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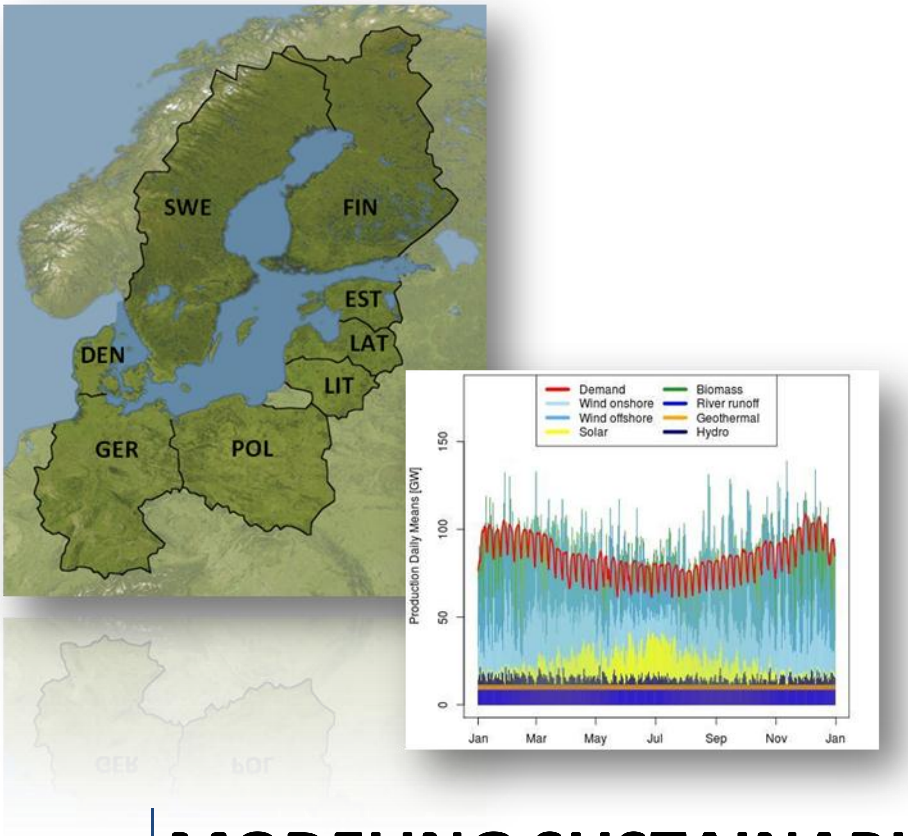
ZENTRUM FÜR NACHHALTIGE ENERGIESYSTEME (ZNES)
CENTRE FOR SUSTAINABLE ENERGY SYSTEMS (CSES)
Department System Integration



MODELING SUSTAINABLE ELECTRICITY SYSTEMS FOR THE BALTIC SEA REGION

A research project study within the Master’s programme “Energy and Environmental Management in Industrialised Countries"

November 2012

Discussion Paper 3

Authors:

B.Eng. Nicolas Bernhardi
Dipl.-Wirt.-Ing. Gesine Bökenkamp
B.Eng. Marian Bons
B.Eng. Rasmus Borrmann
B.Eng. Marion Christ
B.Eng. Lauren Grüterich
B.Eng. Emilie Heidtmann
M.Eng. Martin Jahn
B.Eng. Tomke Janssen
B.Eng. Jonas Lesch
B.Eng. Ulf Philipp Müller
B.Eng. Johannes Pelda
B.Eng. Isabelle Stein
B.Eng. Eike Veddeler
B.Eng. David Voß
B.Eng. Lukas Wienholt
Dipl.-Wirt.-Ing. Frauke Wiese
M.Eng. Clemens Wingenbach

University of Flensburg
Zentrum für nachhaltige Energiesysteme (ZNES)
Centre for Sustainable Energy Systems (CSES)

i² - Interdisciplinary Institute for Environmental, Social and Human Studies
Department Energy and Environmental Management
Munketoft 3b
24937 Flensburg
Germany
Internet: www.znes-flensburg.de

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Executive summary

In the context of climate change the need for a sustainable energy system becomes more and more apparent. The European Commission developed an “Energy Roadmap 2050” that includes the EU’s commitment to reduce its greenhouse gas emissions to 80-95% below 1990 levels by 2050, promotes a stronger use of renewable energies and a higher independency of energy imports in an economically feasible way. The aim of this study by CSES was the simulation of a 100% renewable electricity scenario for the Baltic region countries in 2050. This was done with the simulation model *renpass* (Renewable ENergy PAthways Simulation System) which was developed by the Centre for Sustainable Energy Systems (CSES) at the University of Flensburg. The simulation model uses the open-source software tools MySQL and R.

To model a variety of pathways and solutions for a sustainable electricity system different scenarios have been developed to identify the most important parameters for a secure supply in 2050. Input parameters were the installed power plants and storages, the renewable energy potentials, the electricity demand, the grid capacity of the interconnectors and weather data for the eight countries Germany, Poland, Lithuania, Latvia, Estonia, Finland, Sweden and Denmark. Various scenarios for the different parameter of possible development pathways have been combined to find a base scenario that fulfils the aim of supplying the electricity demand of the target region.

The base scenario assumes conservative renewable potentials (economic potentials) and grid enhancements (grid as planned until 2015), a high efficiency regarding the demand in 2050 (-20% following the EU goals until 2020), a moderate extension of storage options and the deployment of biomass for flexible electricity production. This system produces in total about 98 TWh per year more electricity than the countries will consume in 2050. More than half of the produced electricity comes from wind offshore and onshore (36 and 24% respectively), about 14% from biomass and 10% from PV. In 2050 especially Lithuania, Poland and Sweden are net importers while Germany and Denmark can produce significantly more electricity than they would need to cover their domestic demand. With the current base scenario parameter settings the system will still have a few hours per year in 2050 when the renewable production cannot cover the demand. Regarding the fact that further connections of the countries to other neighbouring countries have not been taken into account it can be assumed that those gaps can be closed with imports (especially since the possible export amounts of electricity exceed the currently necessary import). At times there are also situations when the renewable production is too high and has to be shut off.

Several variations of the base scenario have been simulated to determine sensitivities of the system. It can be seen that the high flexibility of biomass production plays an important role in covering peak demands and that the expansion of the grid does not seem to be highly necessary. In fact the flexibility of the biomass production seems to have a bigger impact on the covering of overdemands than grid enhancements. The size and technology of storages also does not seem to make a very big difference and highlights the importance of the utilization of flexible biomass production as supplement or even replacement for storage or grid enhancements. The system also works without the large Norwegian storage capacities. Another outcome is the necessity to increase the expansion rate of renewable production capacities in order to replace the decreasing fossil capacities, especially in Poland.

Key conclusions are:

1. A 100% renewable electricity system for all Baltic region countries is possible even under conservative assumptions. However the installation of renewable production capacities needs to be ramped up in the years until 2050 to compensate the scheduled gradual phase-out of fossil power plants.
2. Biomass as flexible electricity production holds a key role for the system stability. To ensure the necessary enhancements a market structure with effective incentive schemes (e.g. capacity market mechanisms) needs to be established.
3. The grid transmission capacities between the countries are often not used to capacity in 2050 although they might well be very busy in the years in-between. A 100% renewable electricity system in 2050 probably does not need the full capacities anymore. Flexible biomass power plants can potentially decrease the necessity of large transmission capacities.
4. A 100% renewable electricity system in the countries surrounding the Baltic is even without imports from the huge Norwegian pump storage potential. The production of renewable energies balances itself within the considered region sufficiently.
5. Such a system is not extremely expensive. The roughly calculated costs for the expansion of renewable energy capacities, storage systems and grid capacities between the countries are around 50€/MWh.

The central conclusion of the scenario is that a 100% renewable electricity system for the Baltic Sea Region in 2050 is possible. However, measures have to be taken to focus on flexible electricity generation through customized energy market structures.

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1 Introduction

In the context of climate change and with dwindling fossil resources the need of a more sustainable energy system becomes more and more apparent. The European Commission developed an “Energy Roadmap 2050” that includes the EU’s “commitment to reducing greenhouse gas emissions to 80-95% below 1990 levels by 2050 in the context of necessary reductions by developed countries” (European Commission, 2011, p. 2). It promotes a stronger use of renewable energies as a way to reduce the greenhouse gas emissions and to achieve a higher independency of energy imports in an economically feasible way.

Figure 1: Map of the geographical scope of the study – eight countries bordering the Baltic Sea

Following the idea of the EU roadmap, the objective of this study is the development of a 100% renewable electricity supply scenario for the Baltic Sea Region in the year 2050. The Centre for Sustainable Energy Systems (CSES) at the University of Flensburg has developed the open-source modeling software *renpass* (RENewable PAthway Simulation System) with which the Baltic Sea countries (see Figure 1) were simulated. Detailed data on the energy systems, the economies and the climate were collected and their interrelations in terms of the electricity systems were examined. Subsequently different scenarios have been developed to identify the most important parameters for a secure electricity supply in 2050.This report shows one possible scenario for a 100% renewable electricity system in the Baltic Region.

The study was part of the summer semester 2012’s curriculum of the Master’s programme “Energy and Environmental Management in Industrialised Countries” and has been conducted between April and October 2012 by 14 students and four lecturers. The beginnings of cooperation with several Baltic institutions were started during the course and the results presented at the Tallinn University of Technology in July 2012.

2 Simulation model *renpass*

The modeling of a sustainable electricity scenario is based upon the simulation model *renpass* (Renewable ENergy PAthways Simulation System) for the electricity sector that is currently under development at the University of Flensburg's Centre for Sustainable Energy Systems (CSES). It is yet in a test phase thus one of the aims of the course has been the testing of the model's functionality.

The core of *renpass* is the program code that is built on the open-source platform and programming language R and works in combination with a respective MySQL database management system which stores the necessary data (see Figure 2). One of the aims of the open-source approach is to facilitate international research collaboration. R ultimately connects the *renpass* simulation with the database, i.e. it reads data from the database and writes the results into the database. *renpass* can be used for quantitative analysis of the electricity sector.

Input data for the modeling are the existing fossil power plants, assumed renewable energy installations, demand curves, information on grid and storages as well as data on costs and the weather. Each data set defines a certain state of the electricity system that will be simulated. The model has been only operating for the grid regions of Norway and Germany before the extension in within this study. First calculations have proven the viability of the model.

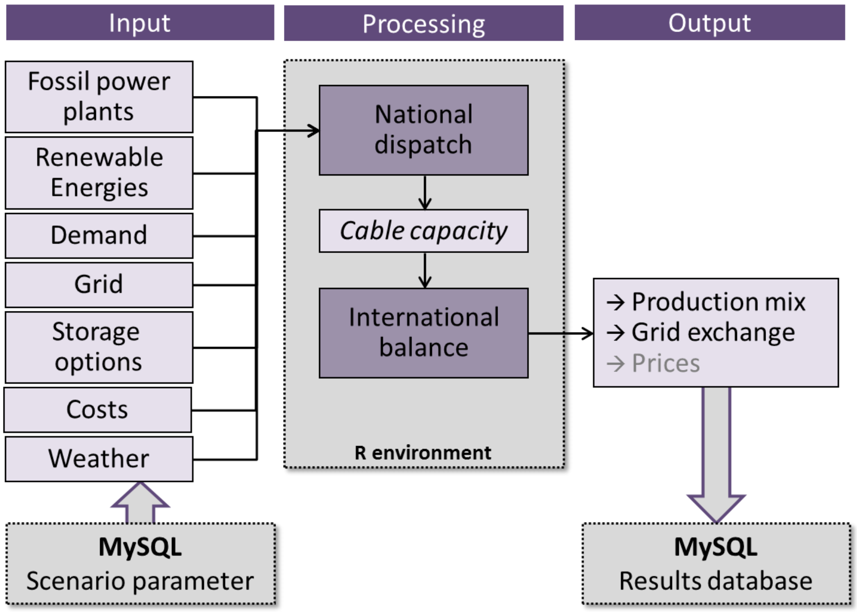

Figure 2: Schematic illustration of the modelling process

The first step of the simulation is the so-called national dispatch (cp. Figure 2). It is mainly driven by the feed-in of non-dispatchable renewable energies and the load. For each time step *renpass* calculates the renewable electricity production on the basis of the weather data. The feed in power of the volatile renewable electricity sources primarily depends on the assumed capacity of the respective scenario in combination with the weather data. For the electricity fed in by wind power plants and PV parks the power production is calculated with algorithms that convert e.g. the wind speed or solar radiation into a power production. The algorithms themselves are based on performance curves. By deducting the currently produced renewable power from the demand the model determines the residual load that has to be covered by the dispatchable power plants (including existing storage capacities). The dispatchable power plants are used in order of their production costs. In the next step (international balance), the electricity is exchanged between the regions to level out the prices as far as grid capacity will allow.

Each model run covers one year in 15-minute-steps (35,040 steps and result data sets per year calculated) or one-hour-steps (8,760 per year). However due to limitations of the processing time it is set to one-hour-steps for this project. The input parameters will be varied for different scenario runs. The given output parameters are shown in Table 1.

Table 1: output parameters given by *renpass*

Output parameter (per time interval)	Unit
Power production per technology	[MW]
Cable flow/grid usage	[MW]
Direction of flow and frequency of changes in direction	[-]
Approximate prices in each grid region	[€/MWh]
Approximate prices in each grid region (after exchange between the grid regions)	[€/MWh]
Filling level of storage reservoirs	[Mio. m^3]
Water spillage	[Mio. m^3]
Pumping power per pump	[MW]
Renewable energy curtailment	[MW]
Excess demand	[MW]

The main output of the scenario calculations is hourly data on the electricity production for every country and every production technology. Other indicatirs are data on the exchange between the countries including various prices and the influence of the exchange on the electricity price. Although at the current development stage of the model the price does not equal a “real” electricity price. It is rather an indicator for the balance or imbalance between the grid regions with regards to exchange capacities.

Furthermore, hourly data on the carbon dioxide emissions, the possibly resulting overdemand and the residual load are given as results by the model. The reduction of renewable energies and the influence of storage capacities on this reduction and the resulting filling level of the hydro storage capacities are outputs as well. All the results are stored in form of tables in the MySQL data base, which makes a detailed analysis possible. To get a first impression about the most important outcomes of the model some of the outputs are visualized in graphs which are automatically created for every scenario by the modeling tool.

Although the program is able to model any kind of future scenario, the underlying idea is to show how a possible sustainable electricity system could look like.

3 Modeling data input

The input data which are required to calculate the scenarios are primarily data which describe the status quo of the electricity system in each country. Variations of the values for each coutry also define the respective scenarios for the future. The parameters characterising the electricity systems are the production capacities of fossil power plants and renewable energies, the demand as well as the grid and storage capacities. Additional important information is the representative weather data.

3.1 Fossil Power Plants

The fossil power plants data base defines the status quo for the year of 2010. It is based on information by the U.S. Energy Information Administration (U.S. Energy Information Administration, 2012), the International Energy Agency (International Energy Agency (EIA), 2012), the European Commission (European Commission (Directorate-General for Energy and Transport), 2008) and the German Federal Network Agency (Bundesnetzagentur, 2012).

Whereas for Germany the Bundesnetzagentur's database includes power plant sharp information (e.g. with the year of construction) the sources for the other countries only include summarized production capacities by technology. To calculate the virtual phase-out of those power plants it was assumed that with an average lifetime of 30 years and an average construction year of 1990 each year from 1975 to 2005 (i.e. 1990 +/- 15 years) a 30th of the overall capacity has been installed. If for example a country has 30 GW of coal power plants each year from 1975 to 2005 1 GW were assumably installed and subsequently beginning in 2005 until 2035 each year 1 GW will be decommissioned after 30 years of lifetime. Furthermore it is assumed that in order to achieve a 100% renewable electricity supply by 2050 retired fossil power plants will not be substituted with new power plants. Thus fossil energy production slowly fades out linearly as given by the respective lifetimes of the individual power plants. Figure 3 shows the installed capacities of fossil power plants in 2010.

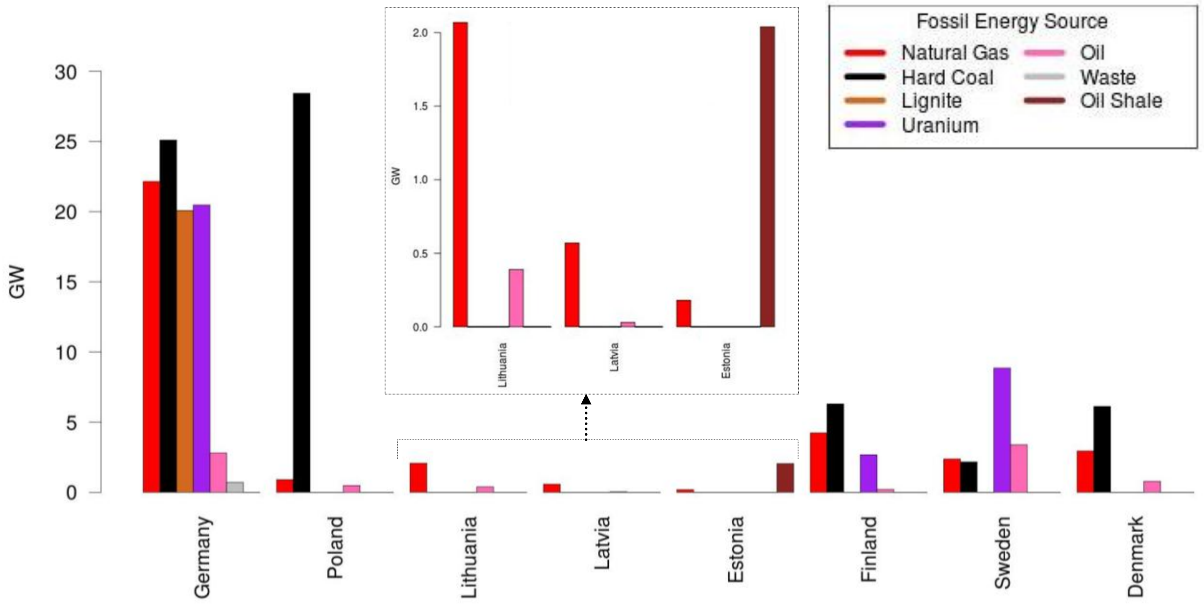

Figure 3: Installed fossil fuel capacity in 2010

3.2 Renewable energy potential

Similar to the database of the installed fossil power plants a database with the currently installed capacity of renewable energies has been collected for each country based on different studies (the European Wind Energy Association, the International Energy Agency or the Geothermal Energy Association). Additionally various sources have been analysed to determine possible scenarios for different extension pathways for the installation of renewable capacities until 2050 (technical, economic and political potential, see Figure 4).

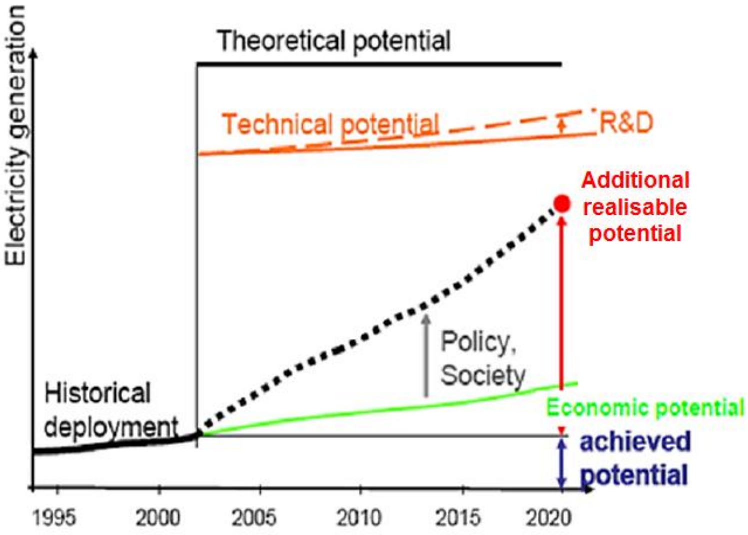

Figure 4: Different types of potentials (adapted from (Resch, Faber, Haas, Ragwitz, Held, & Konstantinaviciute, 2006, p. 16))

Data for en economic potential of the different countries in the Baltic Sea region has been taken from a study by the German Aerospace Centre (DLR, (Trieb, et al., 2006)). The economic potential is defined as “those with a sufficiently high performance indicator that will allow new [power] plants in the medium and long term to become competitive with other renewable and conventional power sources, considering their potential technical development and economies of scale” (Trieb, et al., 2006, p. 44). The economic potential includes data for wind onshore, wind offshore, photovoltaic, biomass plants, run-of-river and geothermal energy. The tables 2 and 3 show the current installed capacity and the assumed economic potentials for the extension of the installed renewable capacity in 2050.

Table 2: Currently installed capacity (in GW)

Country	2011						
	Wind Onshore	Wind Offshore	PV	Biomass	Run-of-river	Geothermal	Total
Germany	27.1	0.1	24.9	4.9	4.3	0.01	**61,3**
Poland	1.1	-	-	0.1	0.8	-	**2,0**
Lithuania	0.2	-	-	0.02	0.1	-	**0,3**
Latvia	0.03	-	-	0.01	1.5	-	**1,5**
Estonia	0.2	-	-	-	0.01	-	**0,2**
Finland	0.2	0.03	0.01	1.8	3.1	-	**5,1**
Sweden	2.0	0.2	0.02	3.2	3.2	-	**8,6**
Denmark	2.9	0.9	0.02	0.6	0.01	-	**4,4**
Total	**33,7**	**1,2**	**25,0**	**10,6**	**13,0**	**0,01**	**83,6**

Table 3: Assumed economic potential in 2050 (in GW)

	2050						
Country	**Wind Onshore**	**Wind Offshore**	**PV**	**Biomass**	**Run-of-river**	**Geothermal**	**Total**
Germany	50.8	32.0	67.2	10.4	5.2	3.0	**168,6**
Poland	14.0	2.0	3.4	6.8	1.3	0.2	**27,7**
Lithuania	1.4	0.2	0.7	1.7	0.2	-	**4,2**
Latvia	0.8	0.2	0.7	0.4	0.7	-	**3,4**
Estonia	1.8	2.0	0.5	0.5	0.1	-	**4,9**
Finland	2.1	10.0	2.1	7.0	3.0	-	**24,2**
Sweden	8.0	11.0	4.7	10.4	3.4	0.2	**37,7**
Denmark	3.5	12.0	1.4	0.9	0.01	-	**17,8**
Total	**82,4**	**69,4**	**80,7**	**38,1**	**13,9**	**3,4**	**288,5**

The technical potential for each country was derived from (Trieb, et al., 2006) and (European Environment Agency (EEA), 2009). Additional data for the political potential (i.e. the political extension goals) have been taken from the respective National Renewable Energy Action Plans (NREAP) of each country (European Commission, 2010). Both potentials were primarily used as reference points for the variation of different scenario parameters in order to achieve a stable electricity production (see chapter 4.1).

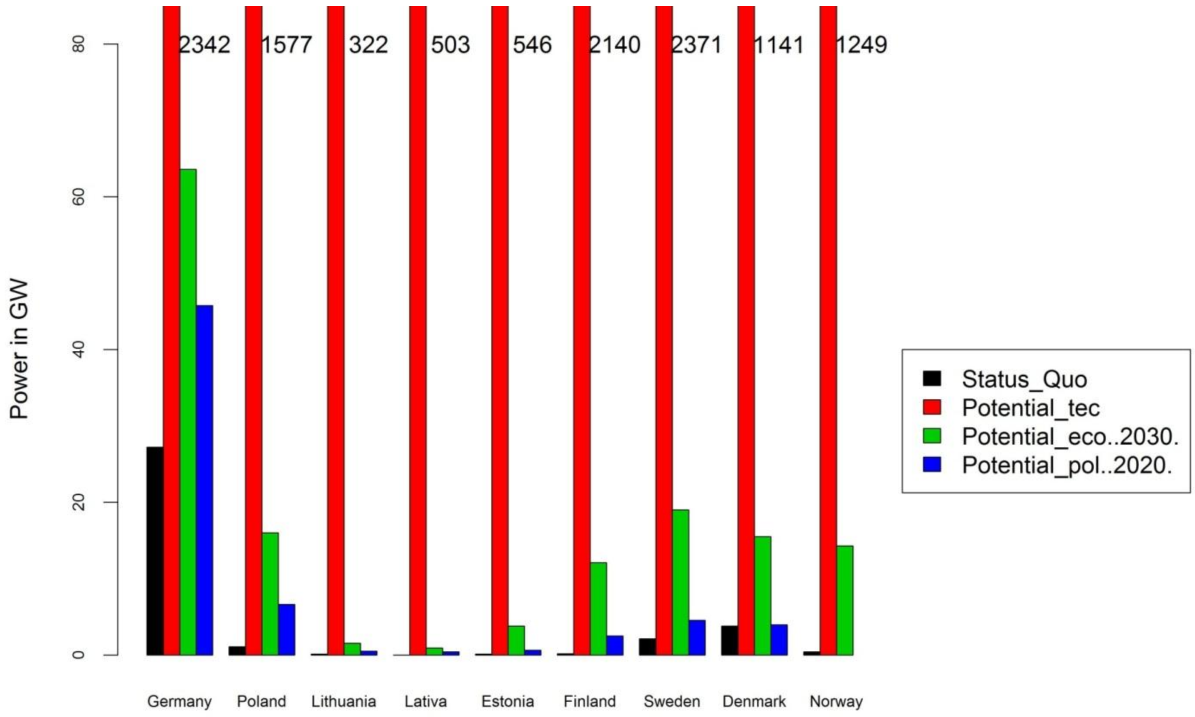

Figure 5: Exemplary comparison of the status quo of installed onshore wind capacities with economic, policital and technical potentials

3.3 Demand

Data for the demand of each country are based on the ENTSO-E databases (European Network of Transmission System Operators for Electricity (ENTSO-E), 2012). Complete data for all Baltic countries could be retrieved for 2010 and 2011. For the modelling only data for 2010 was used due to the fact that the weather data (see 3.7) for the same year were the most consistent. Figure 6 shows the summarized daily consumption of all Baltic countries over the year 2010. The maximal demand was 174.9 GW, the minimal demand 74.6 GW.

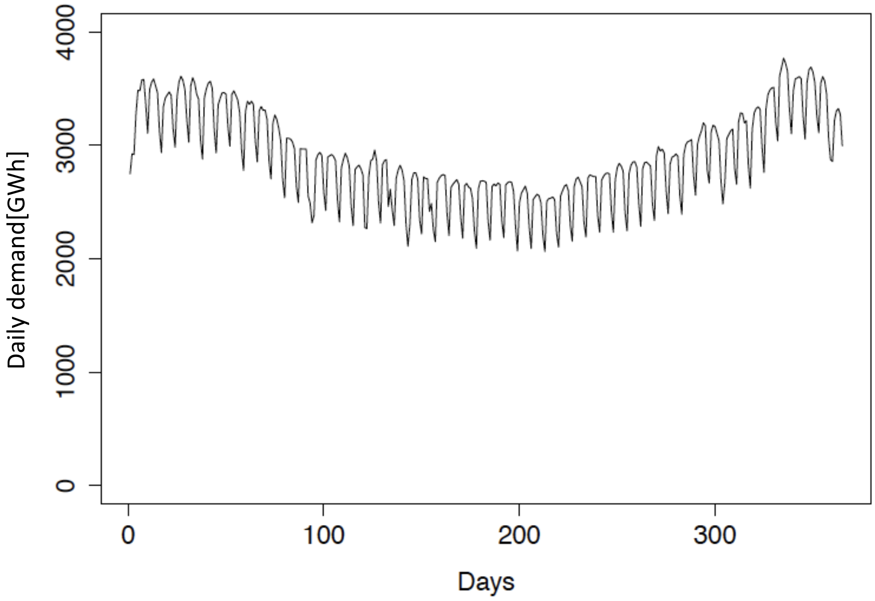

Figure 6: Summarized daily consumption for the Baltic region 2010

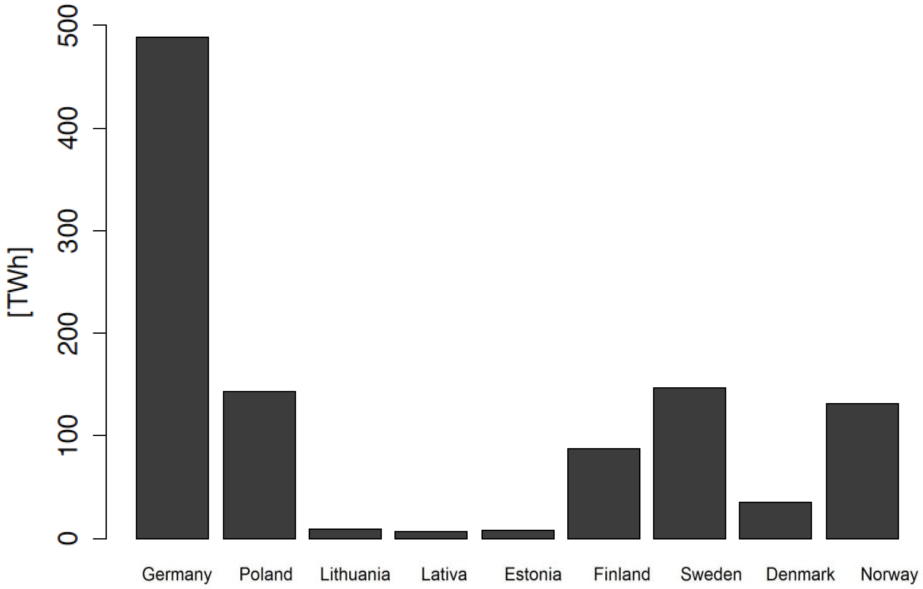

Figure 7: Consumption 2010 by country

3.4 Grid

In order to model and illustrate the hourly load flows between the Baltic countries, the transmission capacities and their future development must be determined. Due to the simplification of the model only the interconnection capacities with 110kV or more between the countries could be taken into account. The grid structures within the countries as well as low-voltage interconnectors with less than 110kV were not considered.

Existing transmission lines and their voltages were analyzed from ENTSO-E's grid map (European Network of Transmission System Operators for Electricity (ENTSO-E), 2011). Since transmission lines with the same voltages do not necessarily have the same capacity, further research on the capacity of each interconnecting line was necessary. For the Scandinavian countries and their neighbors, NORDEL, the former association of Scandinavian transmission system operators (TSO), could provide this information (NORDEL, 2008, p. 13). Similarly, but in a more detailed structure, the former Union for the Coordination of the Transmission of Electricity (UCTE) published data for its continental European member states (Union for the Coordination of the Transmission of Electricity (UCTE), 2009, p. 155 ff.). Table 4 shows the determined summarized interconnector capacities between the considered countries and their characteristics

Table 4: Summarized interconnector capacities

Country 1	Country 2	Electric flow	Capacity 1 -> 2 [MW]	Capacity 2 -> 1 [MW]	type
Germany	Poland	AC	3,408	3,408	land
Germany	Denmark	AC	1,650	1,100	land
Germany	Denmark	DC	600	600	sea
Germany	Sweden	DC	600	600	sea
Poland	Lithuania	AC	1,000	1,000	land
Poland	Sweden	DC	600	600	sea
Lithuania	Latvia	AC	1,950	1,750	land
Lithuania	Sweden	DC	700	700	sea
Latvia	Estonia	AC	1,050	1,100	land
Estonia	Finland	DC	1,000	1,000	sea
Finland	Sweden	AC	1,280	1,680	land
Finland	Sweden	DC	1,350	1,350	sea
Sweden	Denmark	AC	1,350	1,750	sea
Sweden	Denmark	DC	740	680	sea

As there is a constant development within the European grid the plans for a future enhancement of transmission lines were analyzed. Only projects which are planned or under construction and will be operating until around 2015 were considered (cp. (European Network of Transmission System Operators for Electricity (ENTSO-E), 2011)). Grid losses have been assumed with 8%.

3.5 Storage

The storage data base is calculated on the capacity values of power and storage of the U.S. Energy Information Administration (U.S. Energy Information Administration, 2012), the International Energy Agency (International Energy Agency (EIA), 2012) and the European Commission (European Commission (Directorate-General for Energy and Transport), 2008).

The data comprise figures of total installed storage power capacity per country. The actual storage capacity had to be additionally calculated using an average factor of power to energy capacity on the basis of German pump storage power plants. The average value is 0.19, which means that the energy capacity is about 5 times higher than the turbine power (i.e. a pump storage power plant can produce on average about 5 hours on full load before the storage is empty).

Regarding the enlargement of pump storage facilities it is assumed that all hydroelectric power plants and reservoirs are also used as pumped storage power plants. Their power and capacity was calculated as described above. In addition the usage of other storage technologies e.g. battery systems, compressed air or power to gas are assumed based on different studies (e.g. by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety) and geological and geographical information for the countries. Due to already very high pump storage capacities no additional storage capacity was added for Sweden, Latvia and Lithuania. The storage capacity was calculated with a power to energy factor of 0.2 (i.e. 5 hours storage capacity at full load). The assumed different storage capacities are shown in Figure 8.

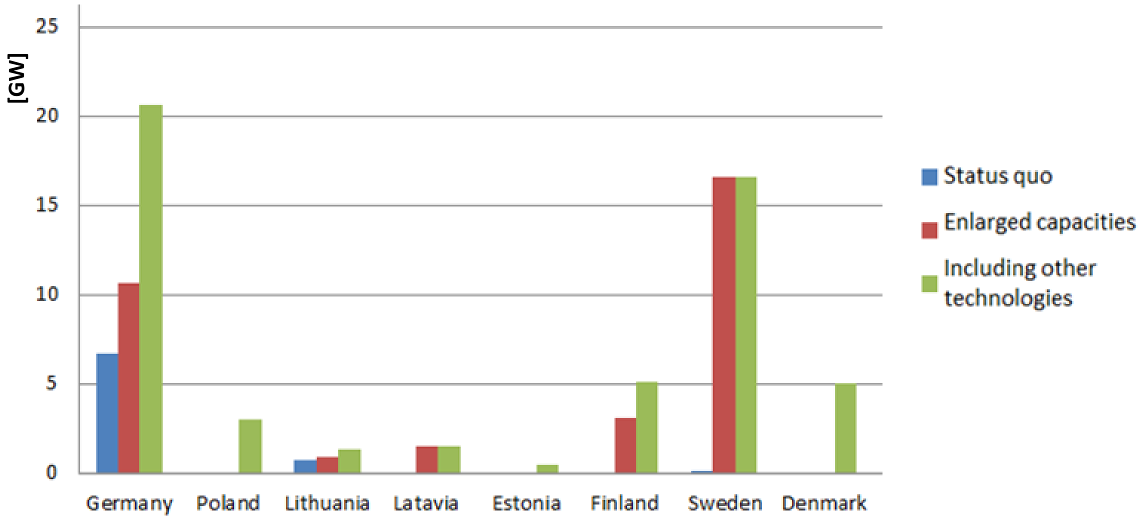

Figure 8: Assumed storage capacity scenarios for 2050

3.6 Costs

Data were collected for the investment and running cost of the fossil and renewable energy production facilities, grid components and storage technologies (see Table 5). Assumptions for the renewable energy technologies were derived from the study "Energy scenarios for an energy concept of the German government" (Schlesinger, Lindenberger, & Lutz, 2010, pp. 38 -39). Compared to other studies these assumptions can be considered as rather conservative, especially looking at the costs of run-of-river power plants. The fuel prices were already implemented in the underlying model data and initially taken from the "Pilot Study 2010" by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Nitsch, et al., 2010). Table 5 shows the cost assumptions for the year 2050.

Table 5: Assumptions for investment and running costs of power plants and fuel prices in 2050

Technology	Investment costs [€$_{2008}$/kW]	Running costs [€$_{2008}$/MWh]	Fuel prices [€$_{2008}$/GJ]
Hard coal	-[1]	6	22.82
Lignite	-[1]	5.6	5.44
Gas	-[1]	2.5	47.09
Oil	-[1]	5.6	62.21
Nuclear	-[1]	10.8	2.23
Run-of-river	4,345	50	-
Wind onshore	950	38	-
Wind offshore	1,350	74	-
Photovoltaic	1,000	26	-
Biomass	2,075	140	50.00
Geothermal energy	9,000	320	-

[1] No additional fossil power plants assumed (see chapter 3.1)

Costs for pump storage facilities are based on the costs for run-of-river power plants, assuming the same investment and running costs. The costs for other non-hydro storage options are estimated based on a redox-flow battery according to one manufacturer (Prudent Energy, 2011). The investment costs are given with 1,320 €/kW.

The grid costs are based on the data given in the recently published plan for the German grid development (Feix, Obermann, Hermann, & Zeltner, 2012, p. 331), see Table 6. The lifetime of cables is expected to be 40 years while overhead lines are considered to last for 80 years (Oswald, 2005). Interest rates were generally fixed at 8%.

Table 6: Grid costs assumption

Cable type	type	Cable costs [Euro/(MW*km)]	Converter costs (DC to AC) [Euro/MW]
AC	underground	2,800	-
AC	overhead	560	-
DC	sea	800	130
DC	underground	700	130
DC	overhead	700	130

3.7 Weather Data

In order to calculate the electricity production of renewable energy plants weather data, especially the solar radiation and the wind speed, have to be considered on an hourly basis. For each country weather data was used from five weather stations (MeteoGroup Deutschland GmbH, 2012). The stations were mainly selected according to their geographical position within the countries to assure a preferably even distribution which evens out extreme differences in the weather conditions (see Figure 9). Weather data for five German stations was already implemented in the database (Deutscher Wetterdienst (DWD), 2012).

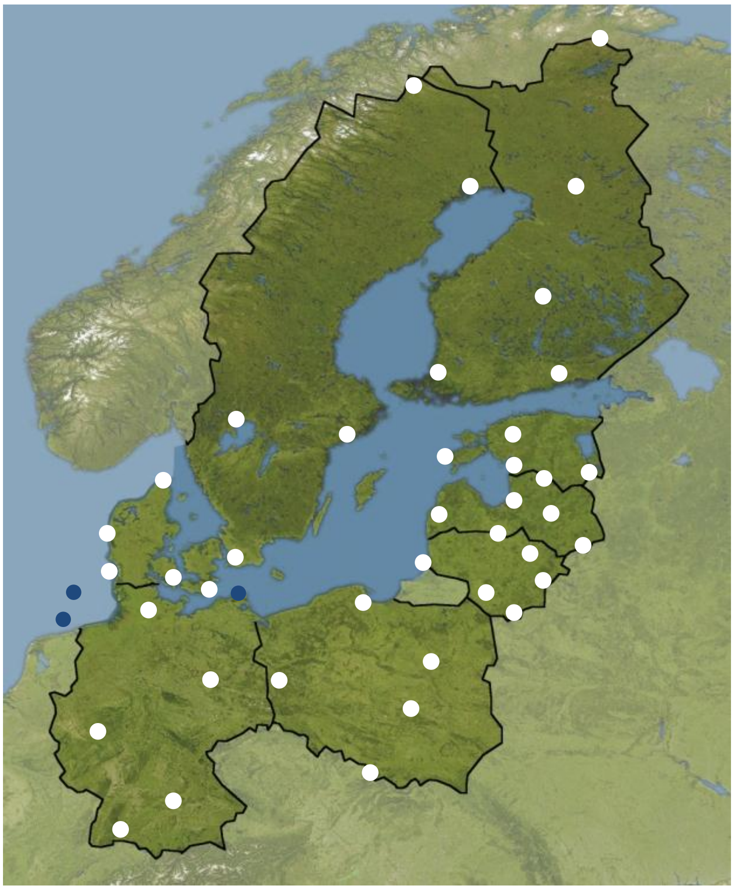

Figure 9: Location of the chosen weather stations (white: onshore, blue: offshore)

One of the weather stations was always close to the shore to estimate the offshore wind potential. For a better calculation of the offshore wind energy wind data from three German offshore research platforms was used additionally. Data was provided by the R&D Centre Kiel University of Applied Sciences (Forschungs- und Entwicklungszentrum Fachhochschule Kiel GmbH, 2012).

The weather database includes hourly information of wind speed, solar radiation and precipitation (used for the filling level of pump storages and the calculation of the run-of-river). Data were available for the years 1998, 2003 and 2010. 1998 was a particularly windy year whereas 2003 was quite sunny.

The offshore wind data for each country was calculated as the mean value from two of the three stations (for Germany and Denmark) or as the mean value from one of the offshore stations and the onshore station which is the closest to the shore (for Sweden and Poland). In all other cases where this approach did not make any sense due to the geographical location of the stations the data of the onshore stations closest to the shore was used for the offshore calculations.

4 Scenario development

Based on the analysed input data a number of scenarios for the year 2050 have been simulated in which different parameters have been varied. In order to keep a focus on a sustainable electricity scenario, three **key research aspects** were established:

1. Renewable energies: Which energy mix of renewable energies would provide the best outcome for the scenario? How much additional renewable capacity has to be installed? Are the economic potentials sufficient?
2. Grid: Which extension of the grid is necessary? Where is grid extension necessary? Where are sensitivities in the grid network? Where are essential grid corridors?
3. Storage: How much storage enlargement is necessary? Is a system without import from the Norwegian hydro storages possible? To what extend can flexible biomass power plants replace other storage options?

4.1 Scenario parameter

In order to find a stable electricity system a number of scenarios and scenario parameters had to be varied to find the optimal combination of configurations. Varied scenario parameters were the expansion of installed renewable energy capacities and the development of the demand until 2050 as well as the development of the grid and storage infrastructure.

Table 7: Overview over parameter scenarios (colour code indicates pessimistic (red) to optimistic (green) assumptions)

	Parameter scenario name	Parameter scenario description
Renewable energy capacity		
🟥	Economic	Economic potentials
🟧	Self-Supply 1	Slight adjustment of the economic potentials to meet the countries respective demands
🟨	Self-Supply 2	Cheap technologies: assumptions as in Self-Supply 1 scenario, but only expansion of the three cheapest technologies in 2050 (according to (Faulstich, et al., 2011): wind on- and offshore plus run-of-river (biomass, PV and geothermal energy capacities fixed at 2011 status quo)
🟩	Self-Supply 3	More wind: assumptions as in Self-Supply 1 scenario, but no PV expansion and more wind energy (on- and offshore)
Demand [1]		
🟥	Linear growth	+30% growth in demand compared to 2010
🟨	Moderate efficiency	No growth in demand (assumption: use of energy efficiency technologies)
🟩	High efficiency	-20 % growth in demand, assumption: forced use of energy efficiency technologies (based on EU goal until 2020, delayed implementation until 2050)
Grid [2]		
🟥	Conservative	Conservative: no additional enhancements over status quo 2015
🟨	Moderate	Enhancements of grid by 30% until 2050
🟩	Extensive	Extensive grid enhancements by 100% until 2050

[1] Linear growth assumes specific growth rates for each country. For the high efficiency scenario given figures are average changes over the whole Baltic region.

[2] The given enhancements are assumed to be implemented across-the-board. No specific grid corridors were considered.

Storage facilities		
🟥	Status quo	Storage capacities and technologies fixed at 2012 status quo
🟨	Upgrade hydro	All status quo (2012) hydroelectric power plants and reservoirs are also used as pumped storage power plants
🟩	All technologies	Assumptions as in upgrade hydro scenario, additional use of other storage technologies (e.g. battery systems, compressed air or power to gas)

Other minor parameters were the initial decision on the use of the weather data, the lifetime of existing fossil power plants and the development of the fuel prices. For the weather year the use of the data for 2010 was decided because it is the most average year in the existing data. The lifetimes of fossil power plants were set to an average of 35 years. The fuel price development was considered as moderate.

Bio-flex parameter

In order to examine the influence of flexible biomass as a potential replacement for grid or storage enhancements a so-called “bio-flex parameter” was introduced as an additional indicator. With its help the installed biomass capacity could be varied. It therefore represents a ratio between the installed biomass production capacity (in MW) and the available energy from biomass (in MWh). The underlying assumption is that the operation of biomass power plants can either be designed to feed-in steadily or flexible depending on the residual load. The latter of which is related to higher investment costs but offers the opportunity to be used as flexible electricity source because of the larger installed capacity. Biomass will in this case just produce electricity when it can't be supplied by weather dependant renewable energies like wind and PV.

Since the total amount of electricity that can be produced from biomass within a year is limited this assumption implies less full load hours per biomass power plant. A bio-flex indicator of 2 for example means that the installed capacity has been doubled compared to the economic potential, thus half as much full load hours. However the total electricity produced by biomass will remain at the level of the economic potential. Biomass can therefore be partly also considered as storage technology since the biogas production or biomass harvest respectively can be continued and the energy be stored while the biomass power plant itself might not be running constantly.

4.2 Parameter variations for a base scenario

The first step was to broadly determine a base scenario with a stable electricity supply. The aim was to combine the above mentioned parameter variations in order to be able to match the demand for every hour and every country as good as possible. This means that there should be as few power shortages as possible in such a system. Additionally the aim was to limit the curtailment of the renewable energy production which is the case when renewable energies could produce a lot of energy while the demand is low and storage and grid transmission capacities are fully used. The initial simulation combinations are shown in Table 8.

Table 8: Initial combinations of parameter scenarios

Scenario name	Renewable energy capacity	Demand	Grid	Storage
Conservative	Economic	Linear growth	Conservative	Status quo
Moderate	Economic	Moderate efficiency	Moderate	Upgrade hydro
Optimistic	Self-Supply 3	High efficiency	Extensive	All technologies
Self supply	Self-Supply 1	High efficiency	Conservative	All technologies
Ultra grid	Self-Supply 2	Moderate efficiency	Extensive	Status quo
Base scenario	**Economic**	**High efficiency**	**Conservative**	**Upgrade hydro**

Based on the first simulation results and their analysis it turned out that the combination of the economic potential of renewable energy capacities, a high efficiency concerning the demand (-20% until 2050), a conservative grid expansion (expected status quo 2015), a moderately extended storage status and a quite flexible electricity production from biomass met the criteria of the lowest overdemand the best. This combination is henceforth referred to as the **“base scenario”**.

5 Results for the base scenario

5.1 Demand and Electricity Production

The total demand for all eight considered countries of the Baltic Sea region in 2050 is 740 TWh while the total production from renewable sources sums up to 838 TWh. The result is an over production of 98 TWh. Comparing to these yearly sums the demand and production has to be examined over the course of the year. Figure 10 shows the demand and the electricity production by the different renewable energy sources for the year 2050 for the whole Baltic Sea region.

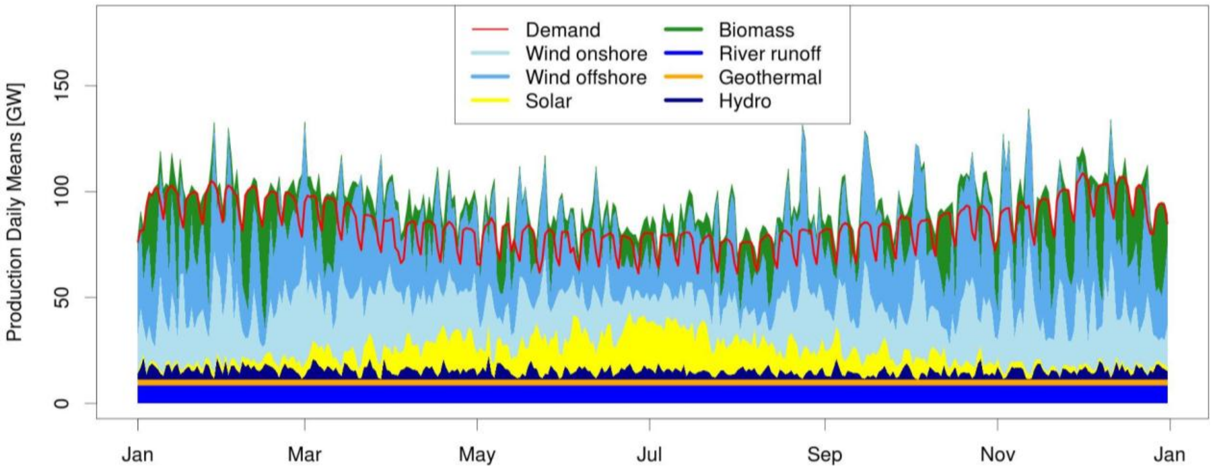

Figure 10: Demand and renewable electricity production in 2050 for the whole Baltic Sea region

It can be seen that geothermal energy and run-of-river are used by the model as base load throughout the year. Solar energy is able to cover a major share of the demand in the summer months. Wind onshore and offshore is mostly used in the winter months when the wind speeds are higher but is producing in the remaining months as well. There is an over production throughout the year because the production of wind and solar electricity is higher than the electricity demand. The situation occurs if there are not enough storage options or grid transmission capacities to neighbouring countries. This leads to the forced shut-off of renewable energy production facilities. The electricity production and demand summed up for each country is shown in Figure 11. Especially Poland has to deal with a net overdemand because its production capacities are not big enough in this scenario. The same applies to Sweden and Lithuania, although to a much lesser extent.

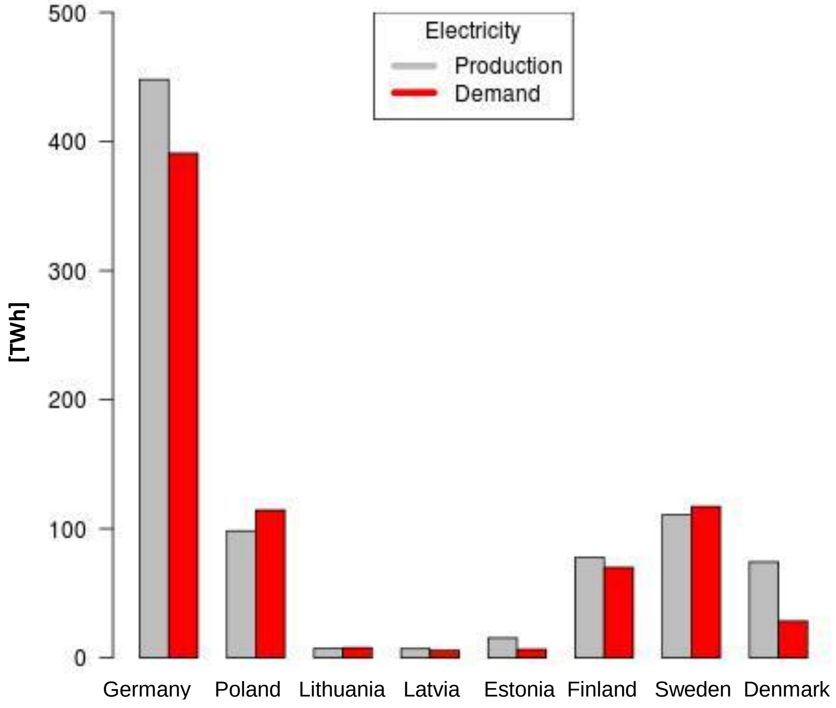

Figure 11: Production and demand for each country in 2050

Figure 12 shows the electricity production by the different renewable energy sources for each country in 2050. Wind offshore holds in total the biggest share of the different renewable energy sources in 2050 with approximately 36 % followed by wind onshore with 24%. Biomass contributes with 14%, PV with 10%, run-of-river with 9%, hydro storages with 4% and geothermal energy with 3 % to the production. Calculations for the intermediate years of 2020, 2030 and 2040 (see chapter 6.4) have shown that the solar and biomass energy shares were higher but have been replaced by cheaper wind energy until 2050.

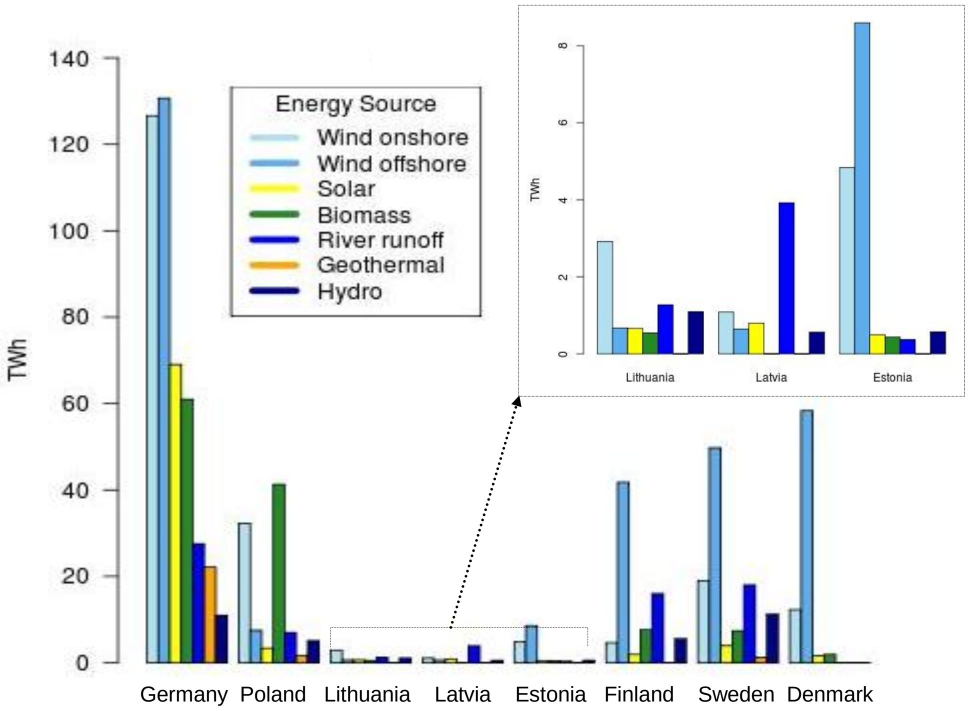

Figure 12: Electricity production of the Baltic Sea region by source in 2050 in TWh

5.2 Residual Load and overdemand

The residual load describes the gap between the demand and the renewable energy production from wind onshore and offshore, PV, run-of-river and geothermal sources. The overdemand is the remaining gap after the flexible biomass and all available storages have been shaving off the residual load peaks as far as possible. Figure 13 depicts the situation of the first week in January 2050.

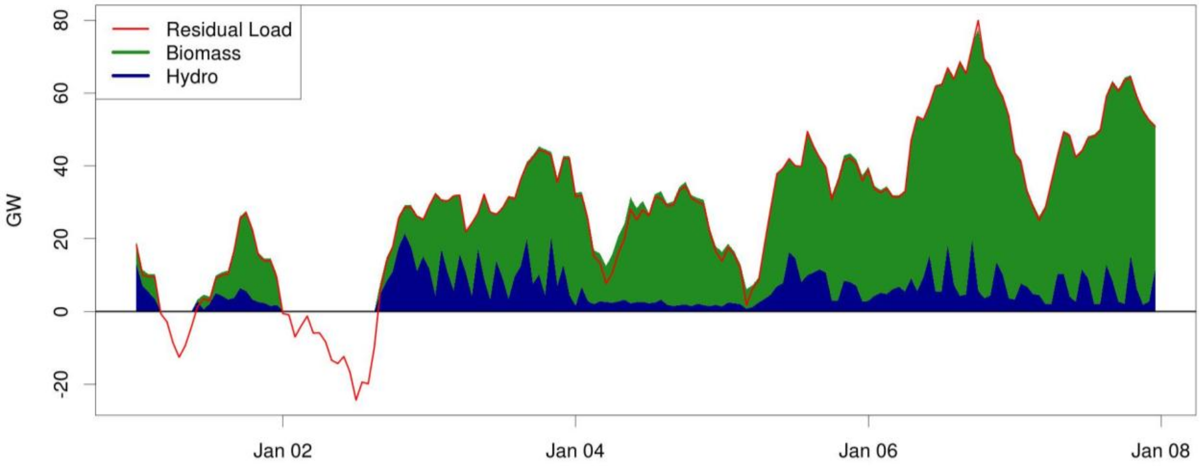

Figure 13: Residual load and biomass production in GW for the Baltic Sea region in January 2050

The red line in Figure 13 shows the residual load that cannot be covered by wind, PV, river runoff and geothermal sources. The maximum residual load during the depicted week reaches about 80 GW. The green and blue areas show how flexible biomass and (hydro) storages can fill the gaps of the residual load so that there is no overdemand during this week (there even is an over production during the first two days).

One of the most important results of the base scenario is the use of flexible biomass. The calculations of different scenario options have shown that no other storage system could cover the overdemand in the same efficient way than a flexible biomass option. But it also has to be considered that the installed biomass capacity has to be significantly increased and requires much higher investments.

5.3 Imports and exports

The balanced exchange of electricity between the different countries is shown in Figure 14. The arrows indicate the amount of imported or exported electricity summed up over the year of 2050. The numbers are given in TWh.

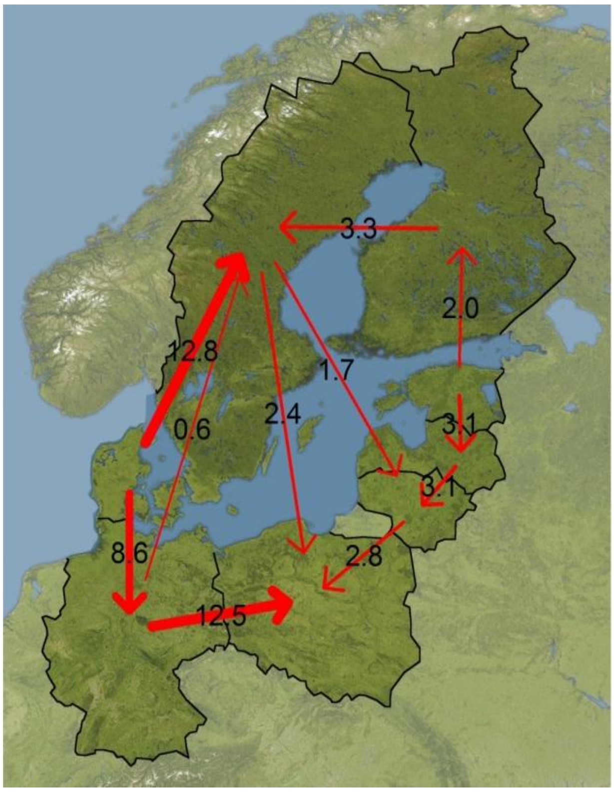

Figure 14: Net import 2050 in TWh

In absolute figures Germany for example has a net import from Denmark (totalling 8.6 TWh) as well as net exports to Sweden (0.6 TWh) and Poland (12.5 TWh). Denmark as another example exports a lot of electricity due to its high wind potentials and its comparatively low demand. The same holds true for Estonia although on a lower level. Sweden and especially Poland are in contrast heavy importers in absolute numbers. The figure shows as well that the grids in Germany, Finland and Latvia are mostly used for transit in order to get the electricity from the centres of production to the centres of the demand.

Especially Denmark seems to have a high dependency on its grid connections to Germany and Sweden since its energy production is highly dependent on wind energy. Should there be a calm it has little other options to substitute wind energy. Thus at times it can have an overdemand even though Denmark is a net exporter of energy (see Table 9).

Table 9: Export and import countries

	Export (TWh)	Produktion (TWh)	Export rate
Estonia	-5,10	15,30	33%
Denmark	-21,40	74,25	29%
Finland	-1,30	77,60	2%
Germany	-4,50	447,99	1%

	Import (TWh)	Demand (TWh)	Import rate
Lithuania	2,00	7,15	28%
Poland	17,70	98,31	18%
Sweden	12,00	110,69	11%

(Latvia’s import/export rate is 0%)

5.4 Renewable energy reduction

The reduction of renewable energy production (i.e. their forced shut-off) is triggered in situations when the demand and transmission capacities to neighbouring countries are not big enough to take the renewable energy production (over production). As a result the production facilities have to be shut off to avoid frequency problems in the grid. In comparison to the overdemand (demand > production) the reduction can also be called over production (demand < production). Figure 15 shows the yearly development of the over production in 2050.

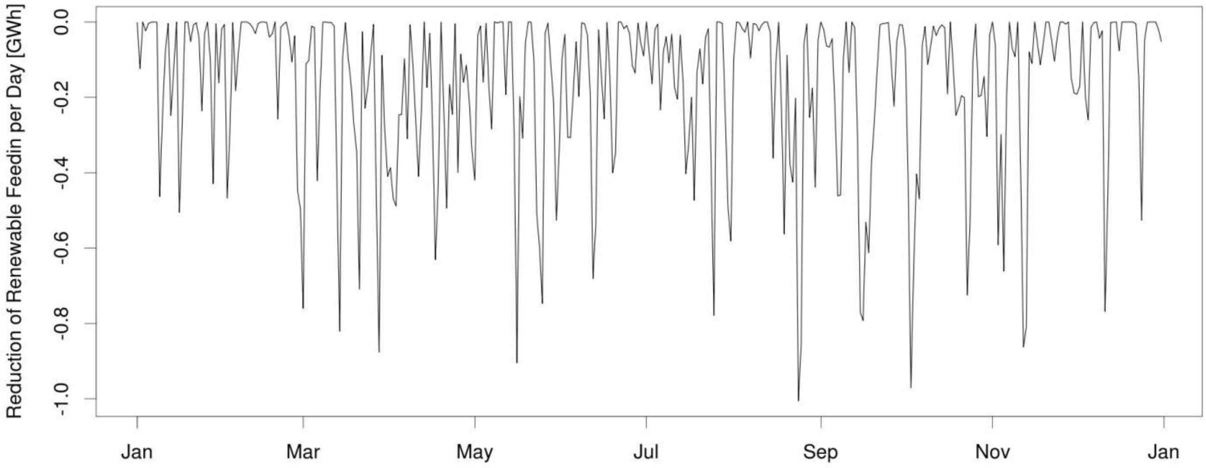

Figure 15: Renewable energy shut-off for the Baltic Sea region in GW

The calculated base scenario still has some hours over the course of the year with a small overdemand (see 5.2). In contrast hours with an over production are much higher (approx. 5100 hours). During these times electricity of 77 TWh and up to a maximum of 88 GW cannot be used. These figures seem to be very high but the consideration of only the Baltic Sea region countries without any connections to neighbouring countries totally disregards such balancing exchange possibilities. The bigger and more diverse the scope region is the more balanced will be overdemand and production.

5.5 Costs

The costs calculations are based on the assumptions explained in chapter 3.6 and are not part of the *renpass* optimization process (i.e. *renpass* at its current state optimizes the operation of installed capacity but does not yet find the cost-optimal electricity system). The costs are only calculated after the *renpass* model finishes its optimization. Investment costs are assumed to be at the 2050 level. Technology-specific lifetimes are considered whereas interest rates and energy taxes are not. Therefore the costs have to be taken as qualitatively rather than as absolute figures. Thus the costs are especially useful for the comparison of different options. For this purpose the comparable cost indicator of the so-called “levelized costs of electricity” (LCOE) was calculated. The levelized cost is the price at which electricity must be generated from a specific source to break even over the lifetime of the power plant.

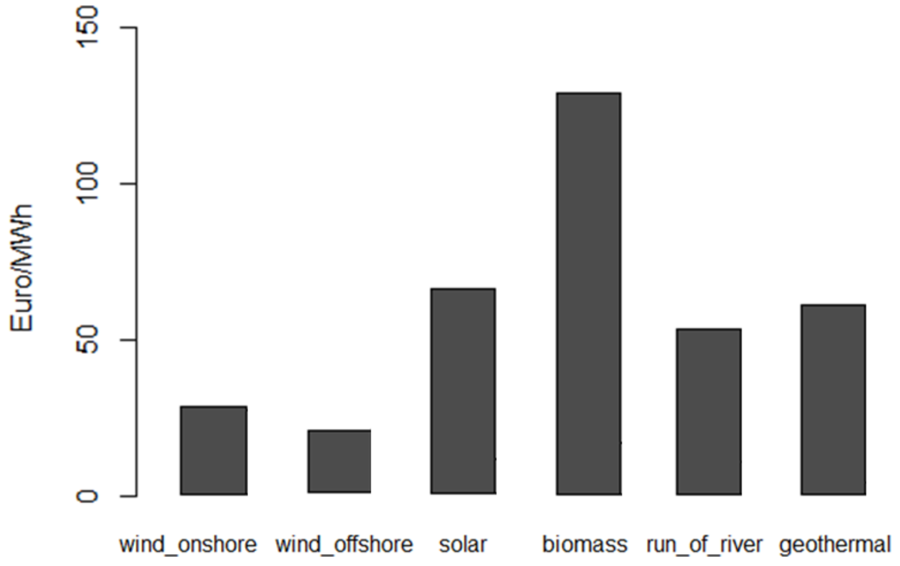

Figure 16: Technology-specific levelised costs of electricity by type

In Figure 16 shows the technology-specific LCOE. In 2050 wind offshore is the cheapest technology with around 25 €/MWh, followed by wind onshore and run-of-river (approx. 30 and 55 €/MWh respectively). It is especially striking and reasonable at the same time that the LCOE of biomass electricity are especially high since there has to be installed three times the capacity to achieve the desired flexibility. Still biomass only contributes less than half the electricity than offshore wind energy facilities do (see 5.1) and at the same time is more than eight times more expensive. But it seems to be a necessary evil to secure a stabile system.

The total LCOE (i.e. the price at which the electricity can be produced in 2050) are at about 55€/MWh (5.5 ct/kWh) for the simulated system of the Baltic Sea region. In comparison the average stock market price of electricity in Germany in 2011 was at 60 Euros/MWh (Brost, Rosenfeld, & Vorholz, 2012). Of these 55€/MWh about 50€ fall upon the actual electricity production whereas the storage costs make up only about 5 €/MWh. This is due to the cheap pump storage and because of the fact that the flexible biomass actually serves as energy storage but appears as renewable energy costs. Furthermore the grid costs are almost insignificant, tending close to 0€. This is mainly due to the fact that the lifetimes of the grid components are very long and costs can be written off over long time periods.

6 Base scenario sensitivities and results

Following the determination of a base scenario and the analysis of the results several minor adjustments had to be made in order to identify more detailed sensitivities for the calculation of additional scenarios and concerning the proposed research questions (see tables 10 to 13). Only slight adjustments had to be made respectively to look at specific details.

6.1 Capacity and mix of renewable energies

With regard to the first research aspect (see chapter 4) it could be already seen from the initial scenarios that the use of only the economic potentials seems to be enough to cover the demand. Notwithstanding some slight adjustments for Poland had to be made as well as the bio-flex factor varied (see Table 10).

Table 10: Scenario matrix for the analysis of sensitivities of renewable energy capacities

Scenario name	Year	RE capacity	Demand	Grid	Storage	Bio-flex
Base scenario	2050	Economic	High efficiency	Conservative	Upgrade hydro	3
Adjustment Poland	2050	**Economic***	High efficiency	**Conservative***	Upgrade hydro	**3**
Static biomass	2050	Economic	High efficiency	Conservative	Upgrade hydro	**2**
Flexible biomass	2050	Economic	High efficiency	Conservative	Upgrade hydro	**4**

1) **Scenario adjustment Poland:**
   Dissenting from the regular economic potential, the wind capacities for Poland and the grid transmission capacities between Poland and Germany have been increased because especially Poland could not fully cover its demand from renewable sources in the base scenario. But it turned out that even with a higher production and exchange capacity Poland’s overdemand remains almost unchanged.

2) **Scenarios static and flexible biomass:**
   For those scenarios the bio-flex indicator was decreased (to 2) and increased (to 4) respectively compared to the assumption in the base scenario (bio-flex = 3). The result is that with a less flexible biomass production the peak overdemand increases from 9 to 20 GW. In contrast the little overdemand in the base scenario could be totally covered with a highly flexible biomass production.

It can be stated that the high flexibility of biomass production plays an important role in covering peak demands. It can be also seen that especially Poland might possibly get problems covering its demand at times because of the relatively low energy production potentials compared to a high demand (subject to a more detailed look at the potentials and further simulation scenarios).

6.2 Necessary grid capacities

Concerning the second research aspect the grid parameter as well as the bio-flex indicator have been varied compared to the base scenario to determine interdependencies between grid expansions and biomass storage options (see Table 11).

Table 11: Scenario matrix for the analysis of sensitivities of grid capacities

Scenario name	Year	RE capacity	Demand	Grid	Storage	Bio-flex
Base scenario	2050	Economic	High efficiency	Conservative	Upgrade hydro	3
Extensive grid	2050	Economic	High efficiency	**Extensive**	Upgrade hydro	**3**
Moderate grid/flexible biomass	2050	Economic	High efficiency	**Moderate**	Upgrade hydro	**3**
Moderate grid/static biomass	2050	Economic	High efficiency	**Moderate**	Upgrade hydro	**2**

1) **Scenario extensive grid**

   With a significant extension of the grid (doubled capacities) the overdemand can be reduced compared to the base scenario (from 9 to 2 GW). It occurs mostly in Denmark due to the very high wind energy production and only few dispatchable sources. Obviously the exchange capacities to Sweden and Denmark are still not big enough. Looking at the whole region it has to be stated that the total reduction of renewable energy production cannot be significantly decreased. The capacity utilization of the grid connections also seem to be quite low in this scenario.

2) **Scenario moderate grid/flexible biomass**

   An only moderately enhanced grid with flexible biomass production as in the base scenario leads to a slight reduction of the peak overdemand (to 7 GW, mostly in Germany and Denmark) but is also not able to decrease the necessary renewable energy reduction.

3) **Scenario moderate grid/static biomass**

   If the flexible character of the biomass production is additionally reduced the peak overdemand (17 GW, mostly in Germany, Denmark and Poland) as well as the forced shut-off of renewable production due to grids used to capacity increases.

The results indicate that the expansion of the grid does not seem to be highly necessary. It does not help to reduce the necessary shut-off of renewable production at times. The flexibility of the biomass production however seems to have a much bigger impact on the covering of overdemands. It could be seen that especially the grid connection capacities between Germany and Poland seem to be a bottleneck and need to be upgraded.

6.3 Storage capacities

With regards to the third research aspect, what extend of storage enhancements might be necessary, the storage parameter has been varied in terms of the utilized capacities (see Table 12).

Table 12: Scenario matrix for the analysis of sensitivities of storage capacities

Scenario name	Year	RE capacity	Demand	Grid	Storage	Bio-flex
Base scenario	2050	Economic	High efficiency	Conservative	Upgrade hydro	3
Current storage	2050	Economic	High efficiency	Conservative	**Status quo**	3
All technologies	2050	Economic	High efficiency	Conservative	**All technologies**	3

1) **Scenario current storage**

   The reduction of storage capacities compared to the base scenario does not result in any significant changes with regards to peak overdemand or the reduction of renewable energy production.

2) **Scenario all technologies**

   The use of additional storage technologies also does not reduce the peak overdemand considering the whole Baltic region but relieves especially Germany’s situation. The reduction of renewable energy production could not be changed compared to the base scenario.

The fact that the size and technology of storages does not seem to make a very big difference highlights once more the importance of the utilization of flexible biomass production as supplement or even replacement for storage or grid enhancements. The system also works without the large Norwegian storage capacities since they have not been considered for the simulation at all. Auxiliary calculations have shown that even when Norway is included into the simulation the additional storage capacities do not necessary improve the system in terms of overdemand. This is due to the fact that the Norwegian grid connection capacities to the neighbouring countries are not big enough to make a significant impact.

6.4 Pathway steps towards 2050

Additional to the before mentioned research aspects the time steps between 2010 and 2050 have been analysed on the basis of the base scenario and with a reduced flexibility of the biomass production (see Table 12). The configuration of the production facilities for the intermediate time steps is calculated on the basis of the construction years and lifetimes of the fossil power plants as well as a linear expansion of renewable energy capacities.

Table 13: Scenario matrix for the analysis of pathway steps towards 2050

Scenario name	Year	RE capacity	Demand	Grid	Storage	Bio-flex
Base scenario	2050	Economic	High efficiency	Conservative	Upgrade hydro	3
Base	**2020**	Economic	High efficiency	Conservative	Upgrade hydro	**3**
	2030	Economic	High efficiency	Conservative	Upgrade hydro	**3**
	2040	Economic	High efficiency	Conservative	Upgrade hydro	**3**
Base (static biomass)	**2020**	Economic	High efficiency	Conservative	Upgrade hydro	**2**
	2030	Economic	High efficiency	Conservative	Upgrade hydro	**2**
	2040	Economic	High efficiency	Conservative	Upgrade hydro	**2**

1) **Base scenario 2020, 2030 and 2040**

   The peak overdemand gradually increases over the years because the renewable expansion cannot keep up with the discontinuation of the fossil power plants. The overdemand is the highest in winter times. While the problem occurs in 2020 mainly in Germany, Poland and Denmark the latter one does not have big problems from 2030 on. Looking at the grid it can be stated that especially around 2030 the utilization is very high but decreases towards 2040 and 2050. The necessary renewable energy reduction also increases gradually, especially in Germany and Denmark.

2) **Base scenario 2020, 2030 and 2040 with reduced biomass flexibility**

   The results do not significantly change when using a less flexible biomass production. Although the overdemand is slightly higher and especially occurs in Poland.

As a result it can be stated that it is necessary to increase the expansion rate of renewable production capacities in order to replace the decreasing fossil capacities. This seems to be a problem especially in Poland. The flexibility of biomass production seems to be less important in years when dispatchable fossil power plants are still available but needs to be built up for the completely renewable system. The grids (no significant expansion) are highly utilized in the intermediate years but less utilized again towards 2050.

7 Evaluation

The data used for the model is mainly based on external reports and at times even had to be collected from different sources. Even though it was paid attention to a coherent and consistent database the absolute accuracy of every single figure cannot be guaranteed. It became obvious that there is a lack of free available data regarding demand, power plants and grids for the Baltic Sea countries. Furthermore many adjustments of scenario parameters are based on assumptions. The main limitations of the data and the model as well as a few key issues for future simulations are described in this chapter. Nevertheless the scenario modeling and the results represent the best state of knowledge.

7.1 Input Data

The level of detail of the used data on **power and storage plants** is low. For most countries, an open source list including every single power plant does not exist. Hence, the installed capacity per country artificially split up into the different power plant types was used. Especially for small countries with only a few big power plants impacts by sudden reductions of capacities due to phase outs are not reflected in the model. Though it reduces the risk of overdemand it is assumed to be unrealistic. The technical **potentials of renewable energies** in the region are much higher than the assumed installed capacities (economic potentials) in this simulation. Despite this conservative approach the difference to the technical potentials indicates the huge possible range of future expansion pathways. Some studies for example even gave a lower overall potential for PV in Germany than the currently installed capacity.

With respect to the **demand**, the assumption of an overall reduction of 20% for the Baltic Sea region by 2050 according to EU goals might be unrealistic. Additionally differences in the demand development between the countries have not been taken into consideration despite certainly differing situations. The data for the development of **grid capacities** does not include single developments and considers only planned projects until 2015. Even though large enhancements of grids do not seem to be essential future changes in the grid may have impacts on the simulation outcome. The expected **storage capacity** for the future is mainly based on assumptions with a relatively high level of uncertainty due to very unpredictable future technology development and implementation.

As for the **costs** of renewable energy production the assumptions are based on very conservative studies thus possibly even overestimating the future costs of electricity. In contrast the **weather data** has a relatively high accuracy level. It is hourly detailed with respect to wind speeds, solar radiation and precipitation and geographically diverse. A limitation though is the availability and location of offshore weather data due to the small number of offshore weather stations.

7.2 *renpass* simulation

Regarding the **system boundaries** the simulation only includes the countries of the Baltic region. However the model does not consider (grid) connections to neighboring electricity systems, e.g. to the rest of the European transmission grid. Furthermore each country is considered as one grid area for which all country data is averaged. Therefore, the model does not calculate load flows within the countries. For example in Germany the industrial areas in the south and west have a high demand while a significant share of the future electricity generation is produced by wind power in Northern Germany.

It has been mentioned that the **pathway** up to the target year of 2050 has been illustrated by the years 2020, 2030 and 2040. Due to the focus on 2050 there has not been any detailed optimization for these years, e.g. with regards to the seemingly higher utilization of the grid. As the pathways are always characterized by a very dynamic development, the constant optimization of the electricity system would be necessary. Furthermore it has been assumed that no new fossil power plants will be constructed and existing ones will be completely phased-out by 2050. This leaves out considerations of gas-fired power plants with relatively low carbon emissions that might be a viable – and compared to biomass a cheaper – option to level out fluctuating renewable power production within the next decades

Considering the still existing (but nevertheless short) times with an **overdemand** where the renewable production cannot cover the demand it must be further examined how these gaps can be avoided, e.g. by load-shedding or flexible demand options. The proposed use of biomass as flexible production to a great extend raises the question of land use conflicts, timing of harvesting and storage facilities amongst other aspects.

One of the main unsolved issues is the fact that **other energy consuming sectors** (e.g. the heat or transport sector) are not yet implemented in the *renpass* model. Countries like Estonia or Latvia have a potentially high share of heat production from biomass and a high heat demand in the winter months. Especially when considering combined heat and power (CHP) power plants which produce electricity and heat at the same time the interdependencies between these two sectors become apparent. Taking this into account will limit the flexibility of biomass electricity production when a constant level of heat production is needed at times. The future wide-spread implementation of E-Mobility will have an influence on the electricity demand, too.

In order to achieve a 100% renewable electricity system by 2050 a working **market structure** has been implied that allows all necessary technologies to be implemented according to the needs for the simulated system. However the necessary characteristics of such a market structure have not been determined. The results for example indicate the need for a technology that is able to level out the fluctuating production of wind and solar power. Flexible biomass power plants have been assumed in the model which can provide these services if they are designed accordingly. In today's energy market power plants are usually run on full power whenever possible because the revenue is based on the amount of energy produced. To increase their flexibility the market structure needs to be modified towards innovative capacity market mechanisms where the short-term availability of power plants is compensated. Germany already has a similar system for a balancing power market in which the allocation of short-term capacities is auctioned trough the transmission system operators.

8 Conclusion

The simulations have proven the feasibility of an electricity system for the Baltic Sea region in 2050 that is solely based on renewable energies. Despite some weaknesses in the model as well as in the data it could be shown that the countries can cover their demand based on conservative assumptions. Furthermore the costs seem to be not significantly higher than today's costs of electricity.

The key conclusions are:

1. **A 100% renewable electricity system for all Baltic region countries is possible.** Even under conservative assumptions the region can cover its demand by 2050. Nevertheless Poland will probably have temporary difficulties due to a lack of power and grid capacities. And even though Germany can always cover its demand on the balance sheet it will have problems with the peak demand at times. A moderate expansion of the demand flexibilities may alleviate these problems. However the installation of renewable production capacities needs to be ramped up in the years until 2050 to compensate the scheduled phase-out of fossil and nuclear power plants.

2. One of the most important outcomes is the fact that **biomass as flexible electricity production holds a key role for the system stability**. Contrary to the popular belief that biomass power plants should contribute to the base load their utilization as flexible energy source seems to be far more reasonable. However there have to be built quite large capacities to ensure the availability of enough production capacity in times when wind, PV and hydro power cannot cover the demand (at times even over a longer period of time). To ensure the necessary enhancements a market structure with effective incentive schemes (e.g. capacity market mechanisms) needs to be established. A new market design should be internationally harmonized and should also consider the transmission systems in order to include sensitivities to storages and to find a cost and system optimal balance between the grid, storages and flexible production.

3. **The grid transmission capacities between the countries are often not used to capacity in 2050**. Despite the fact that they might well be very busy in the years in-between does a 100% renewable electricity system in 2050 probably not need the full capacities anymore. The simulation results show the need for a short-term extension of the grid whereas in 2050 flexible biomass power plants seem to significantly buffer the flexible demand and potentially decrease the necessity of large transmission capacities. However the least expensive option has yet to be determined.

4. **A 100% renewable electricity system is possible even without imports from the huge Norwegian pump storage potential.** The production of renewable energies apparently balances itself within the considered region sufficiently. The above mentioned biomass plays an important role as controllable supplement for wind and solar energy.

5. **Such a system isn't necessary extremely expensive.** The roughly calculated costs for the expansion of renewable energy capacities, storage systems and grid capacities between the countries are around 50€/MWh which is comparable to today's spot market prices.

Overall it could be stated that there is a huge potential and need for further investigations into more detailed scenarios as well as extensive research of specific aspects like the utilization of flexible storage options. The open-source simulation model *renpass* can be used as a good starting point for further simulations and the necessary cooperation with institutions of the Baltic region. Partnerships regarding the further development of *renpass* as well as further simulations are not only necessary to look at the raised issues. Universities using *renpass* for educational purposes or research projects and public authorities and companies using it for strategic decisions also ensure a participatory development of pathways towards a future sustainable energy system.

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University of Flensburg
Zentrum für nachhaltige Energiesysteme (ZNES)
Centre for Sustainable Energy Systems (CSES)

i² - Interdisciplinary Institute for Environmental, Social and Human Studies
Department Energy and Environmental Management
Munketoft 3b
24937 Flensburg
Germany
Internet: www.znes-flensburg.de

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