of the model. For the first years till 2020 the goal to produce 30 TWh of electricity per year from wind by 2020 is set as a limit. Afterwards the Swedish limit can be based on a wind energy assessment by Siyal et al., which considers geographic and environmental restrictions, and a study on power system balancing by Söder. In 2013 Söder stated that 45 TWh of wind power production would already be possible to handle with the current energy system in Sweden (Söder 2013). Siyal comes to the conclusion that in the medium to long-term, considering measures like grid improvements, pressurized air storage and other storage options, a production of 190 TWh of wind power would be possible (Siyal et al. 2015). In OSEMBE the limit of wind power evolves according to the numbers mentioned above. As noted, for the years till 2020 the limit is set to 30 TWh. Afterwards the limit is increased by 6 TWh per year till the 45 TWh are reached. The amount of 6 TWh corresponds to the annual production of 2 GW of wind power capacity. When the 45 TWh are reached, the growth rate is first reduced to 1 GW per year. This is further reduced to 0.5 GW after an annual production of 100 TWh is reached. This limit would allow a maximum wind power production of 147 TWh in 2060, which corresponds to a share of 95 % of the final energy demand. This indicates that the theoretical maximum of 190 TWh by Siyal would exceed the demand by far. Looking at the current development and the political situation, Siyal assumes that Sweden will reach its set goals, but that the wind power capacity will grow slowly (Siyal et al. 2015).

3.5.3 Implementation of the residual capacity

The residual capacity applied in OSEMBE was derived from the power plant database PLATTS (S&P Global Platts 2015). PLATTS differentiates its power plants in a more detailed way than it is required for this model, so the power plant categories from PLATTS were instead classified to the previously quoted categories. A step that was unfortunately not performed when preparing the residual capacity input data was categorizing them by size. Due to this missing categorization, the residual capacity is added to the technology where the average capacity of the certain power plant type fits in, if different sizes of the power plant type were implemented in the model. After an update of the technology data, the implementation of the residual capacity could be improved. A comment on how an improvement could be done is included in chapter 5 in the subsection Residual capacity. The way in which the residual capacity is implemented is not the only improvement that could be made to the residual capacity. A comparison of the capacity installed and in operation in 2015 between PLATTS, the IEA and IRENA indicated that PLATTS is not complete. Mainly the wind power installations appear to be incomplete. The residual wind power capacity was taken from the annual reports by the European Wind Energy Association (EWEA) (EWEA 2016; EWEA 2014; EWEA 2012; EWEA 2010). Unfortunately, these reports do not distinguish between off- and onshore wind. For Sweden the distinction between installed onshore and offshore capacities was done based on numbers by Svensk Vindenergi (Svensk Vindenergi 2016). For the other countries the difference between the numbers from PLATTS and the numbers from EWEA was added to the onshore residual capacity, i.e. the values for the offshore residual capacities are based on PLATTS.

Previously it was indicated that ECs running on biomass would be included in the model, but due to the lack of reliable data the technology could not be implemented. But as the share of ECs in the installed capacity is very small, it does not have significant effects on the results.

3.5.4 Technical lifetime and phase out

When modelling energy systems, technologies have a defined technical lifetime (IEA ETSAP 2010). After exceeding its lifetime, the capacity X installed in Y cannot be used anymore and needs to be replaced by new capacity, either from the same technology or by capacity of a different technology. However, in reality a power plant usually does not stop its operation just because it has exceeded its expected technical lifetime, but rather when it is economically not worth it to continue operation, or due to technical failure or safety concerns. This point can be reached before or after reaching the technical lifetime. If the estimation of the lifetime is good, then it turns out to be the average age that power plants of that type retire.

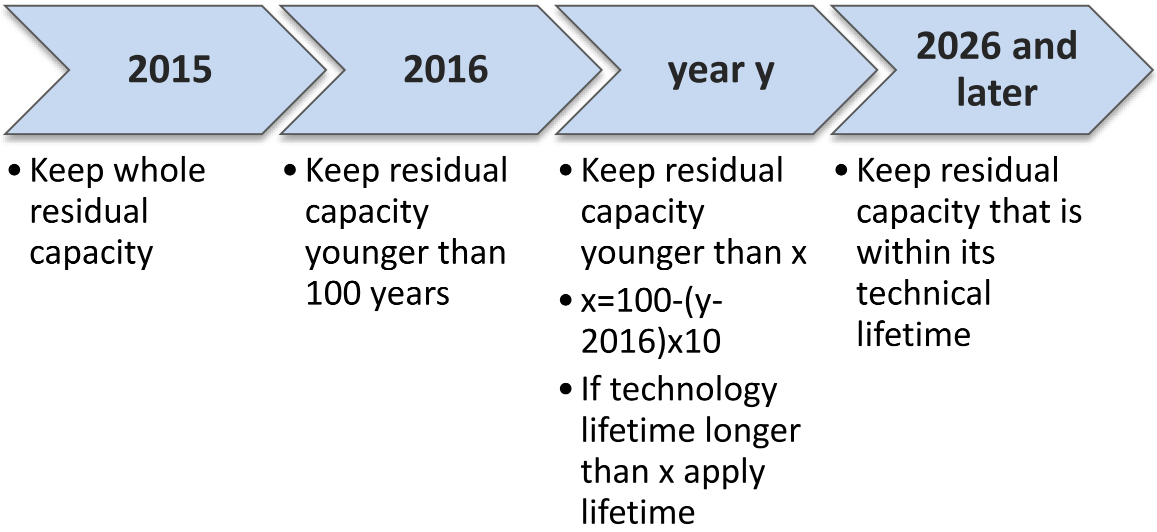


Figure 3.5: Phase-out mechanism for residual capacity

In any case, during the preparation and implementation of the residual capacity in OSEMBE, it was noted that many power plants operate longer than they are originally designed for. The positive aspect of this is that the real-world overall system costs are reduced by longer operation times, but in the model it is necessary to handle the residual capacity in a different way than capacities installed by the model itself. If the model installs a certain amount of a technology in year x the installed capacity is available to produce power till year x + lifetime. In most years some capacity is both added and phased out. However, quitting the operation of all the capacity that has exceeded its lifetime within the residual capacity would cause a big gap in the generation capacity. In reality, such a gap most likely couldn’t be closed in one year. Therefore, a slow-phase-out mechanism for the residual capacity was developed. It is described in Figure 3.5. As indicated on the left side of Figure 3.5, the whole residual capacity under operation is implemented in the first year of the modelling period, independent of the designated lifetime. In the following ten years, i.e. in OSEMBE from 2015 till 2025, the period from which installed capacities are considered reduces from the last 100 years in 2016 to the last 10 years in 2025. If the period considered is shorter than the technical lifetime of a technology, all capacities installed within the technical lifetime of its technology are considered to be available (see also the description in Figure 3.5 below “year y”). From year 2026 onwards only the technical lifetimes of the technologies define the operation time of installed capacities.

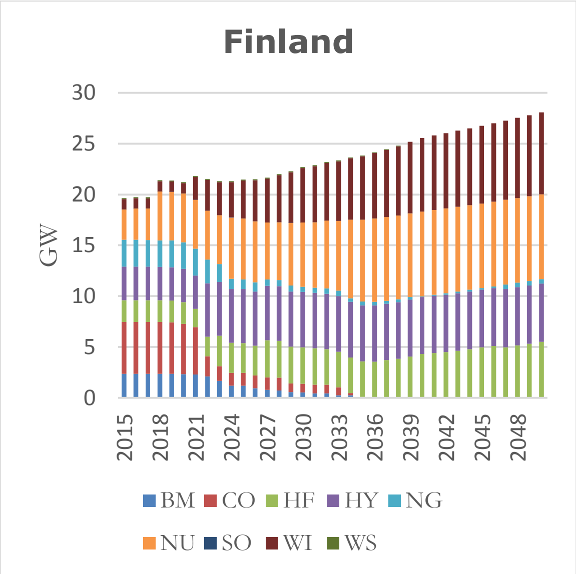
4 Results

In the first three subsections of this chapter the results of a base case scenario will be described and analysed. The fourth subsection deals with a sensitivity analysis of the effect of the RM on the results of the model.

For a better comprehensibility, the graphs and figures used only distinguish between fuels and do not show the different technologies using a fuel.

4.1 Installed capacities

In Figure 4.1 the installed capacities in Finland and Sweden are shown. The results were generated with a RM of 1.2. On the left-hand side of each graph the axis is shown in GW. Below the graphs the legends indicate which colour stands for which fuel. In the graph the fuels are in alphabetical order from the bottom to the top.



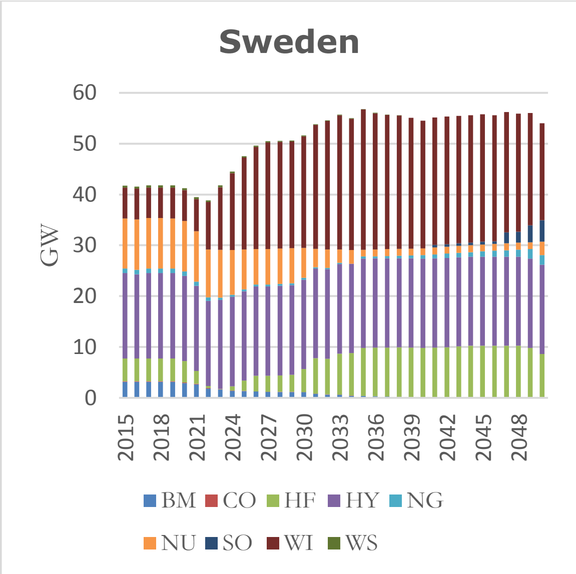


Figure 4.1: Installed capacities in Finland and Sweden with RM 1.2

It is interesting to compare the different patterns in the first years. Where Sweden seems to have an overcapacity, Finland seems to have too little capacity. This can be the case because in order to run the model with a RM of 1.2, the boundary condition that no installations are done in the first two years had to be relaxed for Finland. The boundary condition is based on the assumption that the implemented residual capacity, or rather the existing capacities, should be sufficient to satisfy the electricity demand as they are based on real numbers. However, Finland seems to operate with a lower RM. Previous test runs with a RM of 1.1 were possible without allowing new installation in 2015 and 2016. In general, planned power plant installations are not considered in OSEMBE, but when relaxing the boundary condition that there should be no installations in the first two years, something else was considered. Finland is currently constructing new nuclear power capacities (S&P Global Platts 2015). Those large new power plants might have a significant influence on a small country (in terms of energy and population) like Finland. Therefore, the two nuclear power plants are considered. This is also visible in Figure 4.1. The jump up from 2017 to 2018 is caused by the installation of 1.72 GW of nuclear power (orange). Later in 2024 another 1.2 GW are installed, but that is not as easy to see as the 2018 installation as capacities of other technologies are phasing out at the same time.

In both countries, but also in the other modelled countries shown in Appendix 2 – Results, it can be seen that biomass is phasing out of the energy mix. This is caused by the simplification of considering only one type of biomass or rather biofuel. By using one generic price for biofuels, the potential of certain biofuels for power generation is not showing in OSEMBE. A more detailed description on how biomass could be implemented in a better way than in the current OSEMBE version can be found in section 5.1.1 Differentiation of biofuels.

A constant component in both energy systems is hydro power. Using the parameter TotalAnnualMinCapacity, the model is forced to maintain at least the amount of hydro power installed in 2015. It was assumed to be likely that the hydro power capacities in the modelled region are not going to be reduced over the next decades. However, Figure 4.1 shows that there is only a small increase in hydro power capacity, which is more visible in Finland than in Sweden. This is caused by the already mentioned limitation of electricity generation by hydro power for each country (see also Table 4 in Appendix 1).

After the year 2025, a difference in the capacity development of Finland and Sweden can be noted. After the installation of the already committed nuclear power plants in Finland, more nuclear power is added by the model, whereas in Sweden nuclear power is reduced to a very small amount. This can be explained by the lower resource availability for hydro and wind power in Finland. In Finland the share of installed wind power capacity increases over the entire modelling period in correspondence with the implemented production limit, whereas in Sweden the production limit is not met.

In the context of wind power, a relationship of technologies can be seen in Sweden and Finland - between HF technologies and WI power. In Figure 4.2, which shows the installed capacities of Latvia and Poland, this relation is better visible. In both countries the share of HF and of wind power increases jointly from a certain point onwards. The reason for this parallel growth lies in the characteristics of the technology groups. Some HF technologies have relatively low investment cost and but relative high variable cost (Darrow et al. 2015; EC 2014a).

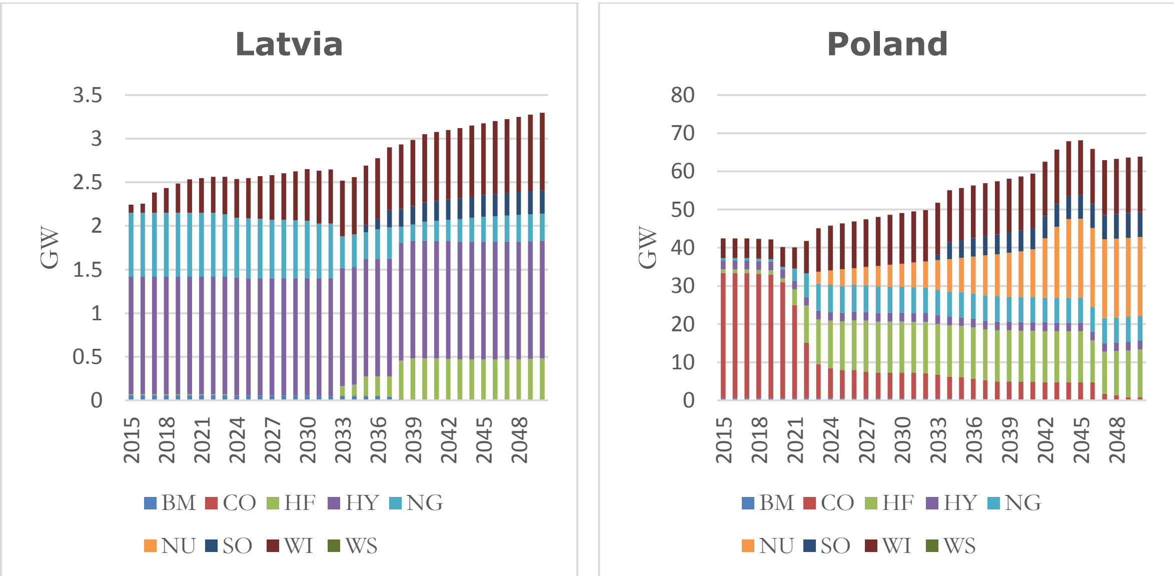


Figure 4.2: Installed capacities in Latvia and Poland with RM 1.2

The low investment costs make them attractive to work in combination with wind power and its fluctuating production, i.e. the HF capacities will be used when there is low or no production by wind power.

The electricity system of Latvia is largely depending on its hydro power capacities. Initially the other main component is NG. But the share of NG decreases when more wind power in combination with HF is added. A similar development can be observed in Poland. Here it stands directly in relation to a large transition that takes place in Poland - starting in 2020 Poland phases out of coal based power production. In the set of countries considered thus far, Poland is the one that is most depending on CO, but due to the emission penalty implemented in the model the operation of CO power plants becomes less attractive and is phased out. As already pointed out, a certain part of the coal capacity is replaced by the wind HF combination. But a certain amount of NG can also be identified in Figure 4.2. That this share stays relatively small can be seen in the context of the limited domestic production of NG in Poland. However, domestic extraction is assumed to be cheaper than imports. After making use of the limited domestic resources of wind, NG, and to a small extend also hydro power and solar PV, the model starts implementing nuclear power (orange). Around the year 2045 a upwards bump in the installed capacity, caused by new nuclear capacity, can be seen. This bump avoids a shortage in capacity after the phase out of the last coal capacities in 2049.

The main characteristics of the installed capacity mixes visible in the modelled countries were described up to this point. The graphs of the installed capacities of all countries are shown in the Appendix 2 – Results.

4.2 Production patterns

In combination with the previous section the production pattern of a country can explain how the different technologies correspond and complement each other. Furthermore, the production patterns indicate how the countries are interrelated.

In Figure 4.3 the production of Finland and Sweden are shown. In the upper half of the graphs a red line indicates the demand of the country. Imports and exports are not considered in the graphs, i.e. if the upper edge of the coloured area is below the red line the country is filling this gap with imports. If the coloured area is above the red line, the country is exporting parts of its production.

The Finnish power production pattern in Figure 4.3 shows the same peak as the capacity graph in Figure 4.1 in the year 2018, which is caused by the implementation of new nuclear capacity. However, the new nuclear capacity only turns Finland into an exporting country for a short time. With the phase-out of coal the country once again becomes a net-importer. Just after 2031 Finland converts to a constant exporting country.

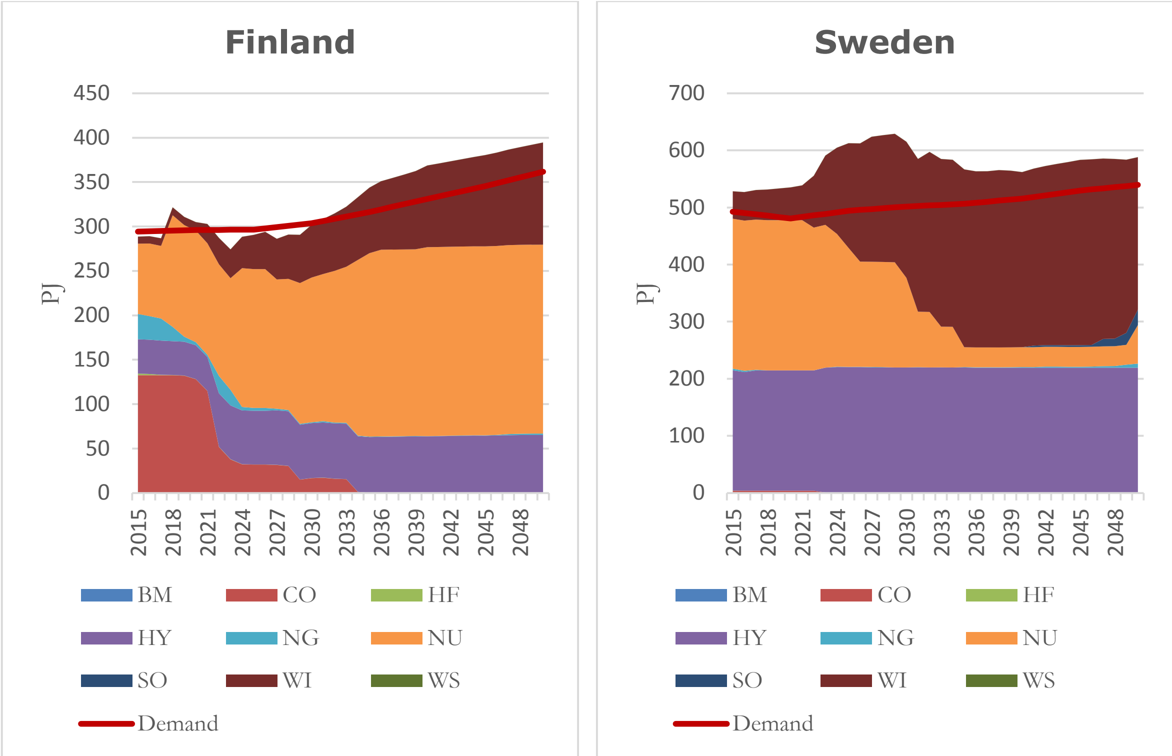


Figure 4.3: Annual Production for Finland and Sweden with RM 1.2

In comparison Sweden has a surplus in production over the entire modelling period. One thing that is interesting to see is the peak in production between 2023 and 2035. The surplus is brought back to its previous level by the reduction of the share of nuclear power. However, nuclear does not phase out completely and seems to increase again in 2050.

Looking at the Finish and the Swedish production pattern together shows that the committed new nuclear power capacities have the potential to change the characteristics of the trans-border electricity flow between the two countries. Namely the fact that Finland is currently a net-importing country.

In Figure 4.4 two countries with a stronger increase in energy demand than Finland and Sweden are shown, Lithuania and Poland. The Lithuanian case is particularly interesting as a large share of its electricity demand is covered by imports.

Comparing the production pattern of Lithuania with its installed capacity (see Figure 5 Appendix 2) shows that the pattern of the installed capacity does not match the ups and downs of the production. The variation of the production is probably caused by changes in the production mix of other connected countries, e.g. the first extreme low in production around the year 2020, in which Lithuania is importing electricity, is in a time when Poland has a peak in overproduction. In 2024, when the overproduction in Poland is smaller, Lithuania is satisfying a larger share of its demand on its own. This two changes in production might be related, but they can also be caused by other events.

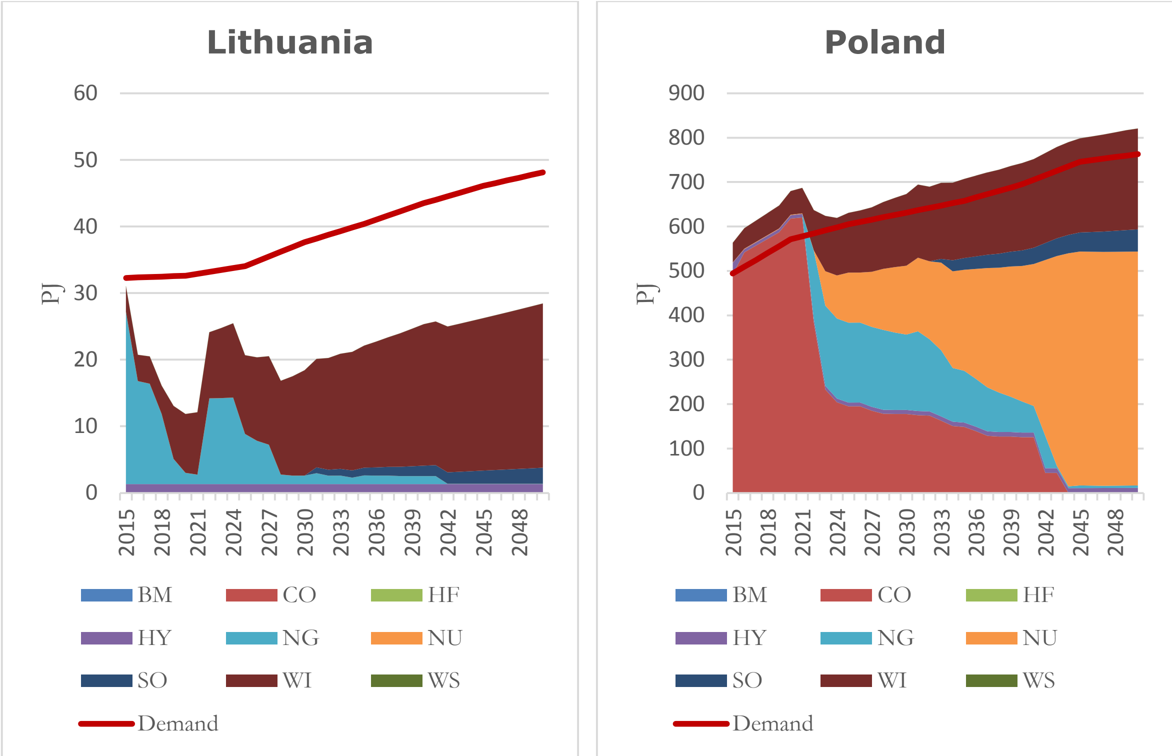


Figure 4.4: Annual Production for Lithuania and Poland with RM 1.2

Looking at the production patterns of the modelled countries, it is interesting to see that the four larger countries – Denmark, Finland, Poland, and Sweden – seem to achieve a production mix that satisfies the domestic demand without, or with only small amounts of, imported electricity, whereas the three Baltic countries are all relying on imports. This might be an interesting aspect to analyse in enhanced trade scenarios, regarding the aspect of dependence. However, it needs to be considered that some important aspects of the energy system of the modelled countries are not yet considered, like trans-border transmission to unmodeled neighbouring countries or storage options like pumped hydro power.

The topic of electricity exchange leads us to the next sub-chapter, which contemplates the development of the trans-border transmission a bit closer. The annual production graphs for all modelled countries are also part of the Appendix 2 – Results.

4.3 Trans-border transmission

The analysis of the trans-border transmission of electricity is one of the key interests for building OSEMBE, and probably in every multi-country model. However, when looking at the results of the first version of OSEMBE, and especially when analysing the trans-border transmission results, it should be considered that the exchange of electricity with countries that are not covered by the model (yet) is not yet implemented. This means that connections that have big influence on the modelled countries are missing, e.g. Norway – Sweden or Czech Republic – Poland. Therefore, there are significant differences between the transmission patterns and the real flows. Nevertheless, as the fundamental characteristics of the country's energy systems did not change there are already many similarities between the real and the model pattern of trans-border transmission.

On the following page in Figure 4.5 the real flows in the year 2015 are compared with the flows in the base case with RM 1.2 in 2015. With the explanation from above it is not surprising that the graphs look different.

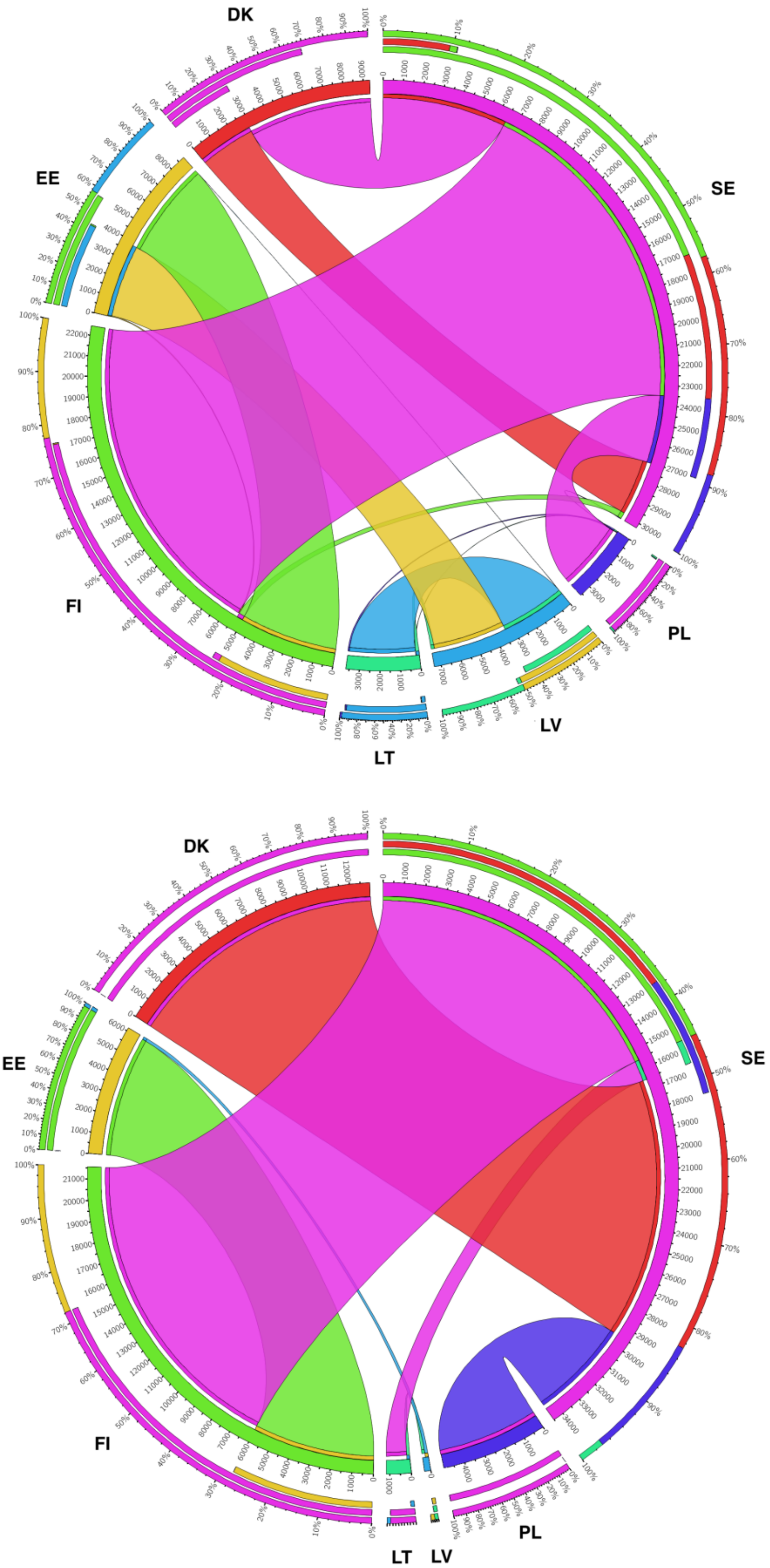


Figure 4.5: Comparison of the 2015 real trans-border flows (top) and the trans-border flows in the base case (bottom) in GWh

However, some elements can be seen that are similar. The largest amount of electricity is in both cases transferred from Sweden to Finland. And in both cases Finland is transmitting significant amounts to Estonia. However, in reality large amounts of electricity are further on transmitted from Estonia to Latvia and then on to Lithuania, but in the model Estonia is only receiving a small amount of electricity from Latvia and not transmitting electricity there. In fact, this should be investigated as in 2015 Estonia was the only country of the Baltics that was a net-exporter, unlike in the model where it is an importing country. This can’t be seen in Figure 4.5 as the trans-border transmission to Russia is not included.

A small mistake in the model is shown by the transmission of electricity from Lithuania to Sweden, because the link between Lithuania and Sweden started operation at the beginning of 2016.

Simpler to explain than the change of importing and exporting countries in the Baltics is the change of direction in the flow from Poland to Sweden. In the year 2015 Poland was receiving more electricity from Sweden than it exported to Sweden, but in the model this is reversed. However, in the model Poland is only connected to Sweden, whereas in reality it has connections to Germany, Czech Republic, Slovakia and the Ukraine. Even though Poland is importing large amounts of electricity from Germany and Sweden in reality, it is a net-exporter because it is also exporting a lot of electricity to Czech Republic and Slovakia. In the model Sweden is missing the imports from Norway, which are replaced by the imports from Poland and Denmark (‘Statistical Factsheet 2015’ 2016).

Denmark’s change from importing to exporting country has no obvious explanation. Reasons could be poor data quality of the residual capacity, or the fact that wind data of 2014 was used in OSEMBE. It is possible that 2014 was a year with very good wind conditions, or the conditions in 2015 were not very good. Also, the reduced number of neighbouring countries could be a reason. Some investigations on reasons before extending the model would be recommendable.

The graphs in Figure 4.6 to Figure 4.8 are showing the development of the trans-border electricity exchange over the whole modelling period. The first thing that draws the attention when comparing the three graphs for 2020, 2035 and 2050 is that the enormous transfer from Sweden to Finland shrinks. This is probably a consequence of the installation of new nuclear power capacity in Finland.

Overall it is important to notice that the total amount exchanged is decreasing from 2015 to 2050. However, it is also visible that many countries change their import/export balance, especially in the sense that the trans-border flows become more bidirectional. Starting the analysis at the top of the graph, the countries shall be analysed clockwise. Denmark starts in 2015 with a very large export to Sweden. However, in the following years the amount of exported electricity reduces, and imports are indicated. Overall it becomes an exporting country with imports at certain times. This fits together with the growing capacities of wind power in Denmark, and the fact that it has the best wind conditions in the set of modelled countries. In 2015 Sweden is a net-importing country, but in all the following years the Swedish exports are larger than the imports. During the modelled period the characteristics of the trans-border transmission changes - in 2015 Sweden is either importing or exporting to the countries it is connected to, but over the years all connections are showing exchange in both directions. In the years 2015 and 2020 Poland is only exporting. First only to Sweden, then also to Lithuania. However, the trade pattern changes, and in 2035 imports and exports are almost equal with a surplus on the export side. In 2050 the pattern looks similar to 2035, but the balance has changed so that Poland has become a net-importing country. The next country, Latvia, has only very little trans-border transmission in the 2015 results. Over the modelling period Latvia develops a pattern that leans towards imports. In 2050 approximately 5% of the Latvian electricity demand are covered by imports. The share of imports in the electricity mix is smaller than in the neighbouring countries – Estonia and Lithuania – which can be explained by the higher availability of hydro power in Latvia and by the fact that both connected neighbours are also relying on imports. Lithuania, the neighbour in the south of Latvia, has a somehow similar development as Latvia, but is even more dependent on imports. The imports are mainly from Poland and Sweden. The development of Finland was already described above. But it can be added that the change from importer to exporter happens without a large change in the figures below. The critical difference is the reduced import from Sweden and the increased export to Sweden. The exports to Estonia are only slightly reduced in 2050. Apart from the large imports from Finland, Estonia is importing on a smaller scale from Latvia in the early years of the modelling period. But in 2035 and 2050 this relationship is inverted and Estonia exports electricity to Latvia.

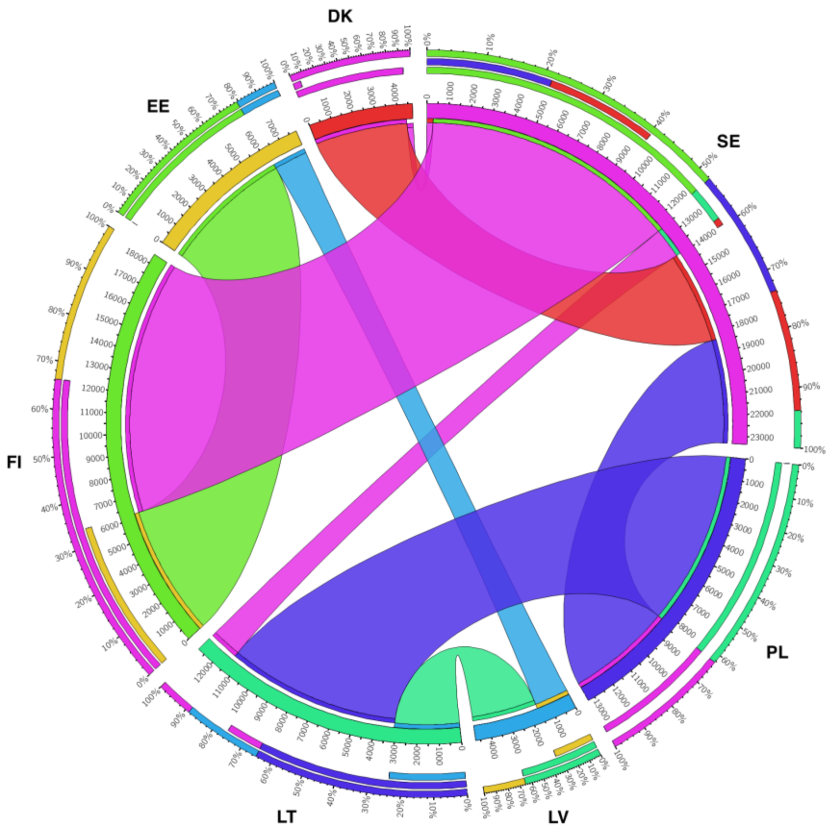


Figure 4.6: Trans-border flows in the base case scenario in 2020 in GWh

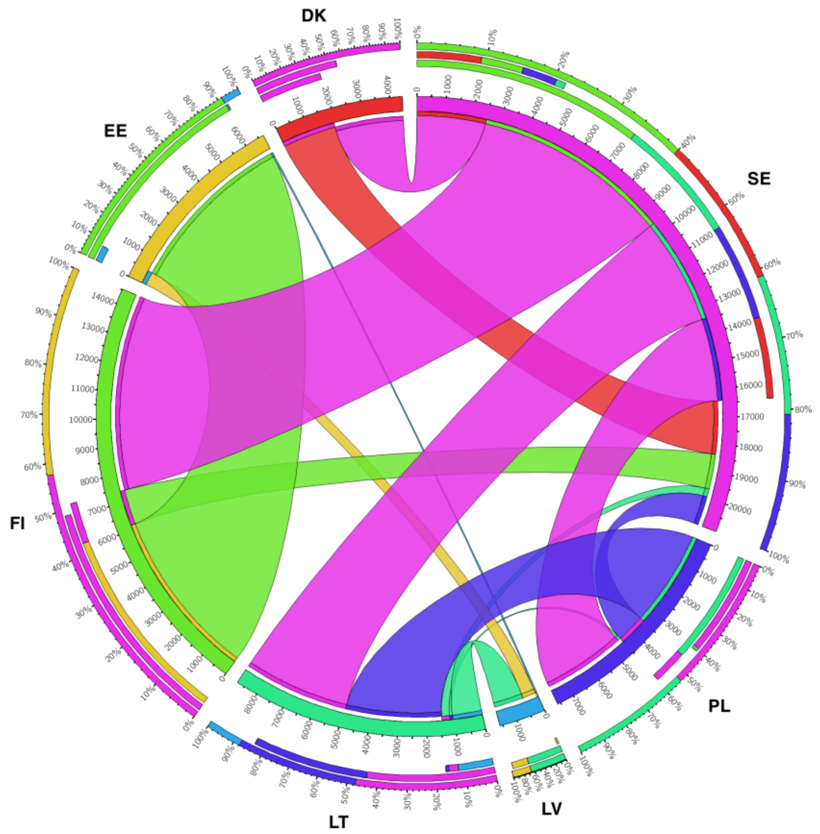


Figure 4.7: Trans-border flows in the base case scenario in 2035 in GWh

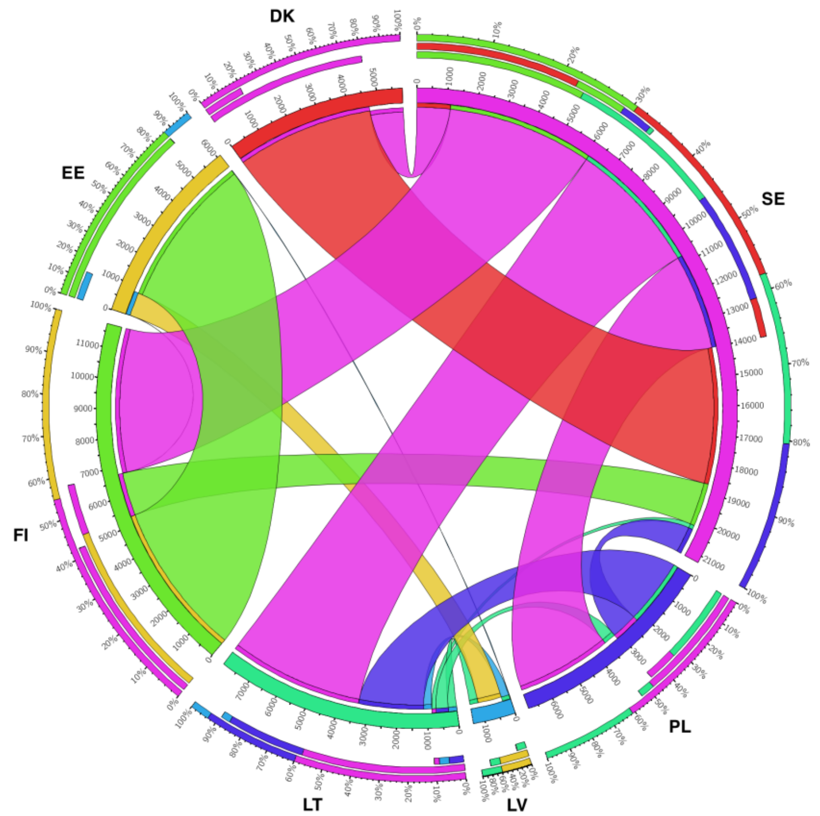


Figure 4.8: Trans-border flows in the base case scenario in 2050 in GWh

Concluding, it can be highlighted that most trans-border connections seem to be more bidirectional in 2050 than at the beginning of the modelling period, but the direction that is mainly evident remains the one from the beginning. Furthermore it was noted that the small countries tend to become importers, if there is not sufficient potential for renewable energy sources, like wind in Denmark. This might be connected to the currently simplified implementation of transmission systems and the assumption that the smaller countries – Denmark, Estonia, Latvia and Lithuania – are not installing nuclear power plants.

4.4 Levelised Cost of Electricity

The LCOE is an indicator for the cost per unit of produced electricity. It contains the discounted investment, fixed and variable operating cost of the corresponding year divided by the final electricity production of the same year.

In this subsection the development of the LCOE over the modelling period within the base case shall be described and analysed. In section 4.5.2 the sensitivity of the LCOE on changes in the RM are contemplated.

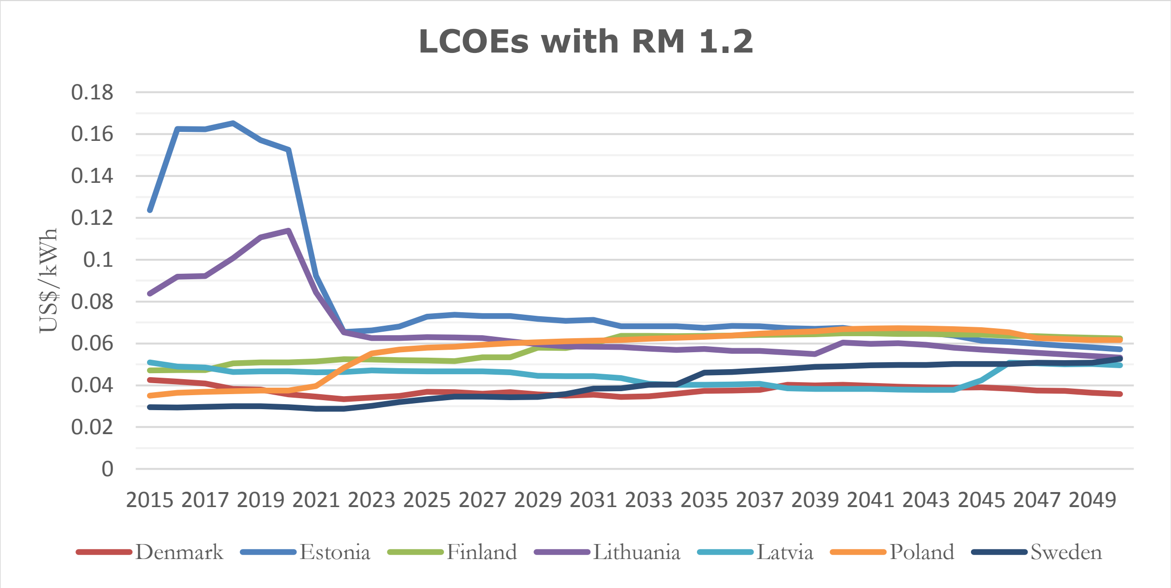


Figure 4.9: Development of the LCOE within the base case scenario

The graph in Figure 4.9 shows the evolution of the LCOE for all modelled countries for the entire modelling period. Contemplating the overall development of the LCOE curves in Figure 4.9, it can be seen that the LCOEs rise from a level of 3 to 5 cents per kWh up to 3.5 to 6 cents per kWh. Exemptions in the first years of the modelling period are Estonia, which starts with a LCOE of approximately 12.5 cents per kWh, and Lithuania, which starts with a LCOE of approximately 8.5 cents per kWh. The Estonian LCOE jumps up to around 16 cents per kWh in 2016 and stays on this level till 2020. The Lithuanian LCOE does not jump upwards but increases as well, up to 11 cent per kWh in 2020. In 2022 both have fallen down to a level slightly above the level of the other modelled countries, and over the remaining modelling period the curves do not show any other extraordinary behaviour. In reality the cost for electricity in Estonia and Lithuania are not very different to the cost in Latvia, with a maximum difference of 2 cents (Eurostat 2016a; Eurostat 2016b). Therefore, the reason for the special patterns in the first years has to be searched within the model. When looking at the production patterns of Estonia and Lithuania in Figure 9 and Figure 12 respectively in the Appendix 2, it is conspicuous that the countries are satisfying more than half of their demand by imports. However, in reality both countries have sufficient capacity to satisfy their demand, as Estonia is in reality a net exporter and for Lithuania it is indicated in Figure 4.4. The existence of the capacities to supply themselves and the shift to import large amounts of electricity explain the high LCOEs in the years till 2020. The existing capacity relates to fix costs which are occurring independently of the usage of the capacity, i.e. if the capacity is not or only little used the LCOE rises as the cost are divided by a smaller number. The drop after 2020 occurs as a major phase out takes place in 2021.

In Figure 4.10 the composition of the LCOEs of all countries in four different years are shown. Of course, the peaks of Estonia and Lithuania are dominating the picture here also, at least in 2015 and 2020. But when looking at the development over the years many things can be noticed. In the first years, the LCOEs are dominated by the fixed operating (blue) and fuel costs (green). But over the years the investment cost (turquoise top section of the bars) gains more and more relevance. The third important parameter are the emission cost. At the beginning it is visible in all countries that the emission cost are disappearing out of the graph, except for Estonia, even though the emission penalty is increasing over time (see also Figure 9 in Appendix 1). It is observable that no country has a permanent cost advantage or disadvantage. For example, Finland already has a significant share of investment costs in its LCOE in 2020 due to the installation of new nuclear power plants, but in 2050 the structure of the LCOE is similar to the structure in Sweden where only a small amount of new nuclear power capacity was installed.

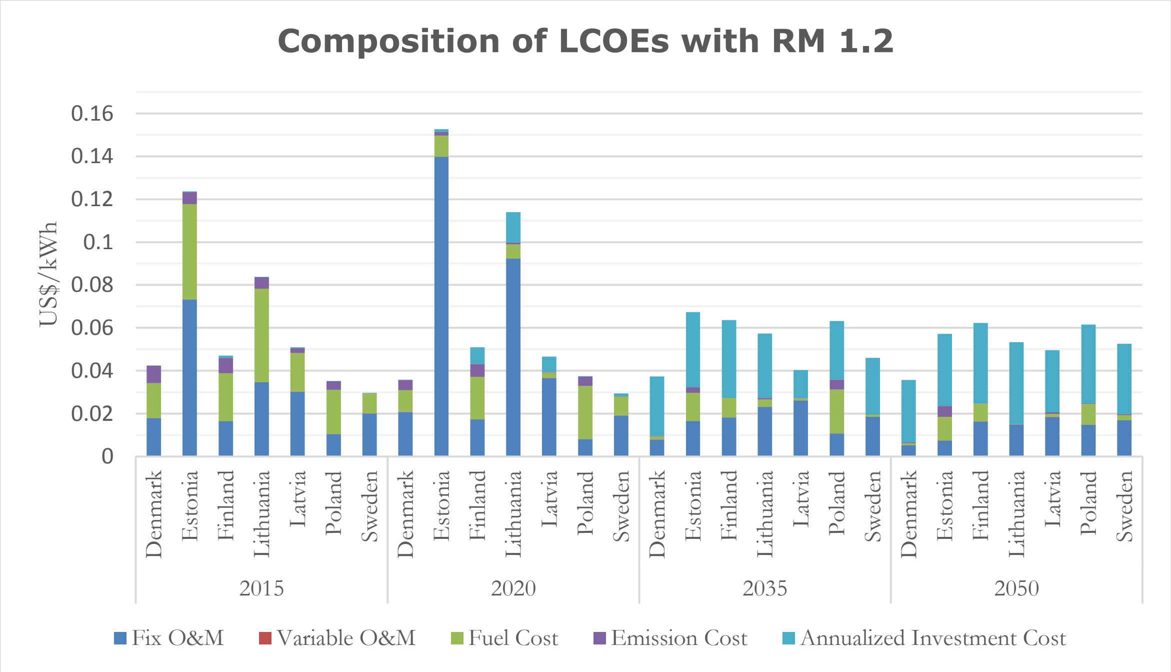


Figure 4.10: Composition of the LCOEs with RM 1.2 in different years

Overall it can be admitted that the level of the LCOEs is too low. Except Estonia and Lithuania, the LCOEs are between three and five cents per kWh in 2015 and between three and a half to six cents in 2050. In reality the basic price without taxes and levies for industrial and household consumer were between five and 20 cents per kWh in Europe in 2015 (Eurostat 2016b; Eurostat 2016a). This issue of low LCOEs, but also the issue of the high LCOE and the peak in Estonia and Lithuania in the first six years of the modelling period, are to a certain extend caused by the lack of transmission cost. Domestic but also trans-border transmission are not yet connected to any cost in OSEMBE. The only assumption made in the transmission context is that 5% of the electricity fed into a transmission system is lost. By implementing transmission cost the overall level of the LCOEs would be increased. In Estonia the import of electricity would be less attractive as there would not only be an additional loss of electric when importing, but also an additional cost. By the reduction of the imports the LCOE in Estonia in the first years might decease, as there could be more domestic production but no big changes in the cost pattern as they are mostly fixed. The peak in 2020 might still occur but maybe to a smaller extend.

4.5 Sensitivity analysis

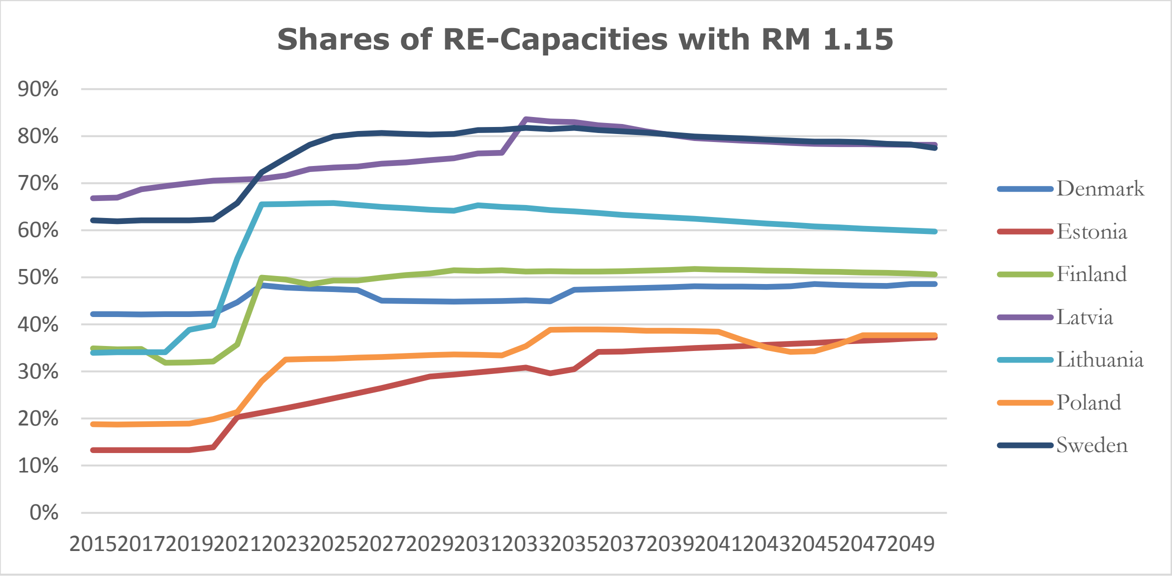
In this section, the influence of the RM – reserve margin - shall be investigated. Without changing any other parameter, two additional runs to the base case with a RM of 1.2 were done. In the first run the RM was reduced to 1.15 and in the second run it was increased to 1.25. In the first subsection of the chapter the effect of a change of the RM on integration of RE shall be investigated, by comparing the shares in installed capacities and by comparing the share in production. In the second subsection of the chapter the effect of the RM on the LCOE shall be investigated. This is done by comparing the development and composition of the LCOE of Denmark in the different scenarios.

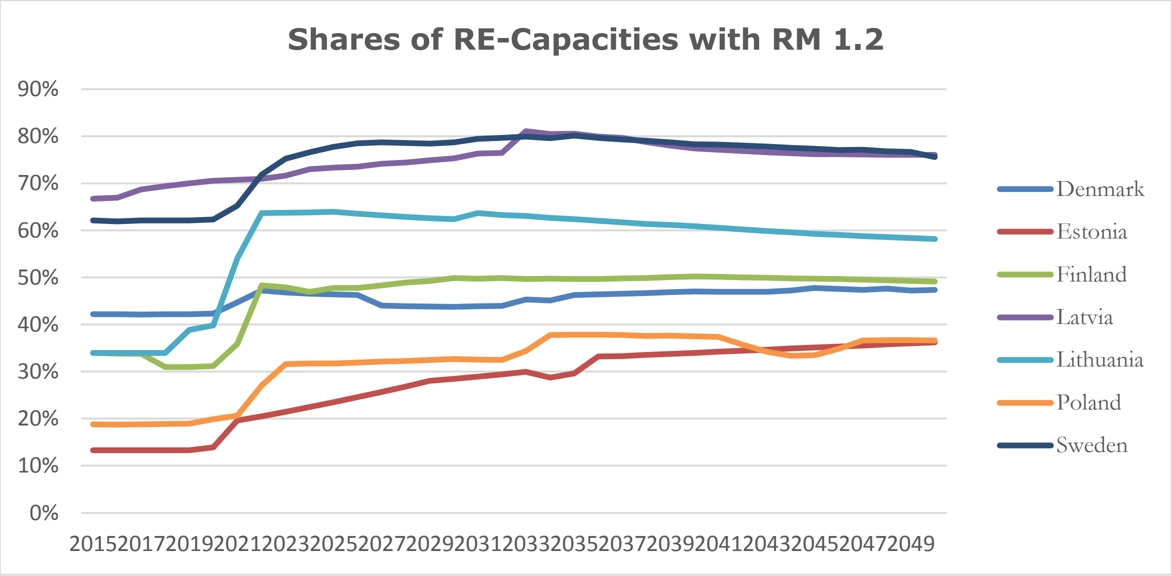
4.5.1 Shares of RE in capacity and production

As mentioned above, this subsection analyses the effect of the RM on the share of RE, first in the total installed capacity and afterwards in the production.

Figure 4.11 shows how the share of RE-technologies develops over the modelling period in each country. First, it might be noted that the general pattern of each country is not affected by a change of the RM. When comparing the characteristic spots in each graph like the peak in 2022 in Lithuania (turquoise) or the low in 2035 in Estonia (red) it shows that a higher RM leads to lower share of RE-technologies in the installed capacity. A difference of 5% in the RM causes a change of roughly 3% in the installed capacity. These results seem reasonable as a larger RM requires more capacities of technologies that have secured fuel supply or rather storable fuels. Due to that, out of the set of RE-technologies only HY is electable. The consequence is that more fossil fuel technologies are installed. However, it does not imply that less RE-capacities are installed overall, but their relative share decreases. A good example for this effect is Denmark, where more HF capacities are installed with a higher RM, but not used (as shown in the next section (4.5.2)). This leads us to Figure 4.12 and the share or RE-technologies in the annual production. The three graphs in Figure 4.12 do not show any major differences in the share of RE-production when changing the RM. No consistent pattern in terms of a lower or a higher share with a lower or higher RM is visible. The only detectable differences are mainly in the small countries, or rather the Baltic countries, e.g. the peak around 2020 in Estonia has a one-year tip with RM 1.15 and RM 1.2 but a two-year peak in the RM 1.25 scenario. These small changes in the production share are possibly caused by changes in the investment patterns due to the different RM. Such changes in the production share also occur in the bigger countries, as their curves are also not identical in the different scenarios, but a similar absolute change in production in a big country, e.g. Poland, does not have the same effect on the share of RE as in a small country like Latvia.

Summarizing this subsection, it can be concluded that the change of RM has a consistent effect on the share of RE-technologies in the total installed capacity, whereas the share of RE in production is only marginal and not consistently affected.





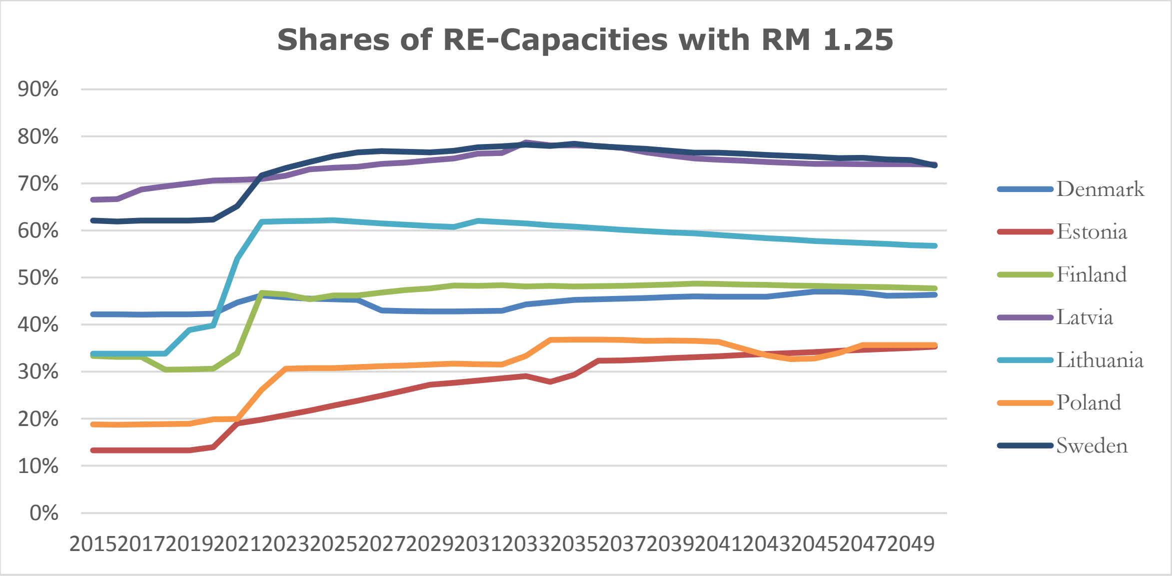


Figure 4.11: RE- Capacities shares with different RM's

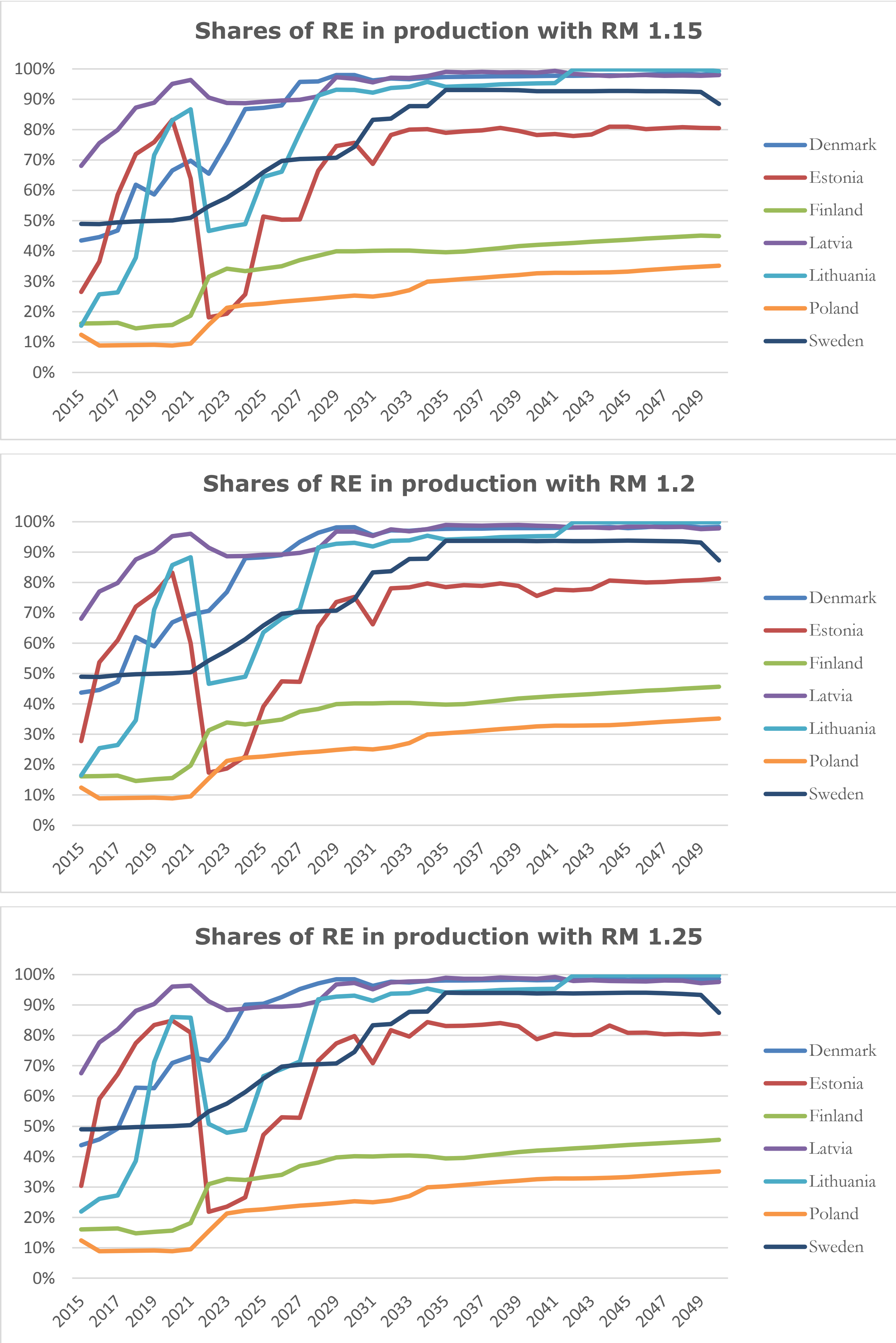


Figure 4.12: RE production shares with different RM's

4.5.2 Levelised cost of electricity

In this subsection the development of the Danish LCOE shall be compared while applying different RM's.

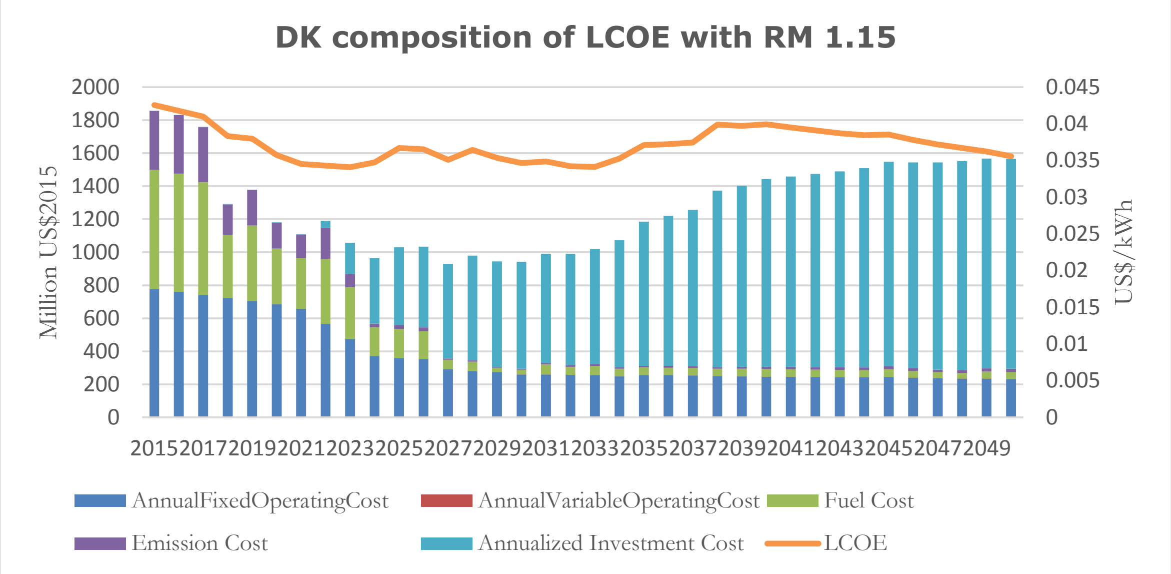


Figure 4.13: Development and composition of the LCOE in Denmark with RM 1.15

On the primary vertical axis on the left-hand side of the three figures in this section, cost is shown in Million US$, the unit for the bar chart of the annualised cost elements. On the secondary axis the cost in US$ per kWh is shown, relating to the orange curve of the LCOE.

When comparing Figure 4.13 to Figure 4.15 it can be said that a change of the RM is not causing big changes in the development of the LCOE, both in terms of overall development or in its composition. The changes are mainly found in the height of the LCOE. To make the small changes visible, only one country – Denmark - was selected. In the graphs below the overall development of the LCOE and structure are shown. The best place to see the difference is probably the last peak of the curve in the year 2045. In the scenario with RM 1.15 the LCOE is clearly below the line of 4 cents per kWh. In the base case scenario with a RM of 1.2, the line of the LCOE is almost touching the 4 cents per kWh line, and in the high RM scenario with a RM of 1.25 the LCOE touches the 4 cents per kWh line. The increase of the LCOE with the RM is caused by the higher investment need to provide the required RM. A closer look at the fixed operating costs in the second half of the modelling period reveals that while the investment costs increase, the fixed operating cost are slightly lower with a higher RM, which can be seen in the Table 1 to Table 3 in Appendix 2.

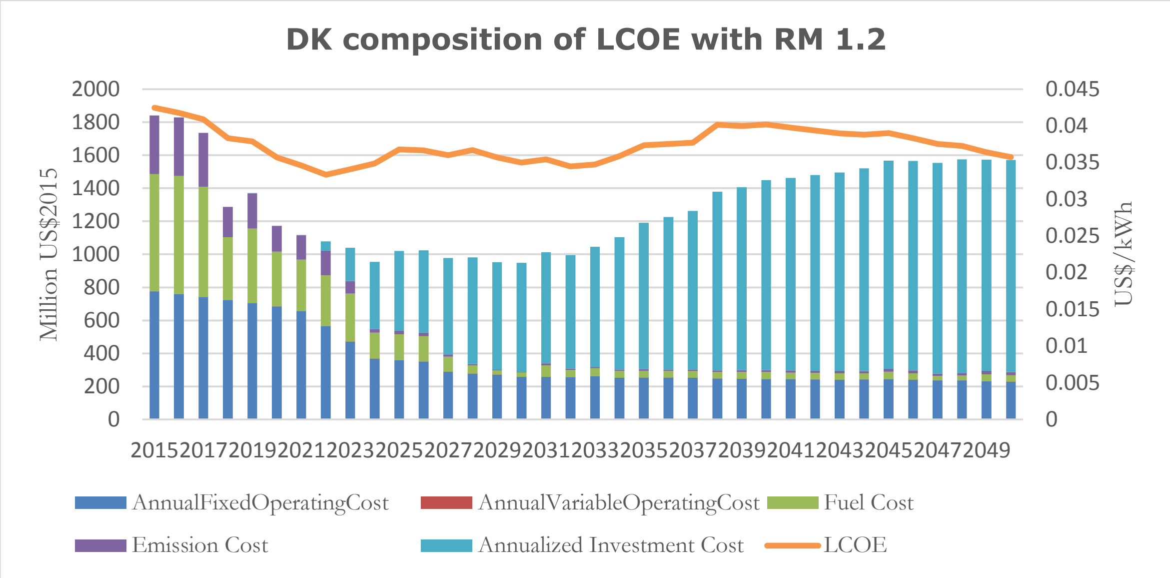


Figure 4.14: Development and composition of the LCOE in Denmark with RM 1.2

This indicates that the model chooses technologies with low fixed operating cost to provide the RM. Figure 1 and Figure 8 in Appendix 2 show the total installed capacity and the annual production of Denmark, respectively. When comparing the two figures it shows that the model chooses HF technologies to provide the RM, as there is a large share of HF in the installed capacity but no share of HF in the production pattern.

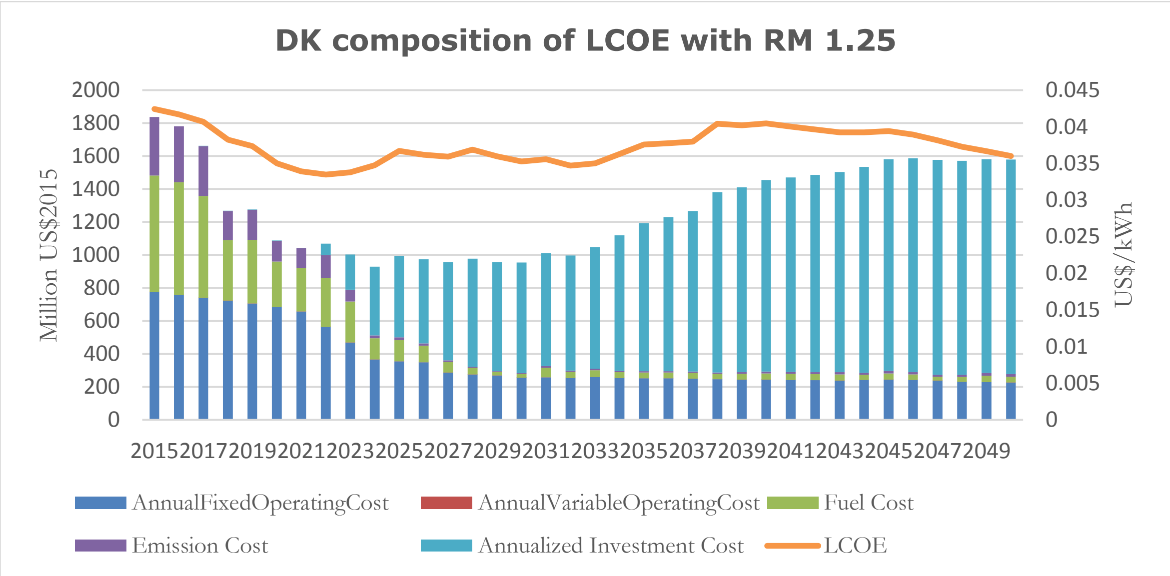


Figure 4.15: Development and composition of the LCOE in Denmark with RM 1.25

Overall it can be detected that the RM has only small effects on the model's results. The changes that occur by applying a different RM are reasonable in the contemplated scenarios. A higher RM decreases the share of RE-technologies in the installed capacity but changes the share in production only marginally and without a clear pattern. The LCOE increases with the RM as more investments are required. However, the increased investments are partly compensated by lower fixed operating cost.

5 Future work – The way to a holistic energy model of Europe

The results presented and analysed in the previous chapter seem to be reasonable. Where they are not, the cause of the inconsistency is indicated, or will be indicated in this chapter, and is assumed to be solvable when the model is extended around aspects that are not fully considered or its data is improved.The following subsections shall outline where OSEMBE needs to be improved and what else might be added to the model to improve it. The first subsection in the chapter deals with improvements that could be done in the existing model, e.g. replacing simplifications by more detailed data. The other subsections are describing topics that are not considered thus far, but are part of the energy system and have or might have significant influence on the electricity system, e.g. heat use, energy storage, and transport.

The next step in the development of OSEMBE should probably be the extension of the countries included. As noted so far only Denmark, Estonia, Finland Latvia, Lithuania, Poland and Sweden are included. As part of this study a large amount of the required data for the missing countries was already prepared, e.g. the day split, the demand profile and the residual capacity. However, to add the missing countries the limitations of renewable energies would need to be investigated. Furthermore, the residual capacities need to be revised as it was noted when implementing the already included countries that the data base used is not complete, and indicates sometimes significantly lower values than installed in reality.

5.1 Improvements in the existing model in the electricity section

In this section aspects of the existing model that could be improved are pointed out, and ways to do so are indicated.

5.1.1 Differentiation of biofuels

In order to keep the number of available fuels - and therewith the complexity of the model - low, only one type of biomass, or biofuel, was implemented in OSEMBE. The critical question during the development of OSEMBE in this respect was how to calculate the price of BM for the model. The decision was made that an average of different types of biofuels will be used, including biomass fuels and liquid biofuels. This simplification needs to be seen as critical since the price difference between biomass fuels and liquid biofuels is about a magnitude (IRENA 2015a, 128; IEA-ETSAP and IRENA 2013, 16). Due to these circumstances, the average price is much higher than the real price of biomass used for power generation. The results for Finland and Sweden are especially affected by this impreciseness, as both countries have vast biomass for power resources in the context of their paper and wood industry.

The suggestion for an update of OSEMBE is to implement two types of biofuel. First biomass, like forest and agricultural residues, mainly used in larger power generation facilities, and second liquid biofuels, like ethanol from crops, mainly used for internal combustion engines or similar generating units.

Implementing the two types of biofuels described above would most likely lead to a growing share of biomass capacity throughout the modelling period, perhaps even hitting the already implemented limitation of domestic biomass production. Whereas generation units using liquid biofuels would most likely not be selected by the model.

5.1.2 Availability factors

A few technologies that are implemented in OSEMBE are not yet mature, or are not even currently available, but are expected to enter the market in the future, e.g. fuel cells and small and medium sized LWR. Therefore, the availability factors for those technologies are estimations, and could be updated when there is better data available when they are applied more commonly.

5.1.3 Capacity factors

The capacity factors are a key parameter for the adaption of renewable energy technologies. Therefore, reliable data is of high importance when comparing technologies, even if the model is doing the comparison. In subchapter 3.5.1 it was mentioned that the capacity factors used are based on weather data of the year 2014. It would be better if those values would be based on the average values of many years, maybe a decade or more. This could be done by using a different data source or by using new data when *renewables.ninja* offers data for more years.

The methodology under which the capacity factors are achieved for each country could be improved as well. The current values are calculated by taking the average of several locations that are spread over the country, aiming to achieve a good coverage. By designing and using a method to choose the locations from which the capacity factors are taken the result quality of OSEMBE would be further improved.

5.1.4 Demand development

In the current model just one demand figure is implemented, covering all sectors. The *specified demand profile*, which defines how much electricity is consumed in every time slice, is assumed to be constant over the modelling period.

However, the overall demand profile will most likely change over the coming decades. This will be caused by the change in consumption of the different sectors like industrial, service and residential. Therefore, it would improve the model if demand by different sectors would be implemented individually. For each sector an individual demand profile would be used. As a result, the overall demand profile would change over time when the shares of sectors in the final electricity demand change.

5.1.5 Fuel use

To improve the model, a question that should be investigated in the future is how much of the domestic fuel production is available for domestic use. This is a question for the traditional fossil fuels, where it might be that a large share of the production goes directly into exports, but for biofuels and waste streams this question has even a higher relevance. For those sources, energy generation can be in competition with other uses, e.g. food production, paper production or other industrial uses.

5.1.6 Phase out of power plants and refurbishment

In chapter 3.5.4 the difference between the phase out of the residual capacity and the capacity installed by the model is described. However, the way in which technologies phase out could be improved. For technologies where significant amounts of capacity are operating longer than the predicted technical lifetime, this could be a hint that the estimation of the technical lifetime is too low. By improving the estimated lifetimes, the differentiation between residual capacity and capacity installed by the model might become unnecessary. New estimates for the technical lifetimes could be taken from different literature than currently used. Another option would be to generate own estimations of technical lifetimes by using data of different versions of databases like PLATTS. By comparing the data of different versions, it would be possible to calculate an average power plants lifetime, and correct the parameters based on that.

A few technologies that are included in the model are not expected to be installed again. This means that the average age of the installed capacities of these technologies will increase continuously till the technology is completely phased out. It is very likely that the old power plants need more maintenance and have more shut down times due to technical problems, which could be considered by decreasing the corresponding availability factors in the years before the technology is phased out.

5.1.7 O&M cost and labour cost

The operation and maintenance costs (O&M cost) are not country specific in this first version of OSEMBE. However, as they include the labour costs that are related to the operation and maintenance of power plants, the precision of the model could be improved by the usage of country-specific data.

5.1.8 Reserve Margin

In the current version of OSEMBE the RM is the same for all countries, and only domestic capacities are tagged to provide the RM.

The first aspect makes it especially difficult to adjust the RM in the model to the right level. In reality the RM depends on legislation, the grid operator and the transmission capacities to other countries. The results indicate that Finland, for example seems to operate its electricity system with a lower RM than the 1.2 that was chosen for the base case, whereas Denmark and Estonia seem to have an even higher RM. Therefore, it could be considered to have country-specific RM that are more closely related to reality. Over the modelling period they could all aim for one general RM.

The second aspect is of importance to countries with strong interconnection. In the current set of countries Sweden and Finland, but also the Baltics, could be an example where it may be important to consider whether the trans-border connections should be able to contribute to the RM, at least with a certain share of their capacity. An example of two countries that are not yet part of the model but where the trans-border transmission should be considered to be part of the RM are Croatia and Slovenia. These two countries have a commonly owned power plant in the border region which supplies both countries, but when implementing the RM in the current way just one country would have this power plant in its RM. One option to solve this issue would be to look on a case-by-case basis at the connection of two countries and allow the trans-border transmission technology to contribute a certain share to the RM. Another option would be to build groups of countries that have a common RM and that provide joint capacities for the RM. This would be a good solution for groups of small countries like the Baltic countries or Croatia and Slovenia.

5.1.9 Residual capacity

Previously it was mentioned that the implemented residual capacity of this first version of OSEMBE is mostly withdrawn from the PLATTS database, but it was also pointed out that this database is not complete. Due to this the residual capacity data could be improved.

One option to do so could be to use national data in combination with PLATTS. Data concerning the latest installations of distributed renewable technologies might be more precise in national data sources.

Precise data for the residual capacity is important to have a solid connection to reality. By using data of good quality, mistakes made in the assumptions might become visible in the results by discontinuities.

A simple improvement of the residual capacity would be to differentiate the residual not only by power plant type, but also by size. PLATTS contains the size of every power plant included, therefore it would not be time intensive to do so.

5.1.10 Scale effects

Many of the implemented technologies in OSEMBE exist in different sizes. Either the size of their units can vary strongly, e.g. GC, or their plants consist out of several units, e.g. wind parks. The change of costs caused by different sizes, so-called scale effects, are only considered for some technologies, e.g. hydro power. Implementing size-dependant cost parameters would be an important improvement of OSEMBE, because the bigger a power plant is the cheaper it is normally per produced unit of energy. However, a larger power plant feeds its electricity to the transmission or distribution grid to deliver it to the consumer, whereas distributed technologies deliver their electricity almost directly to the consumer. A part of the electricity fed to the grid is lost, and furthermore the grid causes costs. This indicates that a set of parameters influences the choice if small scale distributed power plants or large scale centralised power plants are chosen.

But as mentioned above, so far the scale effects are just partly taken into account in OSEMBE. By improving the cost data of the technologies, the accuracy of the model in terms of in which level a technology is installed would be improved.

5.1.11 Solar power

The way solar power is implemented at the moment can, or rather has to, be improved in several ways.

At the moment there are only two solar technologies available in OSEMBE. Distributed PV and Utility PV. As the modelled region is quite far in the north, solar technologies are not a very good option, therefore the results are probably not strongly affected by the scarcity of solar technologies. However, when adding more countries, especially when adding countries that are further in the south, more solar technologies should be implemented, e.g. CSP or PV with tracking. Some technologies that could be used are described in ETRI (EC 2014a). In the excel-file used to prepare the residual capacity for OSEMBE, CSP-technology setups are already included.

5.1.12 Transmission technologies

The transmission technologies are a key element of every electricity system. However, in OSEMBE they are reduced to the core of their purpose. Within a country they connect the secondary with the tertiary energy level and tertiary with final energy level. The losses are assumed to be 5%. Trans-border transmission is only considered between the countries included in the model and is limited to the existing capacities and planned capacities (ENTSO-E 2014). So far, the transmission technologies are not related to any cost.

The current implementation of transmission technologies allows many improvements. A first small aspect could be to include the transmission to countries that are not covered by the model yet, e.g. the Swedish electricity system is strongly connected with the Norwegian one and by considering such connections the model would portray reality in a more accurate way. The transmission to and from countries not included in the model could be limited by data of the existing transmission capacities, and the cost could be based on average market prices.

A more challenging improvement would be to implement the cost of electricity transmission. The work-intensive challenge for such a project would be to define the distances of the transmission lines. This would be necessary as the cost – capital and O&M – are strongly related to the length of transmission lines.

At the current point of development, the improvement of transmission technologies and the consideration of connections to countries that are not (yet) part of the model is assumed to be the most important improvement after the differentiation of biofuels and therefore one of the next steps in the development of OSEMBE.

5.2 Heat

An important improvement of OSEMBE will be to extend the model in terms of integrating heat demand and generation. A great number of technologies already implemented in OSEMBE are designed to generate electricity and heat. By not using the heat they become less attractive, as this can be seen as a reduction in efficiency. CHP plants have the advantage that they can adjust their production in a certain range to the current demand situation. In times of high heat demand, they shift more towards heat production and in times of high electricity demand the power to heat ratio is shifted to electricity production.

The integration of heat includes several challenges. One key challenge are the different fuels that are used. Fazeli et al. indicates how the share of fuels for heating in the Nordic countries changed since 1990 due to political incentives and price development. Furthermore it is indicated how the countries have developed in different ways (Fazeli, Davidsdottir, and Hallgrimsson 2016). The climatic conditions and the wealth of a country are probably factors that are influencing the heating pattern, as well as the choice of fuel. Taking the set of different factors that are influencing the heating demand, pattern and choice of fuel, it becomes clear that modelling national or EU wide heat supply systems, or rather chains, is a complex issue. It is also difficult to find data on the actual heat consumption, as heat demand is covered in many ways. For domestic heat, a wide collection of generation systems in place is available. Those systems can use a wide range of fuels: fuel oil, natural gas, biomass (wood pellets) or electricity. In addition to on-site heat generation, district heating is becoming more and more common in many countries.

As noted above, it is difficult to get heat consumption data. One method to estimate the residential heating and cooling demand is the concept of heating-degree-days (HDD) and cooling-degree-days (CDD). This concept assumes that there is no heating or cooling demand within a certain range of outdoor temperature. For the case that the outdoor temperature is above the range, there will be a cooling demand that increases with the outdoor temperature. If the outdoor temperature is below the range there will be a heating demand that increases with a decreasing outdoor temperature. Based on this concept, country-specific heat and cooling demand could be generated for OSEMBE. An even more sophisticated way to consider heat and cooling demand would be an econometric approach, that combines the outdoor temperature parameter, wealth level – e.g. GDP per capita, and availability of fuels to estimate the heat demand and the choice of fuel to satisfy the demand (Fazeli, Davidsdottir, and Hallgrimsson 2016).

Due to the described complexity, heat was not integrated in this first version of OSEMBE, but as mentioned in the beginning of this section it is an important part of the energy system, and should be added in the future to improve OSEMBE by making it more holistic.

5.3 Storage

The technologies implemented in OSEMBE are not able to store energy. Even though the residual pumped hydro power capacities are considered, they are working as normal hydro power plants. Pumped hydro power plants are well known as an option for energy storage. However, with an increasing share of fluctuating electricity production from renewables in the future, technologies like Compressed Air Energy Storage, Flywheel Energy Storage, batteries and thermal energy storage might become important components of the energy system (EC 2014a). Storage technologies will be of high relevance to be able to operate the future energy systems, especially in front of the already mentioned background of large shares of renewable energies. As a result it would be an improvement of significance to OSEMBE if storage systems would be implemented. The effect of storage technologies might be large, particularly near the end of the modelling period, or rather in the second half of the modelling period. However, the effect will also depend on the assumed GHG emission policies.

One technology that is already providing the option of storage is pumped hydro storage (DS). But in this model pumped hydro storage is implemented with the same parameter as hydropower dams. For the integration of storage technologies, it could be a first step to modify DS technologies in a way that they are able to store electricity and by that balance the system.

5.4 Transport

Up until now the interconnection between electricity sector and transport sector is not very strong. The only type of transport technology that is currently using electricity in significant amounts are trains. But with increasingly strict regulations on vehicle emissions, and many cities beginning to limit the access of cars with high emissions to their centres, it is most likely that the share of electric vehicles on the roads will increase. This increase, and the application of intelligent charging solutions, might be of high relevance to the management of the electricity systems in the future. If the charging systems of the cars and other vehicles shift the charging process to times of high production by renewable energies, electric vehicles could be an important component for managing their fluctuating production. Therefore, additional follow up work on this thesis could be to integrate the transport sector in the model.

6 Conclusion

Within this Master’s thesis the model OSEMBE was developed it covers the countries around the Baltic Sea, except Germany. However, fundamental design elements – like the time slices – were defined with the expectation that OSEMBE will be extended to cover the entire EU.

A central aspect of interest in the development of the multi-country-model is the investigation of trans-border electricity flows. Such investigations are already possible as shown in chapter 4.3. Nevertheless, the representation of transmission lines and possible transmission extensions could be further improved as highlighted in chapter 5.1.12. The analysis of trans-border flows gains special importance in the planning for the transition to a more sustainable energy supply as the renewable resource potential and quality varies from site to site. This implies that potential and quality vary also from country to country. The representation of resource potential is done implementing a country specific limit on the production of electricity by each source of renewable energy. However, the consideration of the quality aspect is more complex. For the current version of OSEMBE country specific availability profiles where calculated for wind and solar PV. But for the future a higher resolution could be considered. Contemplating the relation of these two aspects – trans-border transmission and renewable resource representation – the purpose of creating OSEMBE becomes clear: the identification of cooperation potential on the European level for an economic application of renewable energies.

To make such analysis possible, the next steps in the development of OSEMBE would be the extension of the model to cover all EU countries, and perhaps Switzerland and Norway. After that the most critical aspect of improvement is probably the consideration of storage options, which are already and will be even more important in the future to handle the fluctuating production by renewable energy technologies.

Concluding it can be said that in the context of European energy systems modelling, OSEMBE is not yet a fully-fledged competitor. However, it might be the base for a new approach in the discussion and planning of the future energy supply of Europe. By using an open source modelling system that is designed to be easy to understand, and by making the model accessible to everyone, it might support a sounder public discussion but also more contributions by other researchers on the topic of how the energy supply in Europe should be developed over the next decades.

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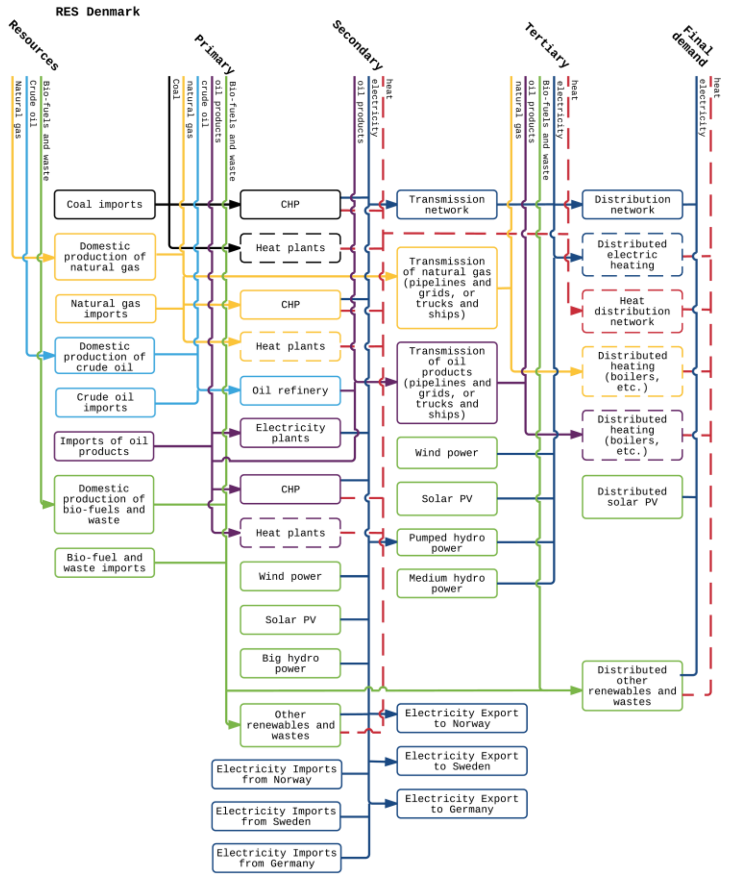
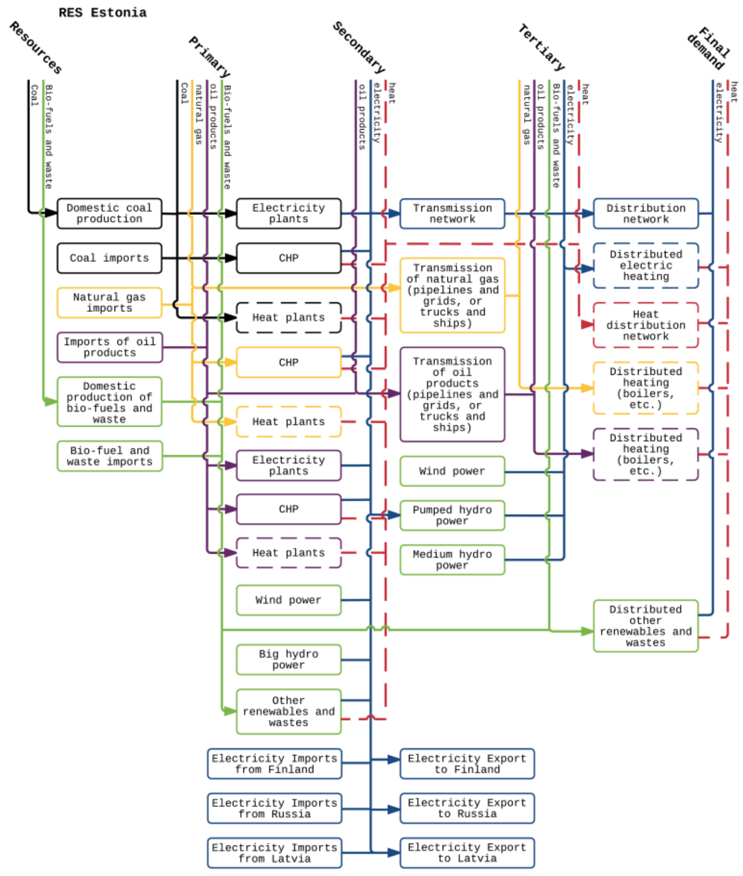
Appendix 1 – Inputs

Reference Energy Systems



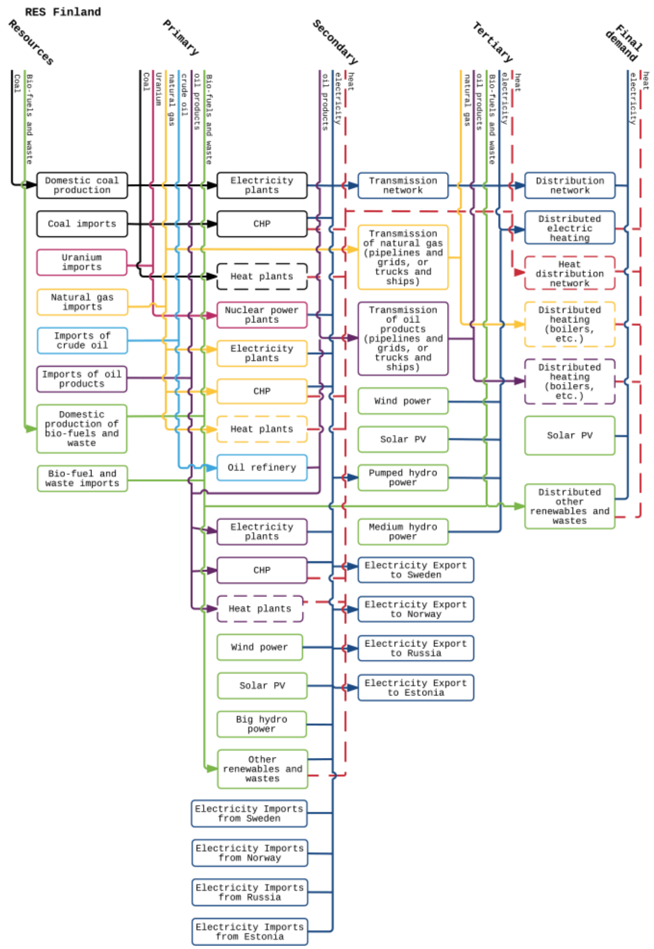
Sources: http://www.iea.org/statistics/statisticssearch/report/?year=2013&country=DENMARK&product=RenewablesandWaste,

Figure 1: RES Denmark



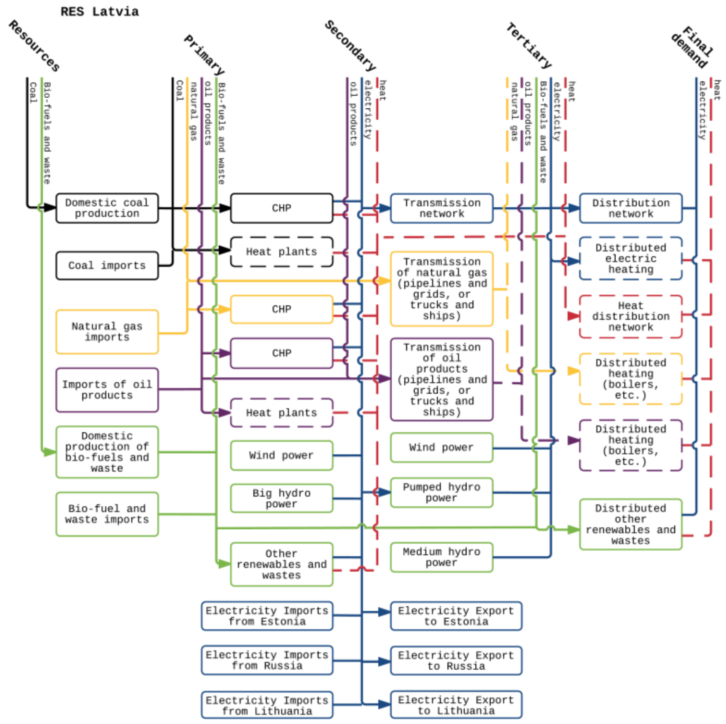
Sources: http://www.iea.org/statistics/statisticssearch/report/?country=ESTONIA&product=naturalgas&year=2013

Figure 2: RES Estonia



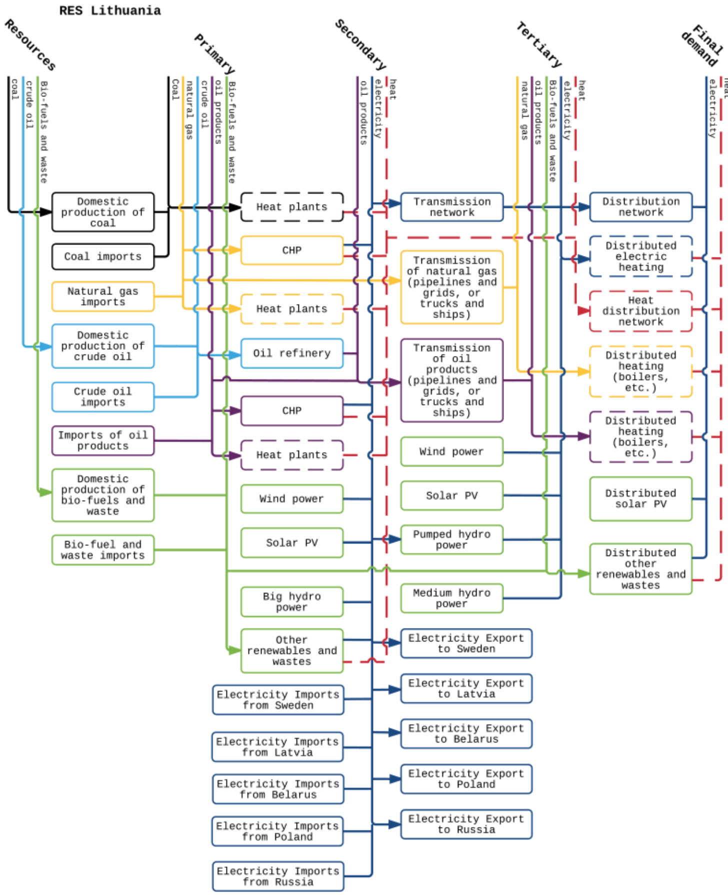
Sources: http://www.iea.org/statistics/statisticssearch/report/?year=2013&country=FINLAND&product=ElectricityandHeat, http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.aspx

Figure 3: RES Finland



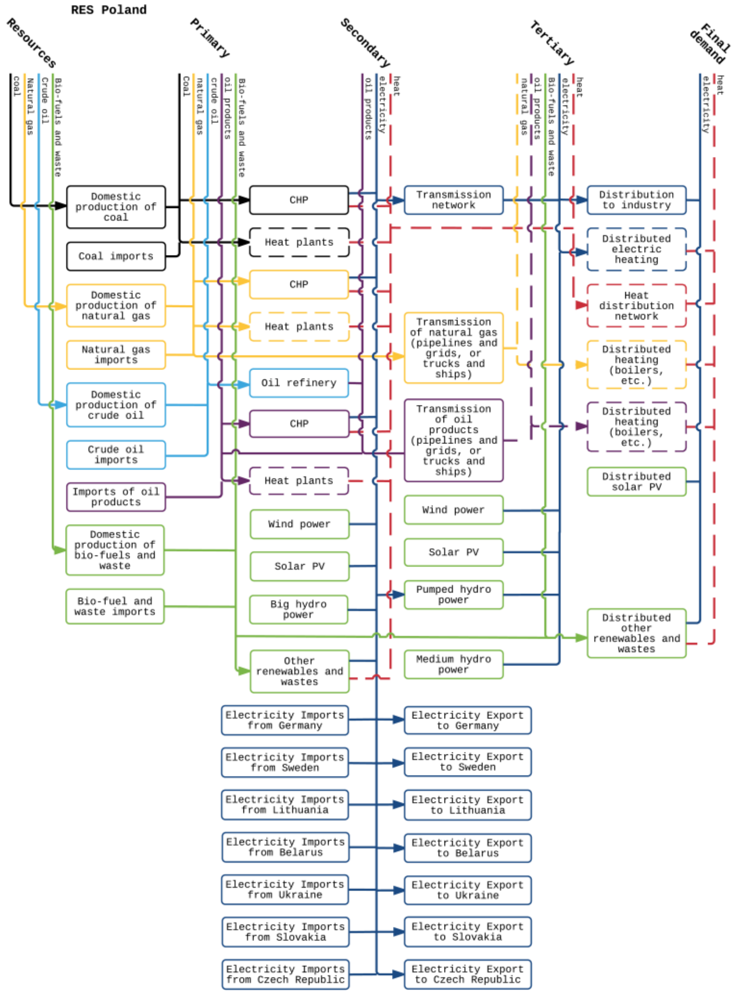
Sources: http://www.iea.org/statistics/statisticssearch/report/?year=2013&country=LATVIA&product=Balances

Figure 4: RES Latvia



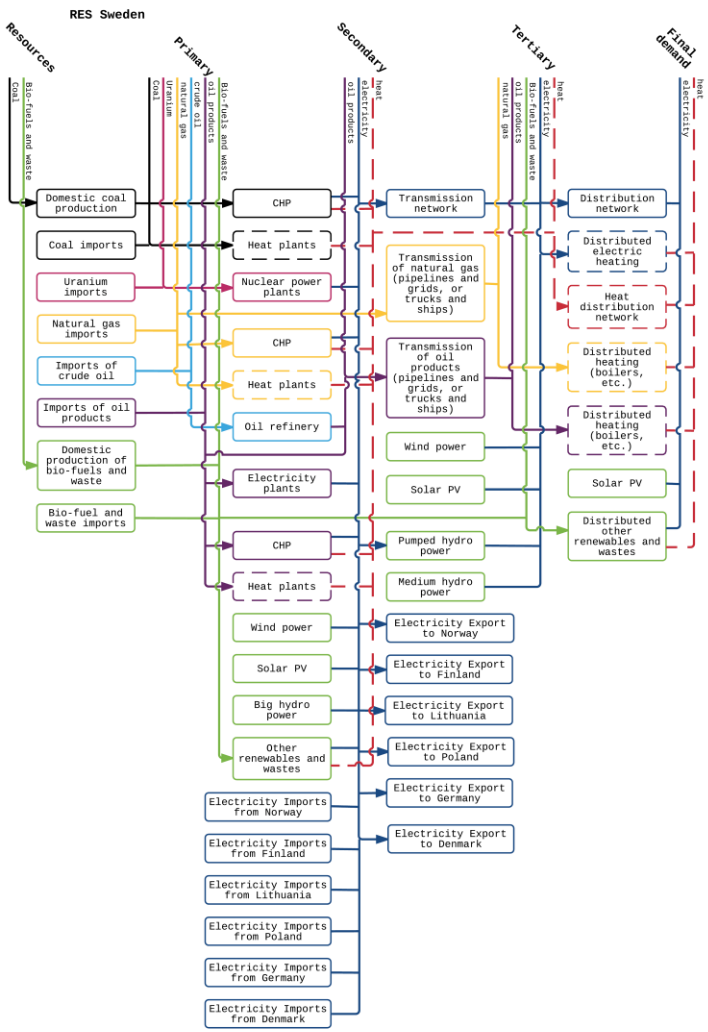
Sources: http://www.iea.org/statistics/statisticssearch/report/?year=2013&country=LITHUANIA&product=Balances

Figure 5: RES Lithuania



Sources: http://www.iea.org/statistics/statisticssearch/report/?year=2013&country=GREECE&product=RenewablesandWaste,

Figure 6: RES Poland



Sources: http://www.iea.org/statistics/statisticssearch/report/?year=2013&country=SWEDEN&product=Balances,
http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.aspx

Figure 7: RES Sweden

Specified Demand Profiles

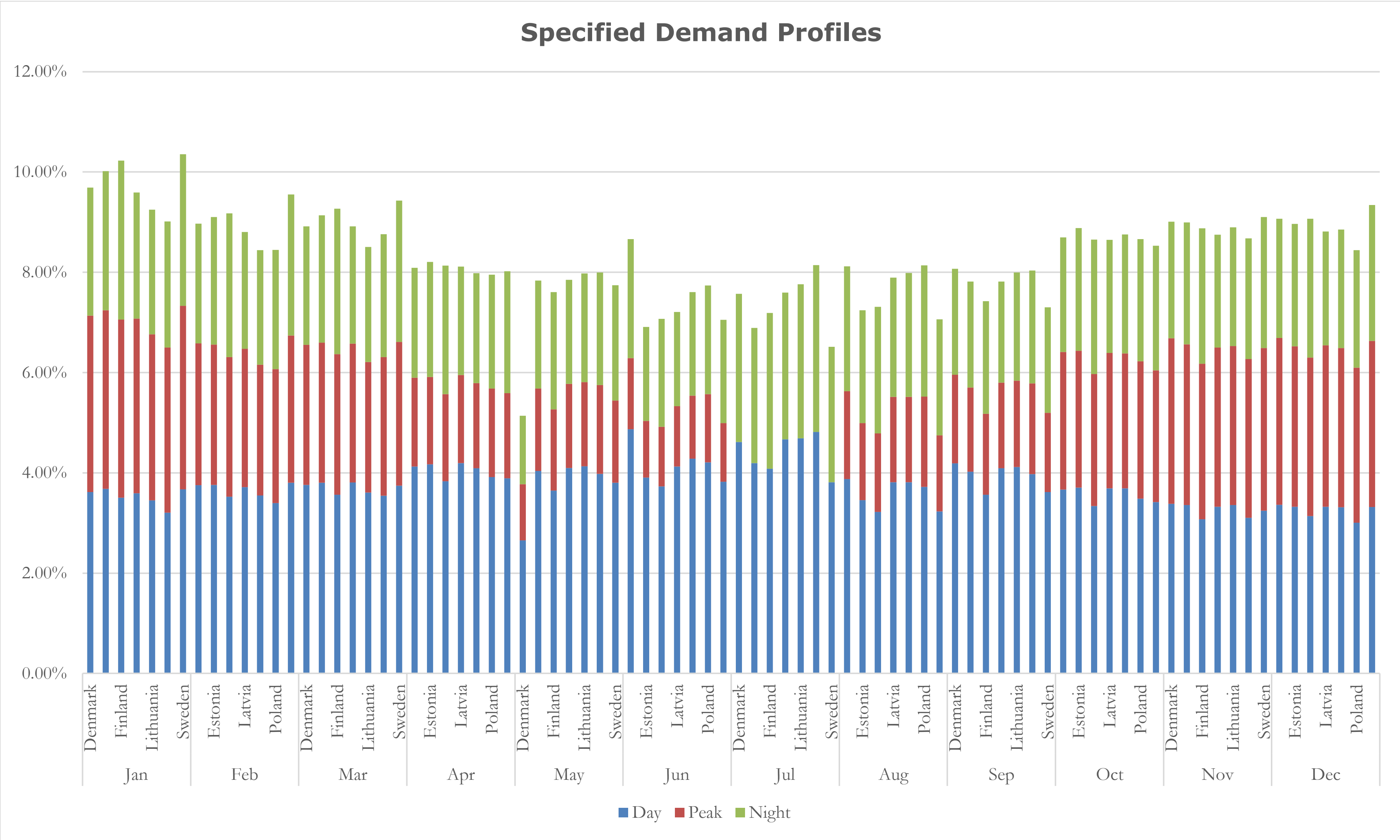


Figure 8: Specified Demand Profiles

Generation technology parameter

Table 1: Generation technology parameter

Name	Availability Factor	Capacity Factor	Electr. Efficiency	Capital Cost [2015 US$/kW]	Fixed Cost [2015 US$/kW]	Variable Cost [2015 US$/kWh]	Construction time [yr.]	Reference
****BMCCDH1**	0.7		35%	5189.48		0.009	3	ETRI
****BMCHDH2**	0.65		30%	4055.31		0.004	2	ETRI
****BMCHFH1**	0.65		30%	4055.31		0.004	2	ETRI
****BMCHPH3**	0.65		30%	3959.54		0.004	3	ETRI
****BMHPFH1**	0.6		65%	5645.04	211.56		2	WEIO
****BMRCFH1**	0.6		65%	5645.04	211.56		2	WEIO
****BMSTDH1**	0.7		35%	2456.16	85.66		3	WEIO
****BMSTDH2**	0.7		35%	2456.16	85.66		3	WEIO
****BMSTPH3**	0.7		35%	2456.16	85.66		3	WEIO
****COCHDH1**	0.85		39%	2190.15		0.006	3	ETRI
****COCHPH2**	0.85		39%	2190.15		0.006	3	ETRI
****COCHPH3**	0.85		39%	2190.15		0.006	3	ETRI
****COSTDH1**	0.8		39%	1754.40	44.38		3	WEIO, ETSAP
****COSTPH3**	0.8		46%	2270.40	68.11		3	WEIO
****GOCVDH2**	0.95		23%	6110.59			2	ETRI, ETSAP
****HFCCDH2**	0.85		58%	917.06		0.002	3	ETRI

Name	Availability Factor	Capacity Factor	Electr. Efficiency	Capital Cost [2015 US$/kW]	Fixed Cost [2015 US$/kW]	Variable Cost [2015 US$/kWh]	Construction time [yr.]	Reference
****HFCHDH2**	0.91		7%	634.79		0.006	3	Catalog of CHP Technologies
****HFCHPH3**	0.91		7%	634.79		0.006	3	Catalog of CHP Technologies
****HFGCDH2**	0.15		38%	830.75		0.015	3	ETRI
****HFGCDN2**	0.15		40%	593.39		0.012	3	ETRI
****HFGCPH3**	0.15		38%	830.75		0.015	3	ETRI
****HFGCPN3**	0.15		40%	593.39		0.012	3	ETRI
****HFHPDH2**	0.97		42%	1457.36		0.017	1	Catalog of CHP Technologies
****HFHPFH1**	0.97		34%	2237.40		0.017	1	Catalog of CHP Technologies
****HFRCDH2**	0.97		42%	1457.36		0.017	1	Catalog of CHP Technologies
****HFRCFH1**	0.97		34%	2237.40		0.017	1	Catalog of CHP Technologies
****HFSTDH2**	0.8		43%	2064.00	61.92		3	WEIO, ETSAP
****HFSTPH3**	0.8		46%	2270.40	68.11		3	WEIO, ETSAP
****HYDMDH1**		0.37		4635.94		0.006	4	ETRI
****HYDMDH2**		0.4		3476.96		0.006	4	ETRI

Name	Availability Factor	Capacity Factor	Electr. Efficiency	Capital Cost [2015 US$/kW]	Fixed Cost [2015 US$/kW]	Variable Cost [2015 US$/kWh]	Construction time [yr.]	Reference
****HYDMFH0**		0.37		5794.93		0.006	4	ETRI
****HYDMPH3**		0.35		2317.97		0.003	4	ETRI
****HYDSDH2**		0.4		3476.96		0.006	4	ETRI
****HYDSPH3**		0.35		2317.97		0.003	4	ETRI
****HYWVDH1**		0.2		9566.90			4	ETRI
****NGCCDH2**	0.85		58%	917.06		0.002	3	ETRI
****NGCHDH2**	0.89		42%	972.39		0.003	2	ETRI
****NGCHDN2**	0.86		57%	1116.04		0.005	2	ETRI
****NGCHFH1**	0.89		42%	972.39		0.003	2	ETRI
****NGCHFN1**	0.86		57%	1116.04		0.005	2	ETRI
****NGCHPH3**	0.89		42%	972.39		0.003	2	ETRI
****NGCHPN3**	0.86		57%	1116.04		0.005	2	ETRI
****NGFCFH1**	0.98		53%	19889.80		0.136	2	ETRI
****NGGCDH2**	0.15		38%	830.75		0.015	3	ETRI
****NGGCDN2**	0.15		40%	593.39		0.012	3	ETRI
****NGGCFH1**	0.15		38%	830.75		0.015	3	ETRI
****NGGCFN1**	0.15		40%	593.39		0.012	3	ETRI

Name	Availability Factor	Capacity Factor	Electr. Efficiency	Capital Cost [2015 US$/kW]	Fixed Cost [2015 US$/kW]	Variable Cost [2015 US$/kWh]	Construction time [yr.]	Reference
****NGHPDH2**	0.97		42%	1457.36		0.017	1	Catalog of CHP Technologies
****NGHPFH1**	0.97		34%	2237.40		0.017	1	Catalog of CHP Technologies
****NGRCFH1**	0.97		34%	2237.40		0.017	1	Catalog of CHP Technologies
****NGSTDH2**	0.8		43%	2064.00	61.92		3	WEIO
****NUG2PH2**	0.84		33%	3429.00		0.015	6	ETSAP
****NUG2PH3**	0.84		33%	3429.00		0.015	6	ETSAP
****NUG3PN2**			28%			0.003	6	ETRI, ETSAP
****NUG3PN3**	0.81		37%	4524.49		0.003	6	ETRI, ETSAP
****SODIFH1**		On request	15%	1482.84		0.000	1	ETRI
****SOUTDH2**		On request	15%	1225.37		0.000	1.5	ETRI
****WIOFDH2**		On request		3779.98			2.5	ETRI
****WIOFPH3**		On request		3779.98			2.5	ETRI
****WIONDH2**		On request		1559.56			1.5	ETRI
****WIONFH1**		On request		1559.56			1.5	ETRI

Name	Availability Factor	Capacity Factor	Electr. Efficiency	Capital Cost [2015 US$/kW]	Fixed Cost [2015 US$/kW]	Variable Cost [2015 US$/kWh]	Construction time [yr.]	Reference
****WIONPH3**		On request		1559.56			1.5	ETRI
****WSCHDH2**	0.8		27%	6559.67		0.008	3	ETRI
****WSCHFH1**	0.8		27%	6559.67		0.008	3	ETRI
****WSSTFH1**	0.7		34%	3118.00		0.004	3	ETRI

Fuel prices

Table 2: Fuel extraction and import prices

Fuel	Unit	2015	2020	2025	2030	2035	2040	2045	2050
Biomass Extraction	$/kWh	0.0546	0.0539	0.0527	0.0516	0.0511	0.0507	0.0502	0.0498
Biomass Import	$/kWh	0.0601	0.0593	0.0580	0.0568	0.0563	0.0557	0.0552	0.0547
Coal Extraction	$/kWh	0.0094	0.0109	0.0123	0.0137	0.0137	0.0137	0.0137	0.0137
Coal Import	$/kWh	0.0104	0.0121	0.0136	0.0152	0.0152	0.0152	0.0152	0.0152
Heavy Fuel Oil Import	$/kWh	0.0353	0.0410	0.0494	0.0578	0.0578	0.0578	0.0578	0.0578
Natural Gas Extraction	$/kWh	0.0221	0.0244	0.0282	0.0319	0.0319	0.0319	0.0319	0.0319
Natural Gas Import	$/kWh	0.0245	0.0271	0.0313	0.0355	0.0355	0.0355	0.0355	0.0355
Oil Extraction	$/kWh	0.0318	0.0422	0.0509	0.0596	0.0596	0.0596	0.0596	0.0596
Oil Import	$/kWh	0.0353	0.0469	0.0566	0.0663	0.0663	0.0663	0.0663	0.0663
Uranium Import	$/kWh	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052

Demand and fuel production projections

Table 3: Final electricity demand and domestic fuel production projections

	Country	2015	2020	2025	2030	2035	2040	2045	2050
Final electricity demand [PJ]	Denmark	111.788	104.168	105.382	108.982	116.226	124.809	136.573	145.826
	Estonia	28.721	30.019	31.108	32.573	33.746	34.709	36.635	38.686
	Finland	294.206	296.090	296.551	303.543	316.438	330.967	345.411	361.530
	Latvia	25.079	26.335	28.596	29.977	31.945	34.792	35.923	36.509
	Lithuania	32.280	32.615	34.039	37.639	40.403	43.501	46.097	48.148
	Poland	493.959	570.954	604.993	631.202	658.039	695.134	745.795	763.170
	Sweden	492.828	480.938	494.126	501.788	506.477	515.772	529.756	539.469
Domestic BM production [PJ]	Denmark	111.913	117.775	119.742	118.445	119.073	123.008	126.232	135.904
	Estonia	48.776	58.364	56.522	55.894	54.093	54.554	52.335	47.771
	Finland	386.190	402.351	374.384	355.920	367.727	403.314	428.017	455.649
	Latvia	85.034	95.417	88.007	87.755	92.068	86.332	95.040	94.873
	Lithuania	48.483	55.978	49.362	58.992	61.797	63.346	65.649	66.779
	Poland	370.741	412.149	484.580	529.840	559.859	579.495	605.997	617.720
	Sweden	550.690	555.337	562.245	557.640	560.989	570.242	578.951	580.123
Domestic CO production [PJ]	Denmark	0	0	0	0	0	0	0	0
	Estonia	185.559	220.184	210.261	196.235	186.982	179.237	173.375	169.733
	Finland	94.203	77.498	80.093	64.812	43.710	39.733	37.723	29.977

	Country	2015	2020	2025	2030	2035	2040	2045	2050
	Latvia	0.126	0.126	0.126	0.126	0.000	0.000	0.000	0.000
	Lithuania	0.335	0.251	0.209	0.209	0.209	0.209	0.209	0.209
	Poland	2,249.149	2,343.101	2,114.418	1,581.396	1,559.667	1,527.763	1,540.868	1,448.758
	Sweden	9.253	8.792	10.383	0	0	0	0	0
Domestic GO production [PJ]	Denmark	0	0	0	0	0	0	0	0
	Estonia	0	0	0	0	0	0	0	0
	Finland	0	0	0	0	0	0	0	0
	Latvia	0	0	0	0	0	0	0	0
	Lithuania	0	0	0	0	0	0	0	0
	Poland	1.717	3.726	6.866	11.807	14.151	16.329	18.254	20.557
	Sweden	0	0	0	0	0	0	0	0
Domestic NG production [PJ]	Denmark	431.240	300.487	239.694	204.651	190.834	152.148	48.734	19.134
	Estonia	0	0	0	0	0	0	0	0
	Finland	0	0	0	0	0	0	0	0
	Latvia	0	0	0	0	0	0	0	0
	Lithuania	0	0	0	0	0	0	0	0
	Poland	151.269	313.047	554.542	545.038	509.534	538.046	555.588	554.416
	Sweden	0	0	0	0	0	0	0	0
Domestic OI production [PJ]	Denmark	436.348	361.363	301.157	209.005	183.256	146.454	63.723	22.023

Country	2015	2020	2025	2030	2035	2040	2045	2050
Estonia	45.594	87.085	88.760	91.021	93.282	95.292	95.543	95.250
Finland	14.193	14.193	14.193	14.193	14.193	14.193	14.193	14.193
Latvia	0.126	0.084	0.084	0.084	0	0	0	0
Lithuania	3.726	2.721	2.135	1.717	1.465	1.089	0.335	0
Poland	42.538	41.449	37.974	35.127	25.791	13.649	0.879	0
Sweden	0	0	0	0	0	0	0	0

Renewable production limits

Table 4: Renewable upper production limits

	Country	2016	2020	2025	2030	2035	2040	2045	2050	Source/ Method of estimation
Max. power production by hydro [PJ]	Denmark	0.0550	0.0578	0.0614	0.0652	0.0692	0.0713	0.0713	0.0713	(GlobalData 2017)
	Estonia	0.0870	0.0870	0.0870	0.0870	0.0870	0.0870	0.0870	0.0870	Assumption: existing is max
	Finland	58.5504	59.0732	60.9987	61.8879	62.7914	63.7081	64.6382	65.2680	(GlobalData 2017)
	Latvia	17.0178	17.0178	17.0178	17.0178	17.0178	17.0178	17.0178	17.0178	Assumption: existing is max
	Lithuania	1.3248	1.3248	1.3248	1.3248	1.3248	1.3248	1.3248	1.3248	(World Energy Council 2017)
	Poland	7.0850	7.4140	8.4309	9.1635	9.8495	10.4163	10.8778	11.2493	(GlobalData 2017)
	Sweden	222.8450	235.1267	244.4016	247.1639	247.1639	247.1639	247.1639	247.1639	(GlobalData 2017)
Max. power production by solar PV [PJ]	Denmark	0.4191	0.9621	1.6893	2.4874	3.4424	4.5445	5.9008	7.2913	Assumption: up to 5% of final electricity are from PV in 2050

	Country	2016	2020	2025	2030	2035	2040	2045	2050	Source/ Method of estimation
	Estonia	0.0414	0.2144	0.4444	0.6980	0.9642	1.2396	1.5701	1.9343	Assumption: up to 5% of final electricity are from PV in 2050
	Finland	0.3412	1.6960	3.3925	5.2063	7.2350	9.4577	11.8434	14.4612	Assumption: up to 4% of final electricity are from PV in 2050
	Latvia	0.0362	0.1881	0.4085	0.6424	0.9127	1.2426	1.5395	1.8254	Assumption: up to 5% of final electricity are from PV in 2050
	Lithuania	0.0463	0.2331	0.4863	0.8066	1.1544	1.5536	1.9756	2.4074	Assumption: up to 5% of final electricity are from PV in 2050
	Poland	0.3888	1.8000	9.9000	18.0000	26.5000	35.0000	43.0000	50.0000	(IRENA 2015b)
	Sweden	0.7072	3.4409	7.0638	10.7565	14.4737	18.4224	22.7049	26.9735	Assumption: up to 5% of final electricity are from PV in 2050
Max. power production by wind [PJ]	Denmark	74.9941	82.8606	90.3665	98.0842	111.3623	125.3758	138.3159	151.2559	Extrapolation of current trend with a decreasing growth
	Estonia	2.7423	4.0150	6.4662	9.9405	12.0900	13.6787	15.8573	18.3830	(Tuuleenergia.ee 2015)
	Finland	11.6100	24.3000	38.4944	59.2285	73.8094	91.9800	102.8040	114.9017	Extrapolation of (VTT 2015) numbers
	Latvia	1.9552	4.7304	6.3303	8.4714	10.3068	12.5398	13.8449	15.2859	Extrapolation of (Atjaunojam 2014) numbers

Country	2016	2020	2025	2030	2035	2040	2045	2050	Source/ Method of estimation
Lithuania	5.2980	8.8301	11.8166	15.8133	18.3320	21.2518	22.8942	24.6636	Extrapolation of (Atjaunojam 2014) numbers
Poland	68.8611	109.9660	134.5917	161.4012	178.2000	196.7472	211.9526	227.2084	(IRENA 2015b), reference case
Sweden	108.0000	108.0000	198.1509	254.4952	319.8799	378.7260	414.8873	451.0486	Siyal et. al, 2015

Development of the CO_2 penalty and the final electricity demand

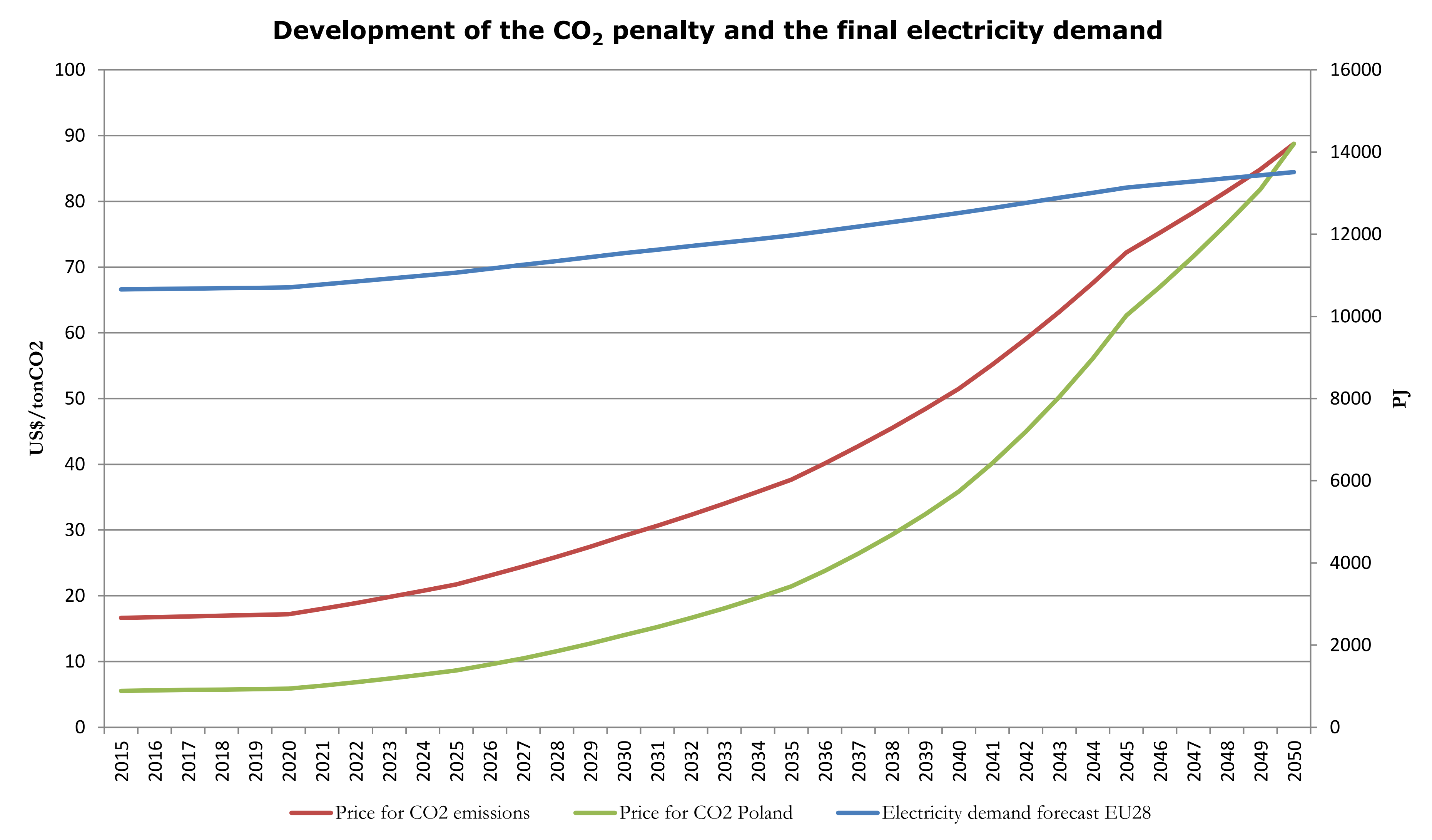


Figure 9: Development of the CO_2 penalty and the final electricity demand

Appendix 2 – Results

Installed Capacities

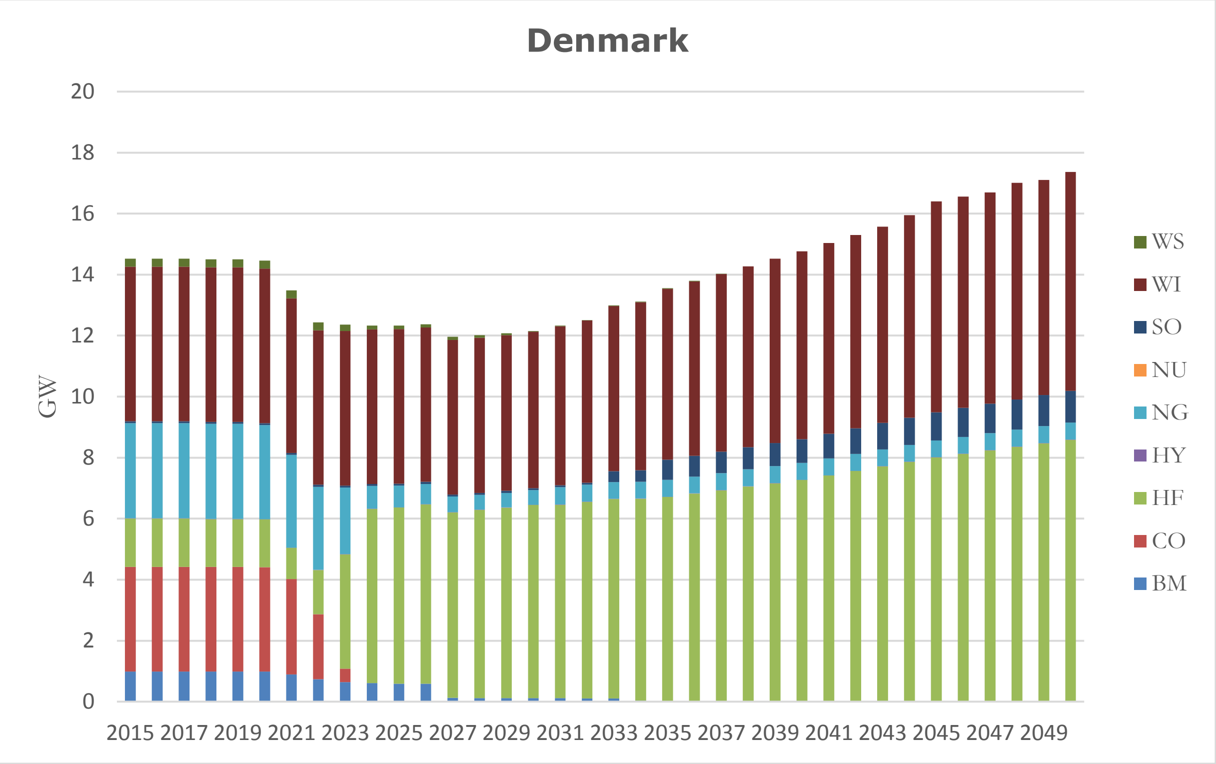


Figure 1: Installed capacities in Denmark with RM 1.2

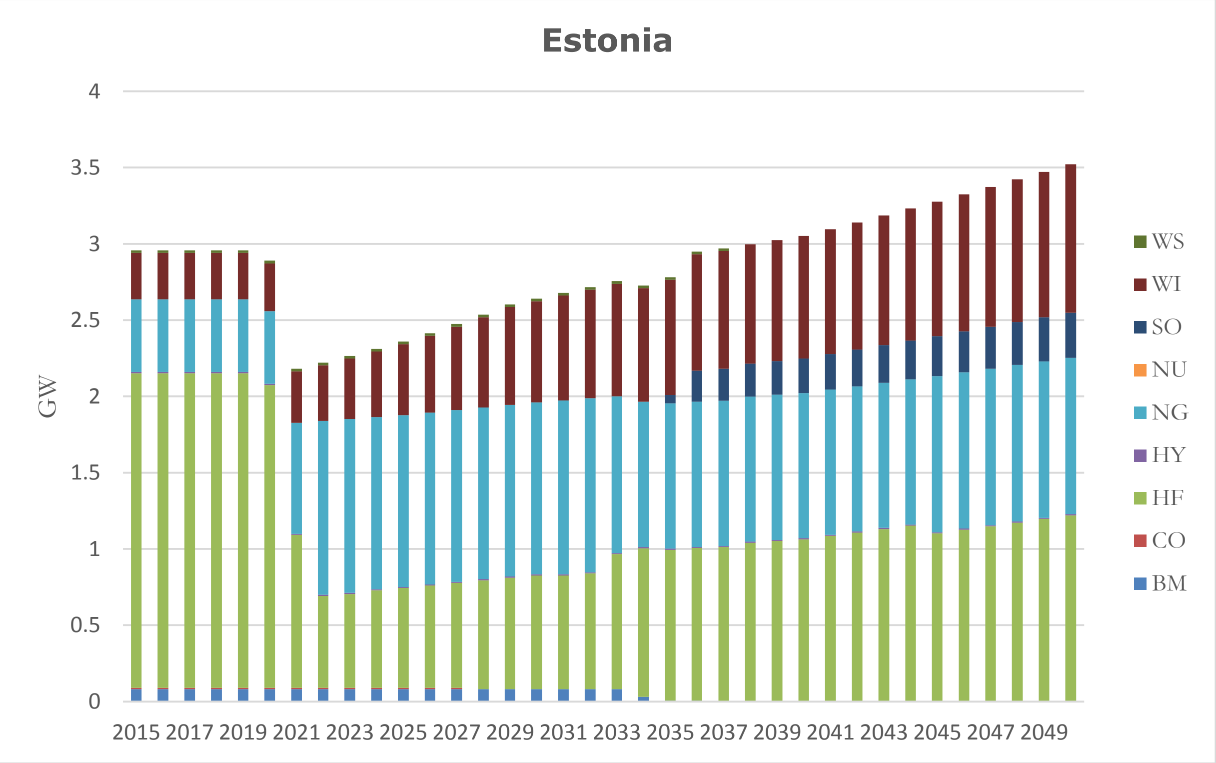


Figure 2: Installed capacities in Estonia with RM 1.2

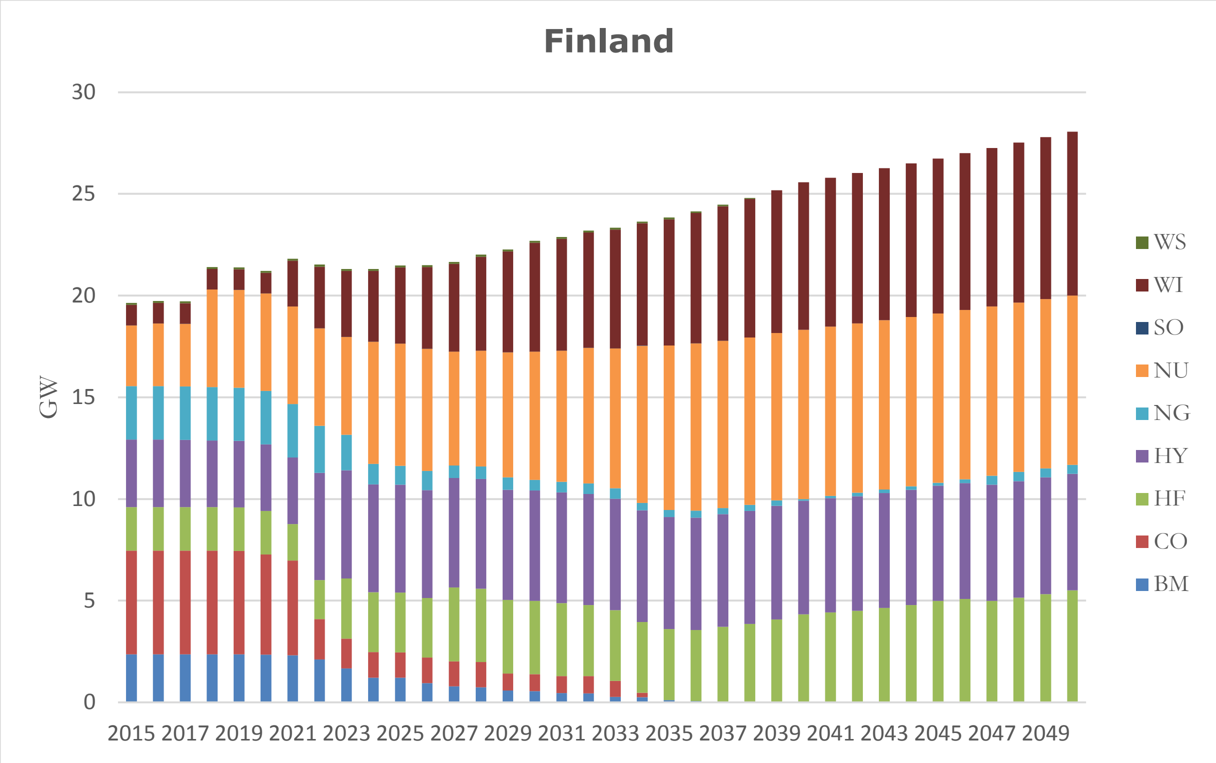


Figure 3: Installed capacities in Finland with RM 1.2

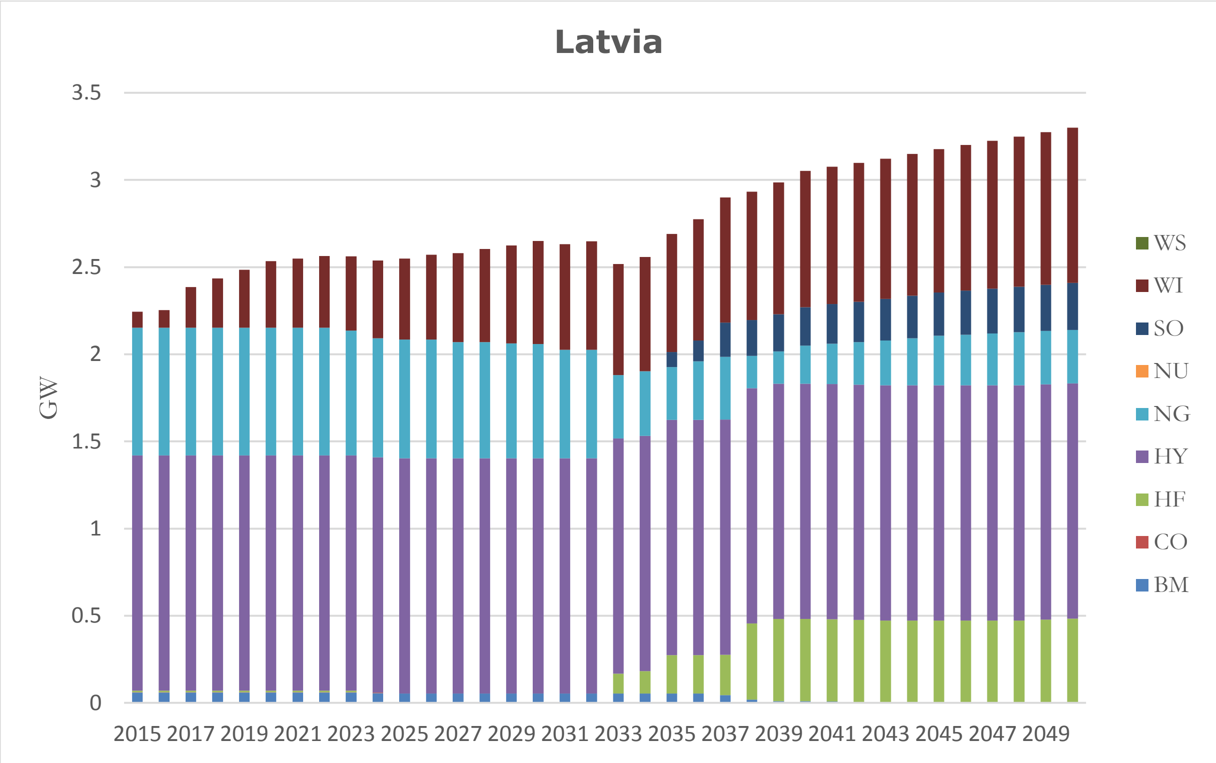


Figure 4: Installed capacities in Latvia with RM 1.2

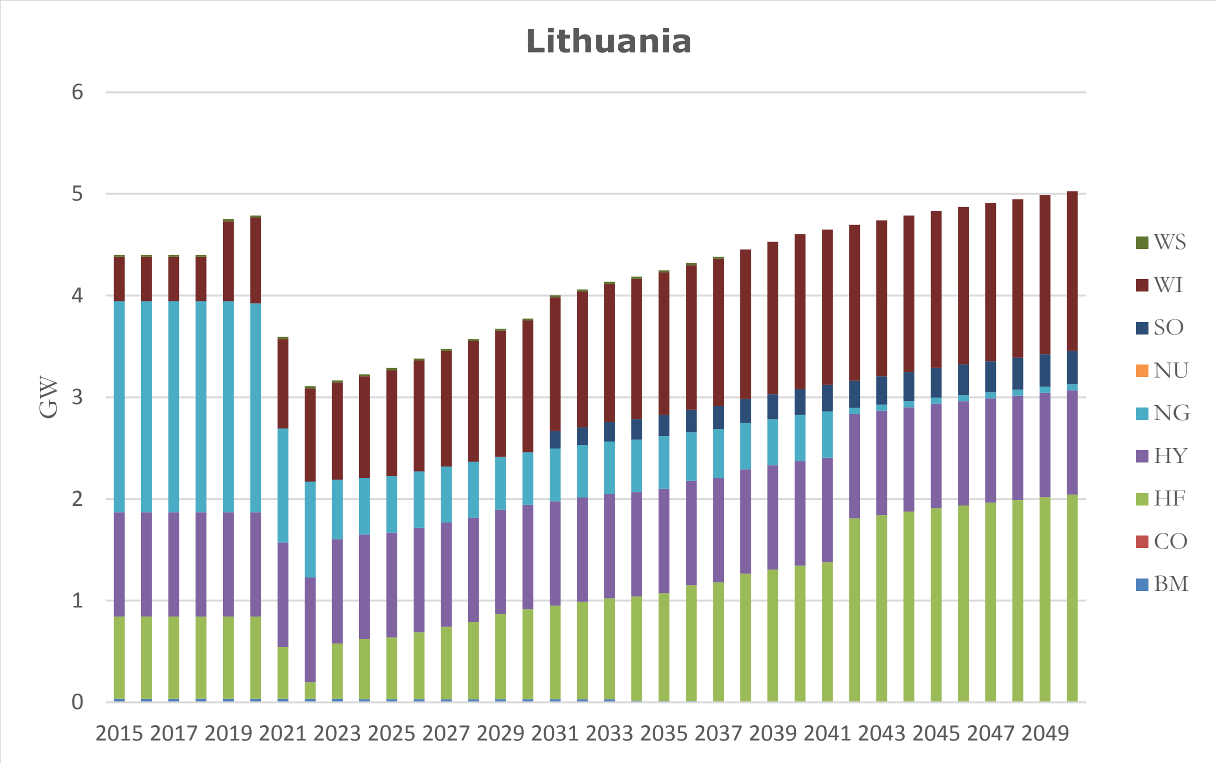


Figure 5: Installed capacities in Lithuania with RM 1.2

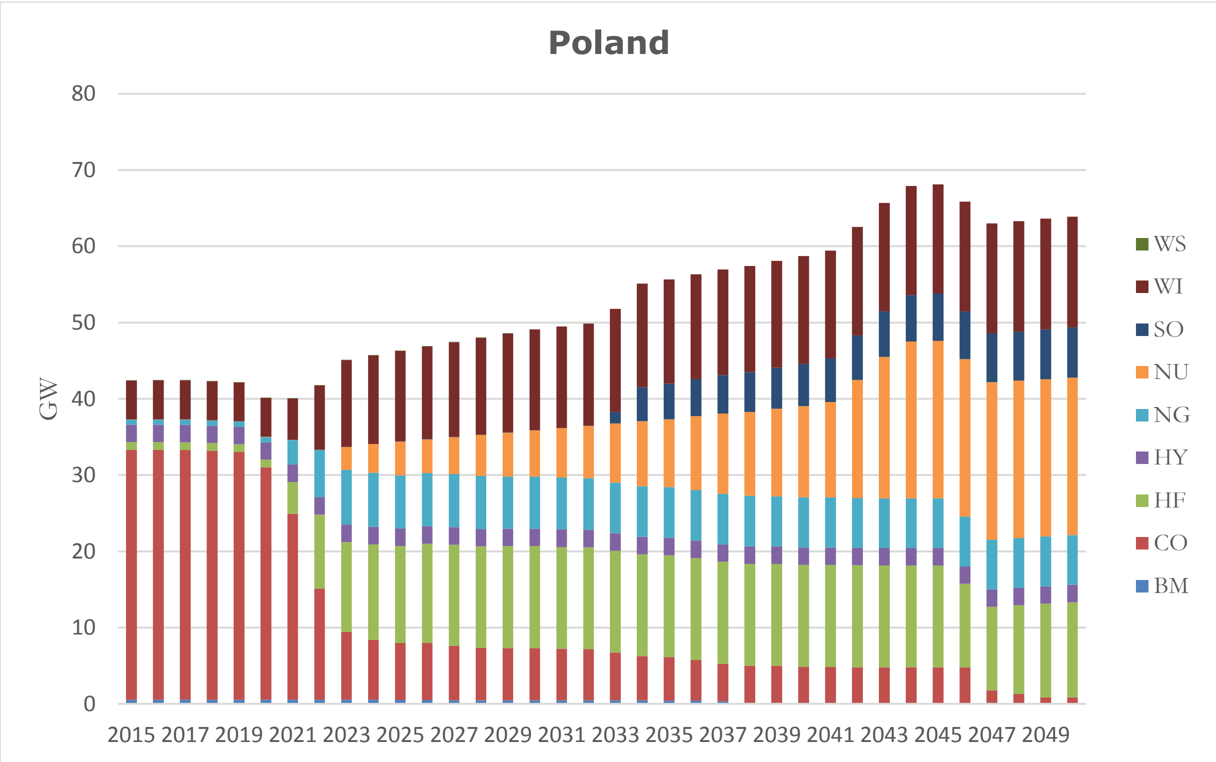


Figure 6: Installed capacities in Poland with RM 1.2

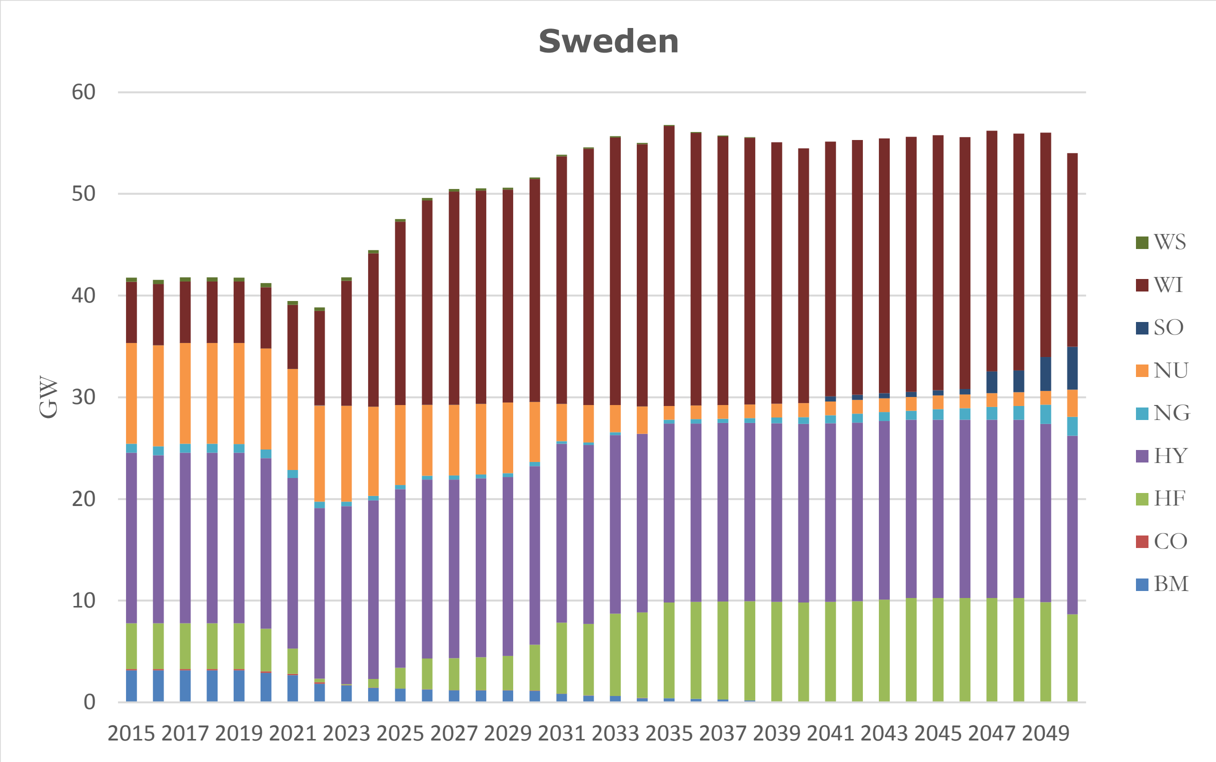


Figure 7: Installed capacities in Sweden with RM 1.2

Annual Production by country

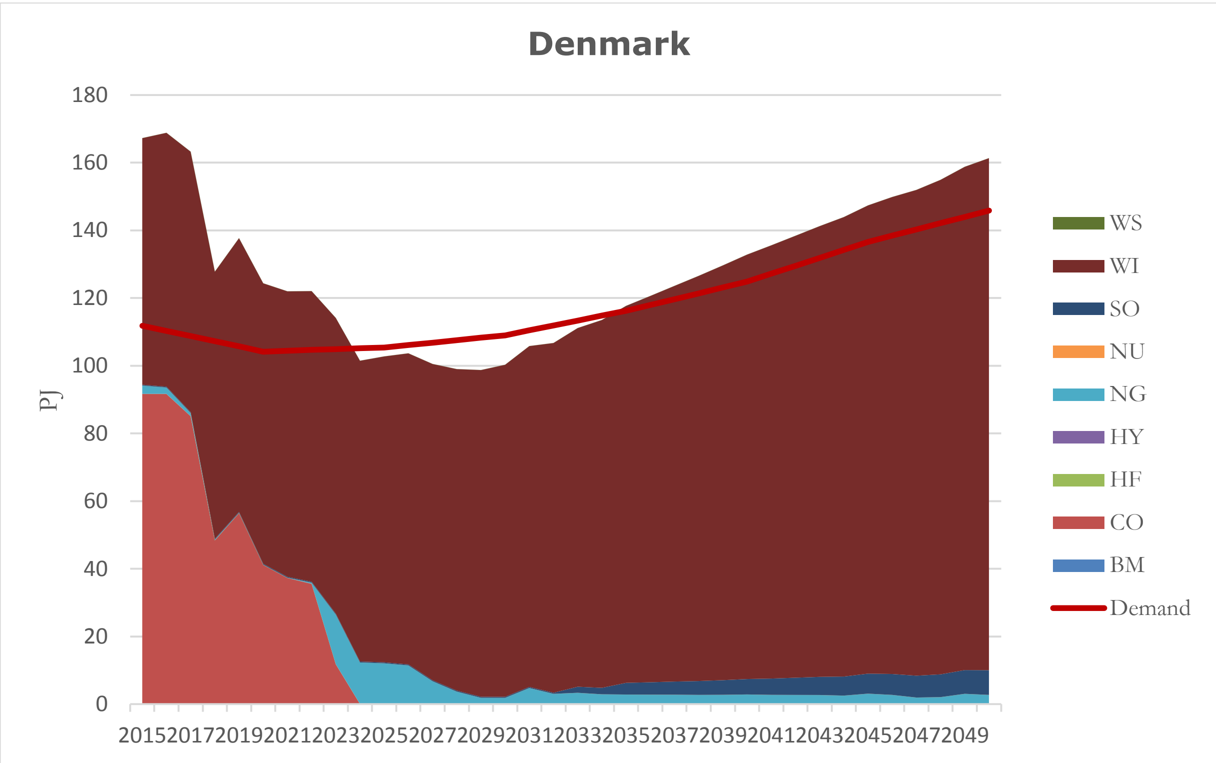


Figure 8: Annual Production for Denmark with RM 1.2

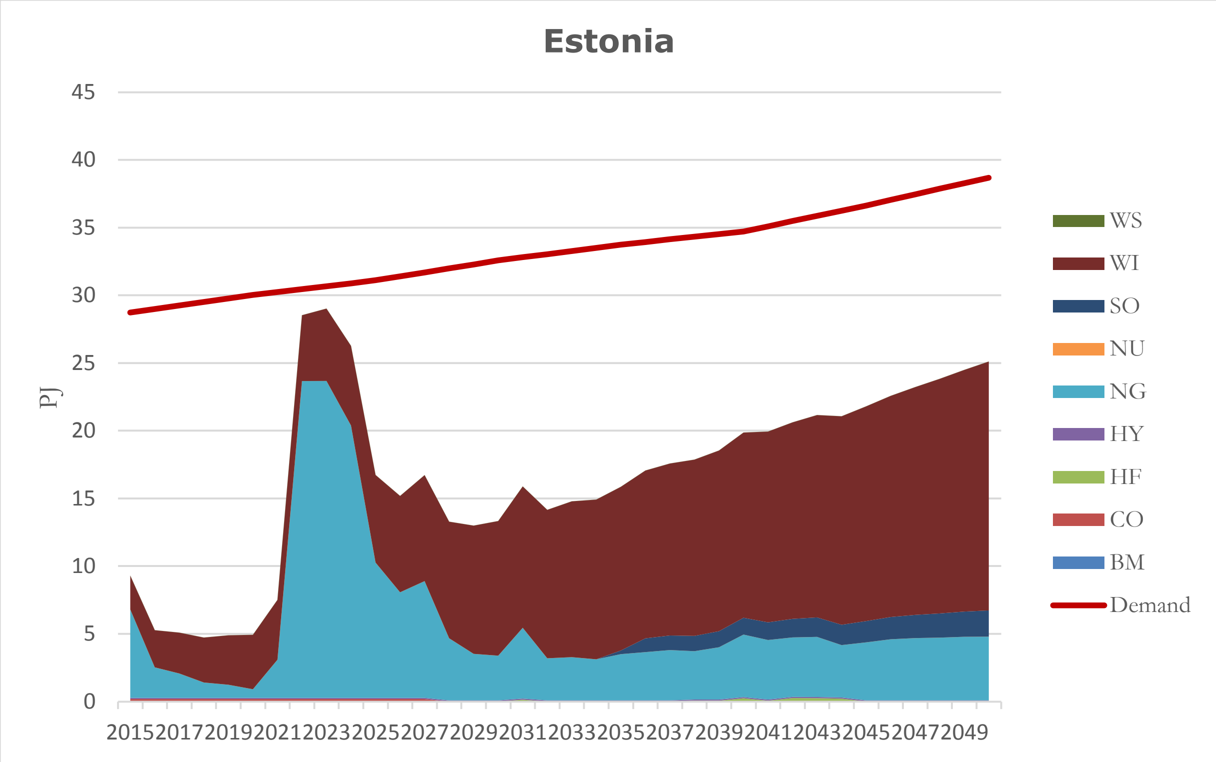


Figure 9: Annual Production for Estonia with RM 1.2

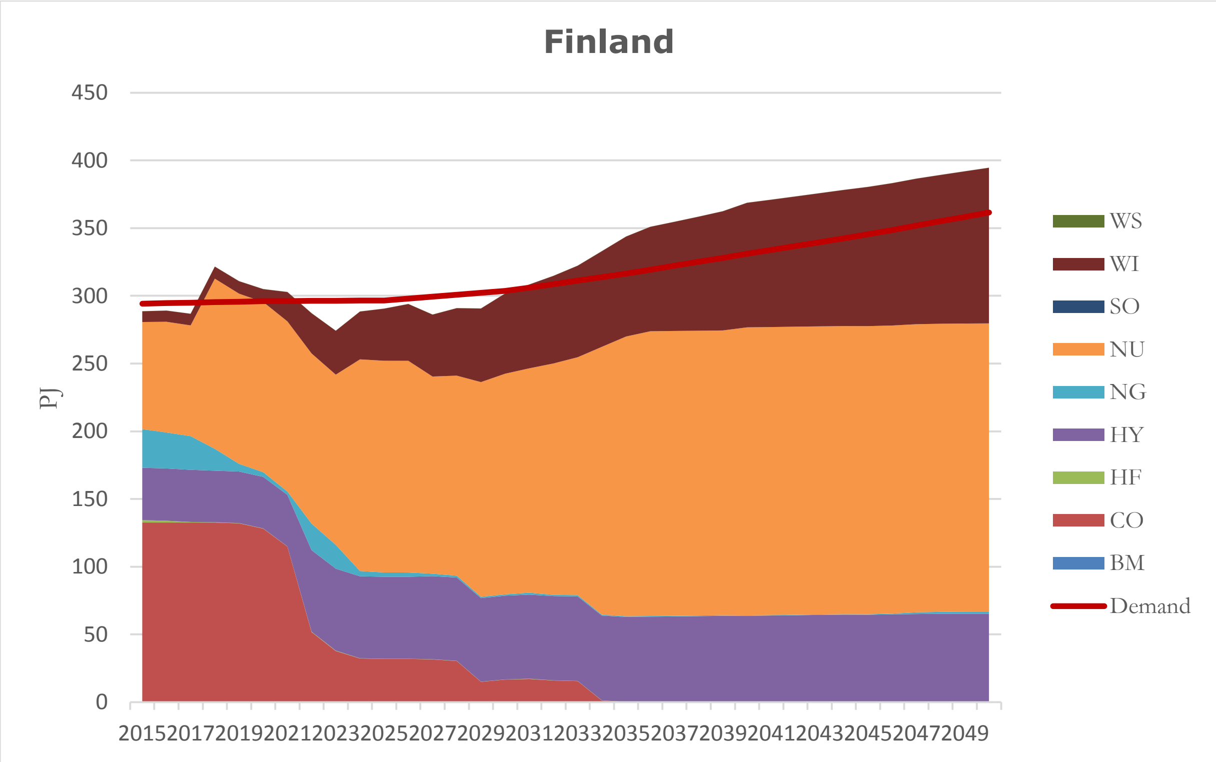


Figure 10: Annual Production for Finland with RM 1.2

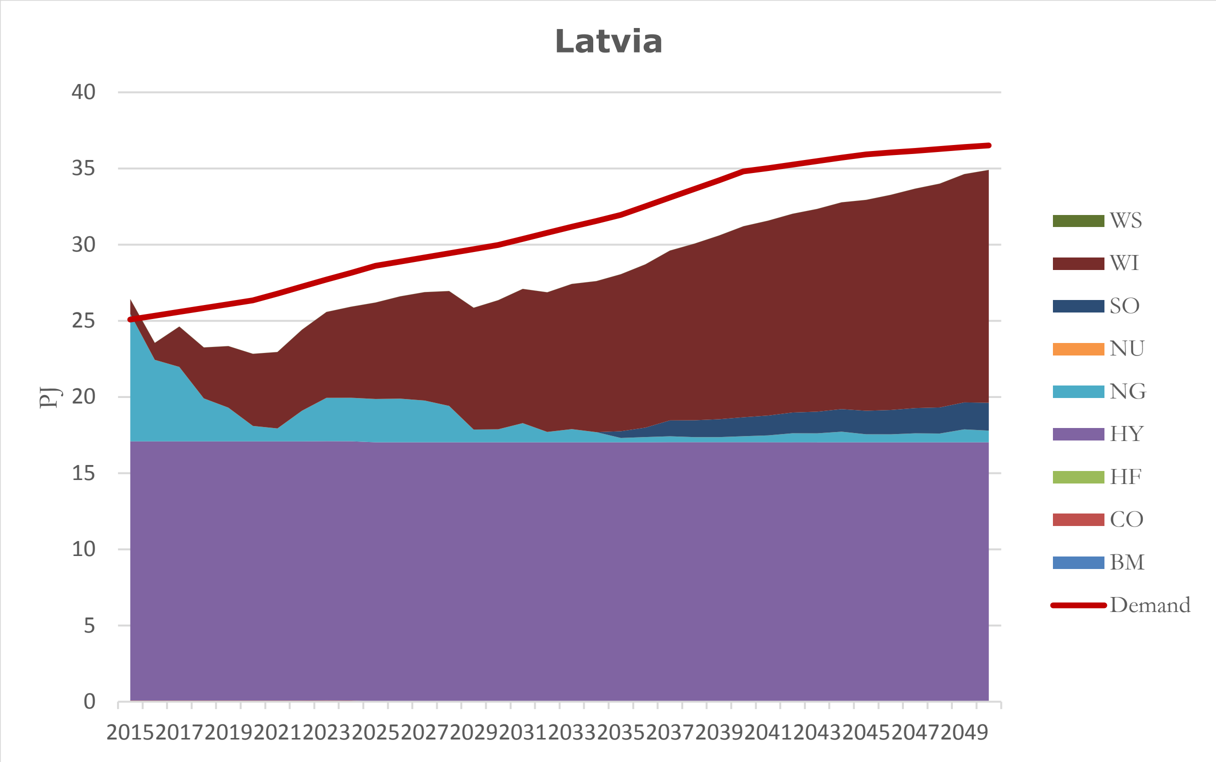


Figure 11: Annual Production for Latvia with RM 1.2

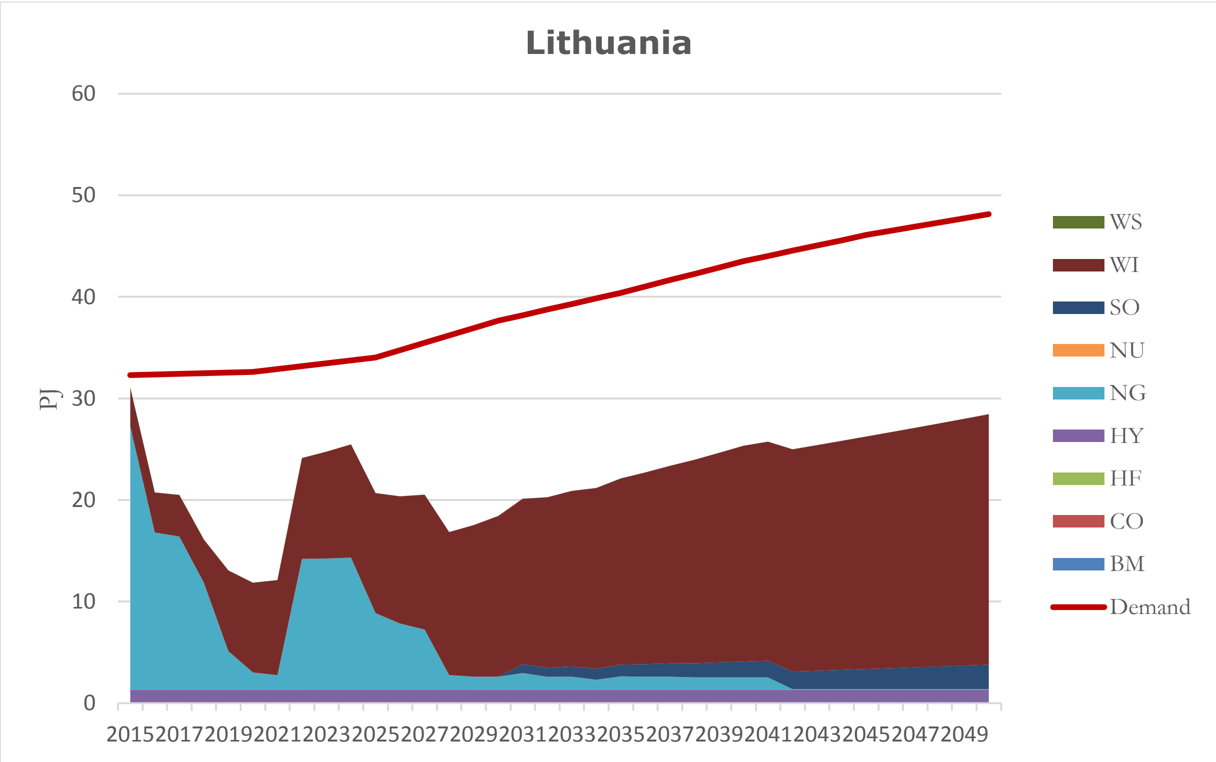


Figure 12: Annual Production for Lithuania with RM 1.2

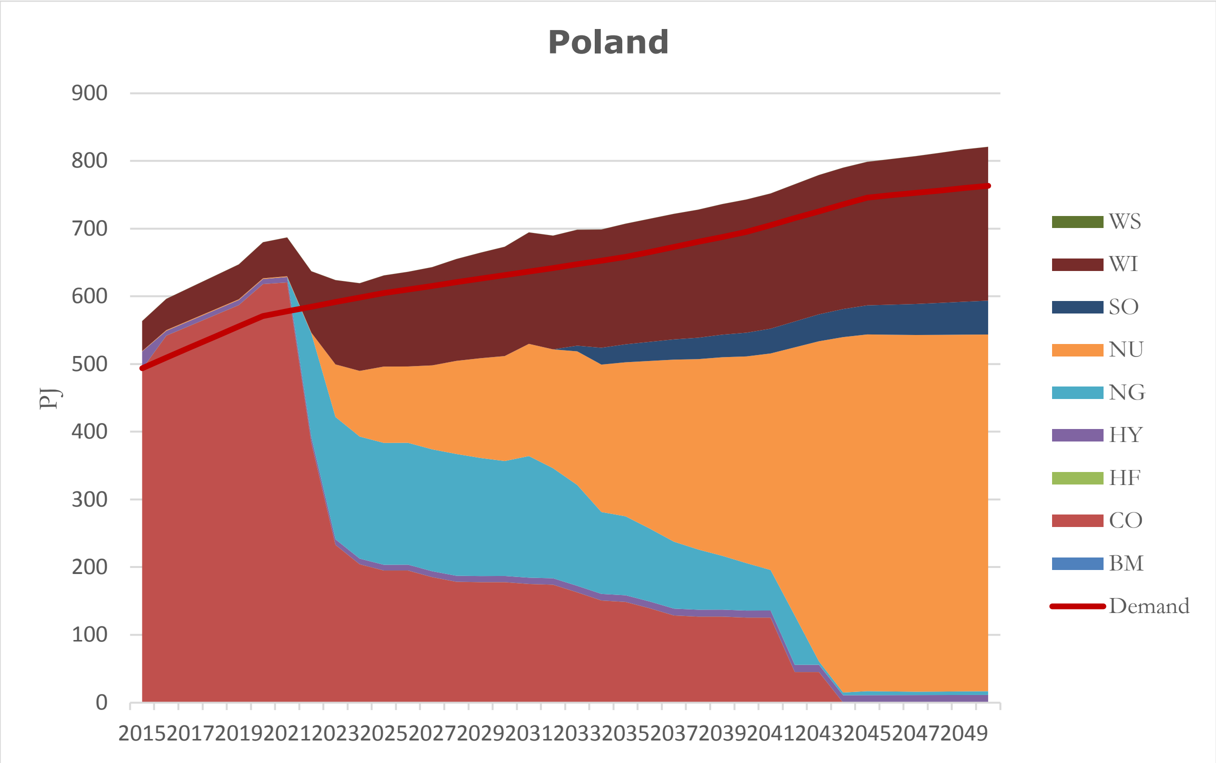


Figure 13: Annual Production for Poland with RM 1.2

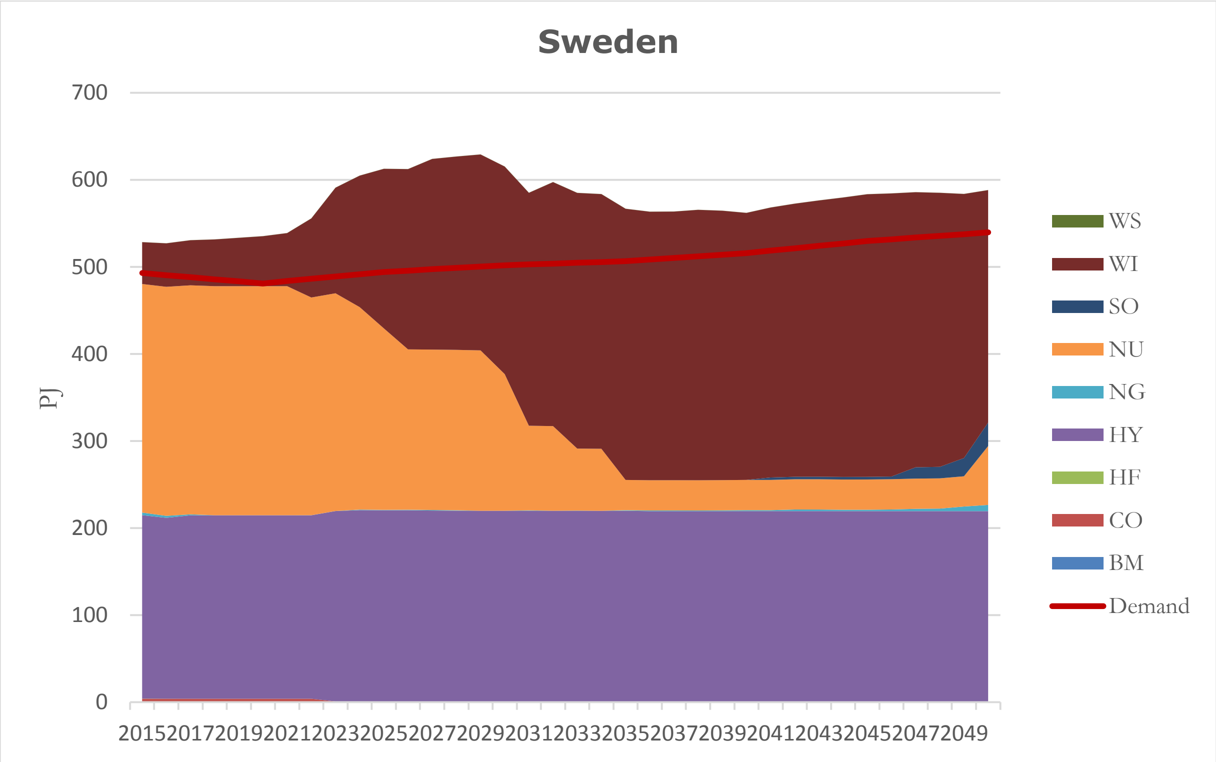


Figure 14: Annual Production for Sweden with RM 1.2

Levelised Cost of Electricity

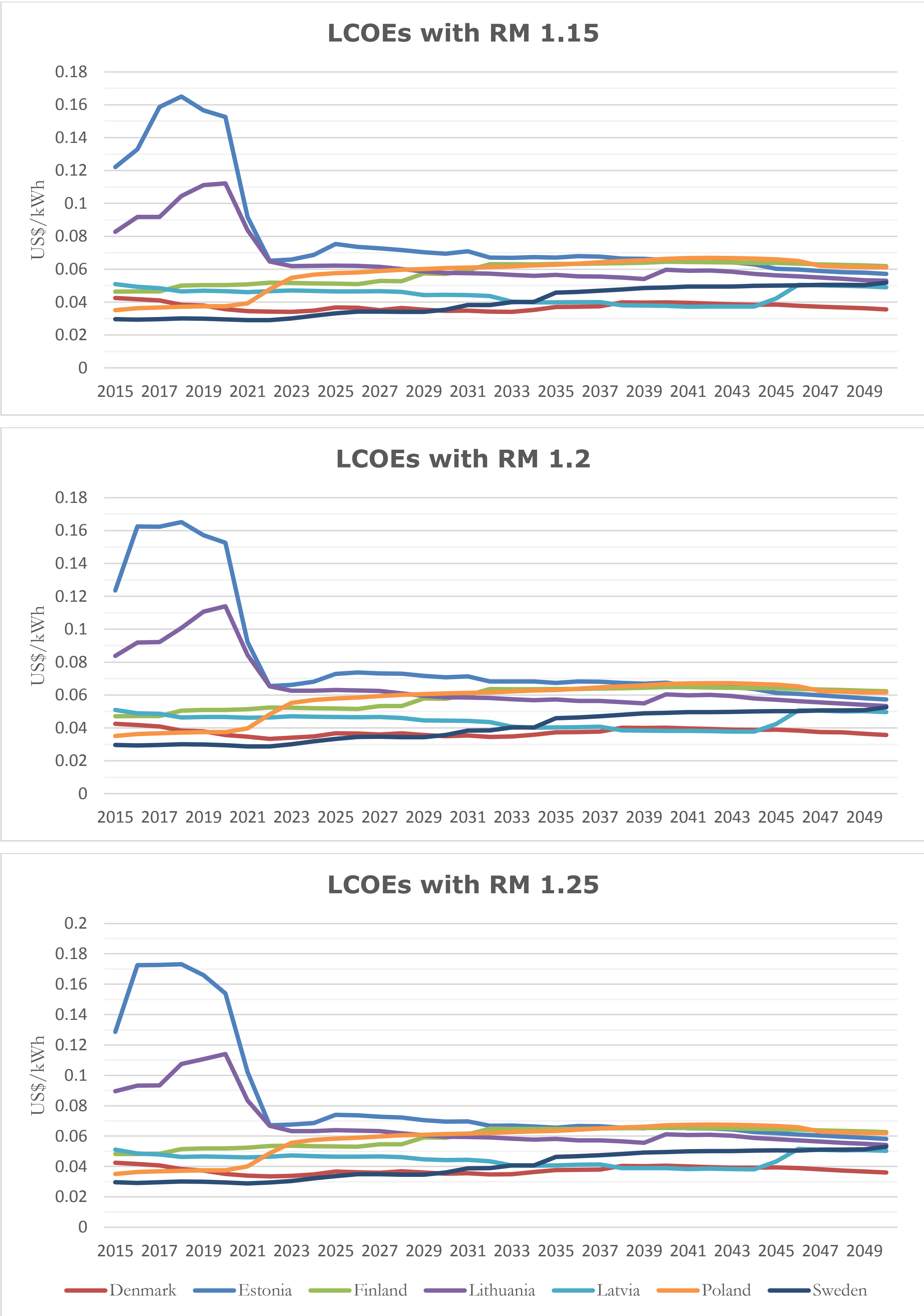


Figure 15: Development of the LCOE's at different RM's

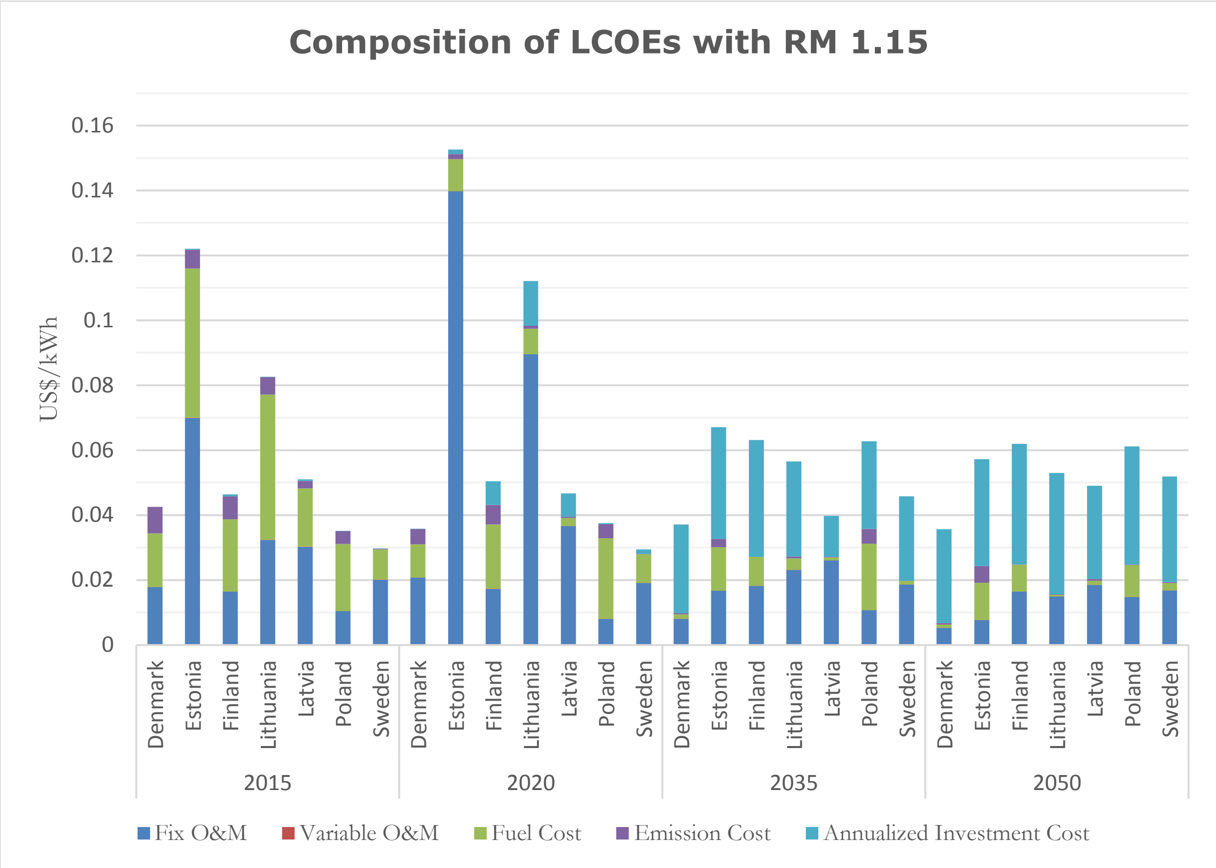


Figure 16: Composition of the LCOEs in different years with RM 1.15

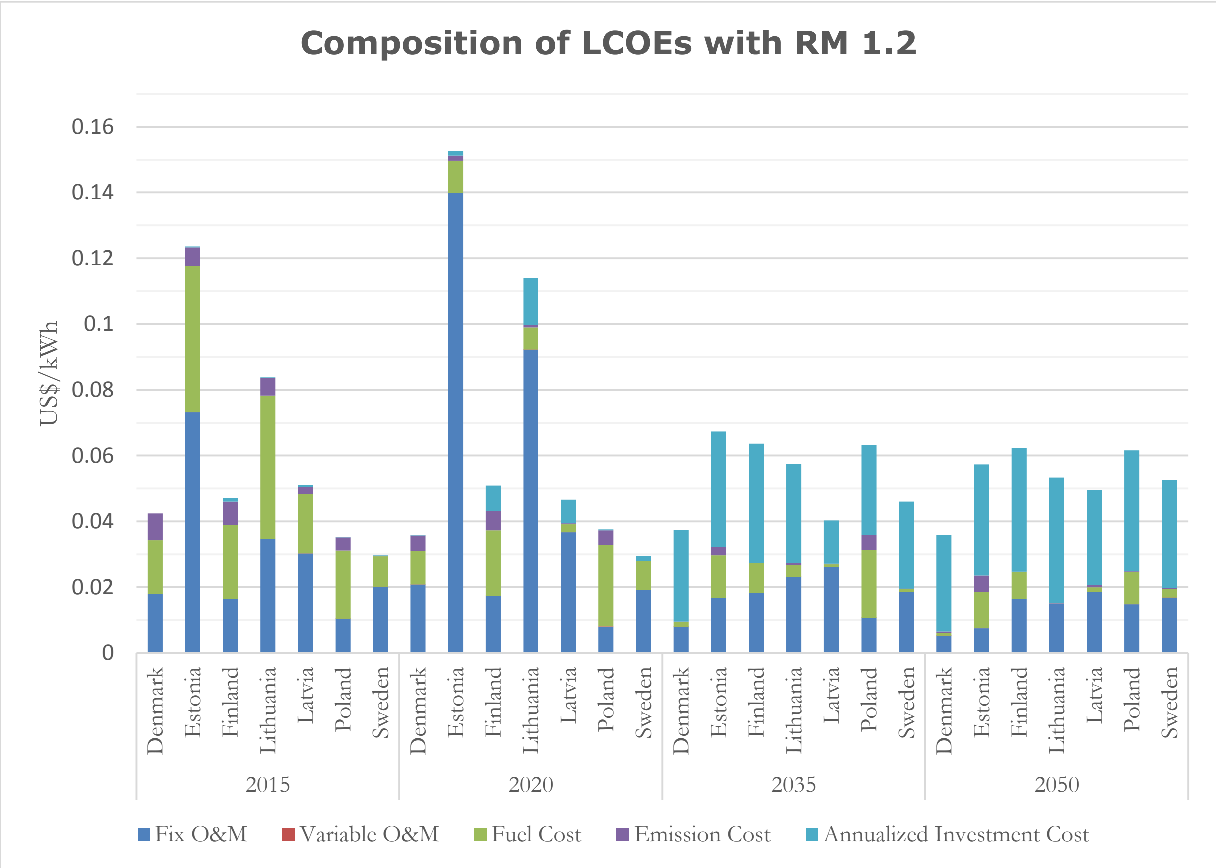


Figure 17: Composition of the LCOEs in different years with RM 1.2

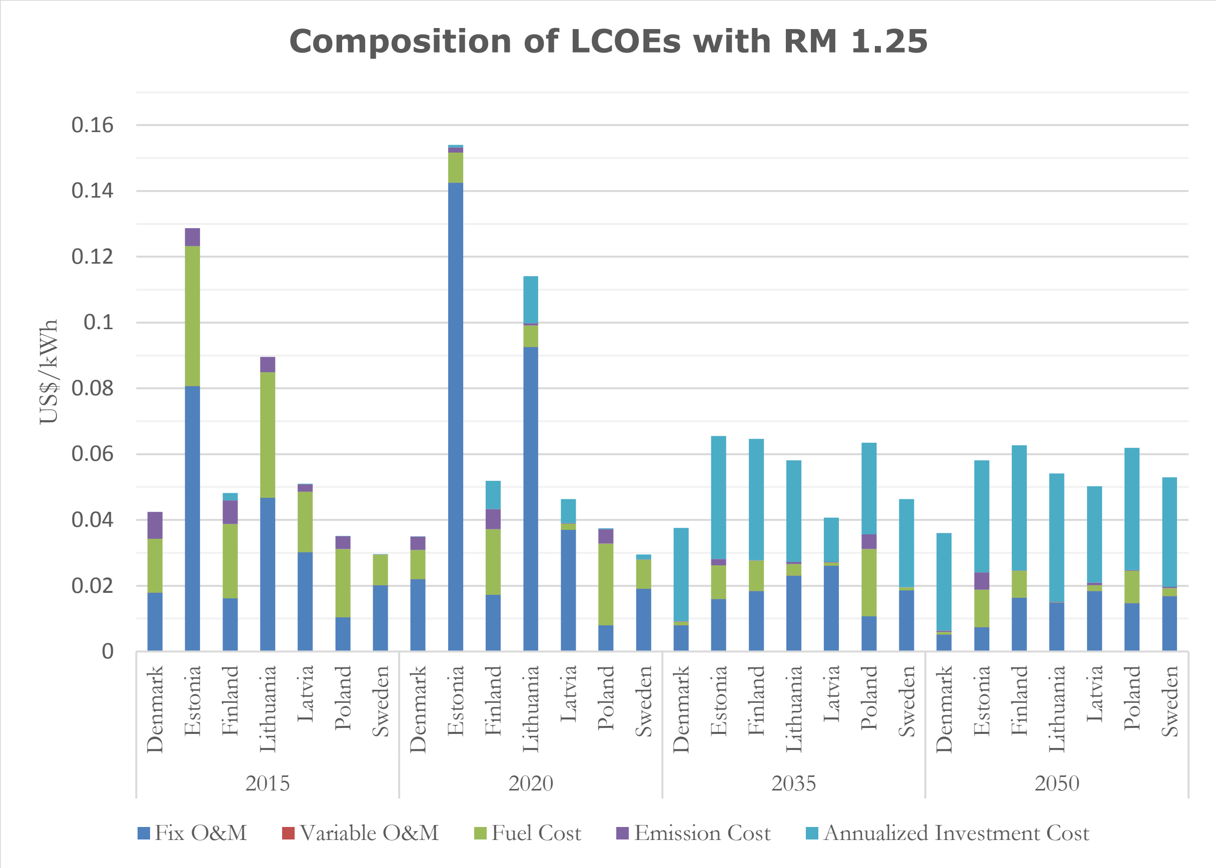


Figure 18: Composition of the LCOEs in different years with RM 1.25

Table 1: LCOE and LCOE composition in Denmark with RM 1.15

		2015	2020	2025	2030	2035	2040	2045	2050
Annual Fixed Operating Cost	M$	775.87	684.43	359.51	260.22	256.30	246.94	244.14	231.64
Annual Variable Operating Cost	M$	0.51	0.22	0.03	0.01	0.01	0.01	0.01	0.01
Fuel Cost	M$	723.19	338.13	175.18	29.31	46.06	46.50	46.94	42.65
Emission Cost	M$	356.96	156.80	24.33	4.76	9.85	13.58	19.22	20.96
Annualized Investment Cost	M$	0	0.98	471.41	647.54	873.10	1135.80	1238.47	1270.94
LCOE	M$/ GWh	0.043	0.036	0.037	0.035	0.037	0.04	0.039	0.036

Table 2: LCOE and LCOE composition in Denmark with RM 1.2

		2015	2020	2025	2030	2035	2040	2045	2050
Annual Fixed Operating Cost	M$	775.87	684.43	357.96	258.67	254.68	245.32	244.27	229.15
Annual Variable Operating Cost	M$	0.51	0.21	0.03	0.01	0.01	0.01	0.01	0.01
Fuel Cost	M$	709.04	332.72	157.23	26.24	40.92	41.68	44.55	38.90
Emission Cost	M$	355.03	154.29	21.82	4.25	8.75	12.17	18.25	19.28
Annualized Investment Cost	M$	0	0.98	482.83	659.39	886.03	1149.75	1260.70	1283.98
LCOE	M$/GWh	0.042	0.036	0.037	0.035	0.037	0.04	0.04	0.04

Table 3:LCOE and LCOE composition in Demark with RM 1.25

		2015	2020	2025	2030	2035	2040	2045	2050
Annual Fixed Operating Cost	M$	775.87	684.43	355.51	256.55	252.77	243.41	244.41	227.23
Annual Variable Operating Cost	M$	0.51	0.17	0.02	0.01	0.01	0.01	0.01	0.01
Fuel Cost	M$	705.69	274.84	127.67	23.21	34.11	37.58	37.42	33.80
Emission Cost	M$	354.58	127.43	17.65	3.75	7.29	10.97	15.323	16.93
Annualized Investment Cost	M$	0	0.98	493.67	670.60	898.13	1162.85	1283.34	1299.81
LCOE	M$/GWh	0.042	0.035	0.037	0.035	0.038	0.04	0.039	0.036