TALLINN UNIVERSITY OF TECHNOLOGY
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RENEWABLE ENERGY SOURCES INTEGRATION IN ESTONIAN ENERGY SYSTEM: THE CURRENT STATE, CHALLENGES AND OPTIMIZATION

TAASTUVENERGIA ENERGIAALLIKATE INTEGREERIMINE EESTI ELEKTRISÜSTEEMI: HETKEOLUKORD, VÄLJAKUTSED JA OPTIMEERIMINE

MASTER THESIS

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Tallinn, 2017

AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.
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List of abbreviations and acronyms

BRP - Balance responsible party

CEEP - Critical excess electricity production

CHP - Combined heat and power

DESIRE - Dissemination Strategy on Electricity Balancing for Large Scale Integration of Renewable Energy

DH – District heating

DHP – District heating plant

EEA - European Energy Agency

GJ - Gigajoule

HDD - Heating degree days

LPG - Liquefied petroleum gas

MREI - Maximum Renewable Energy Integration

MW - Megawatt

O&M, OM - Operations and maintenance

PP - Power plant

RES – Renewable energy source

TJ - Terajoule

TSO - Transmission system operator

VRE - Variable renewable energy

1. Introduction

The importance of clean technologies' development is clear – the global warming is a real threat to our planet and greenhouse gases emissions should be limited. One of the main ways is an introduction of clean energy sources – solar, wind, hydro, biomass and others. The share of RES in the world is showing a fast and steady growth and Estonia is not an exception. Wind energy and biomass are two sources of clean energy already making a substantial contribution to the total energy balance and there are future plans for the expansion of these and other technologies.

While the benefits of renewable energy sources are evident, there are also obstacles, the possible effects of which should be carefully estimated. Every country has a unique energy system and the way RES are influencing these energy systems is also different. It shows the importance of the modeling in the development of clean energy sources.

The main objective of this thesis is to evaluate the perspectives of the integration renewable energy sources in the current design of the Estonian energy system and to estimate the limits for the RES integration. The approach used in this work can be divided into three main parts. Firstly, the current state and the development of Estonian energy system were analyzed; the place of Estonia in the European market was shown and possible challenges and obstacles for the future development of renewable energy sources were described. Secondly, a study of openly available sources was made, all necessary data was collected and the model of Estonian energy system was created using the most recent set of data available. The model was shown to produce the results close to the official statistical data available. In the final part different scenarios of the future development of Estonian energy system were analyzed using the model created. Based on the results of modeling, the limitations for the RES integration were found and insights into the way the Estonian energy system responds to the growing share of sustainable energy sources were provided.

Although there are similar studies analyzing country scale energy systems of different countries, at the moment of writing there was no single one for Estonia using the latest data available and showing the same level of detail. This thesis' framework is limited by Estonian electricity and heat network and interconnections with Finnish and Latvian electricity systems. Although the software used in this work can simulate the interaction between the neighboring energy systems, the capability of this simulation is limited by one modeled interconnection while all the rest are assumed to be "fixed" and are not responding to the changes occurring in the system. There are some other noticeable limitations of this thesis.

Firstly, while the possibility of the system's balancing by increasing interconnection capacity or use of hydro power or batteries are described in the literature review, there are no scenarios representing these possibilities. Secondly, the costs used for the economical calculations might be updated and revisited since some of these were not determined for Estonian market and were taken from the available studies dealing with the other countries. These aspects can be the topic for the following studies in the field of RES integration in Estonia.

The results of the thesis should be important for policymakers and since the model is thoroughly described, it might be used for the future studies related to Estonian energy system e.g. energy saving measures, economic aspects of development, expansion of interconnection capacities, an introduction of new technologies and many others.

2. Characterization of Estonian energy system

This chapter is giving the introduction to the current state of Estonian energy system, the way it was developing and the challenges which it is facing. First part is providing the historical insight into the Estonian energy system development with the accent on oil shale sector is given. Then, the position of Estonia in the European energy system is characterized. The development of renewable energy sources in Estonia is described in the third part of the chapter.

After the description of the current state of the Estonian energy system this chapter is assesses the challenges which Estonia is facing. This part is showing how the developed oil shale sector is influencing the future integration of RES in the system and describes possible ways of its evolution with existing constrains.

The final part of this chapter is describing additional requirements for the energy systems with the large or growing share of renewable energy sources. These aspects are showing the importance of the thorough analysis of RES integration studies for the organic development of the modern energy systems.

2.1. Estonian energy system

2.1.1. The historical development of Estonian energy system

Estonian energy system is unique among European countries because of huge reserves of oil shale available. Oil shale mining in Estonia started 100 years ago in 1916 when the first sample of oil shale was mined and sent to St. Petersburg for analysis [1]. Since then oil shale sector in Estonia was rapidly developing and had its peak in the early 80s after which a decline has begun (Figure 1).

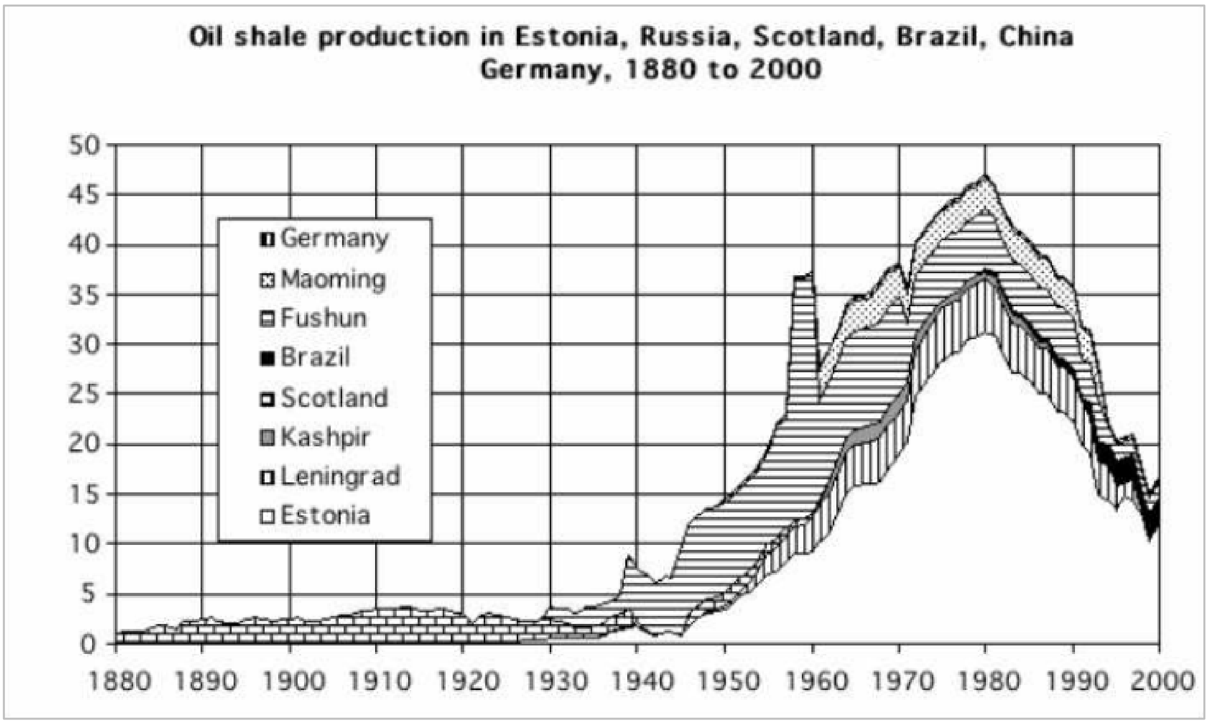

Figure 1. Oil shale production in different countries 1880-2000, millions tons [2].

Despite of negative forecasts for oil shale sector in 80s-90s, production of oil shale started to grow again in the beginning of 2000s as it can be seen from the Figure 2. In 2004 new Põhja-Kiviõli mine was opened. It was the first new oil shale mine opened in Estonia in 30 years. Two more mines were open in the period between 2005 and this day.

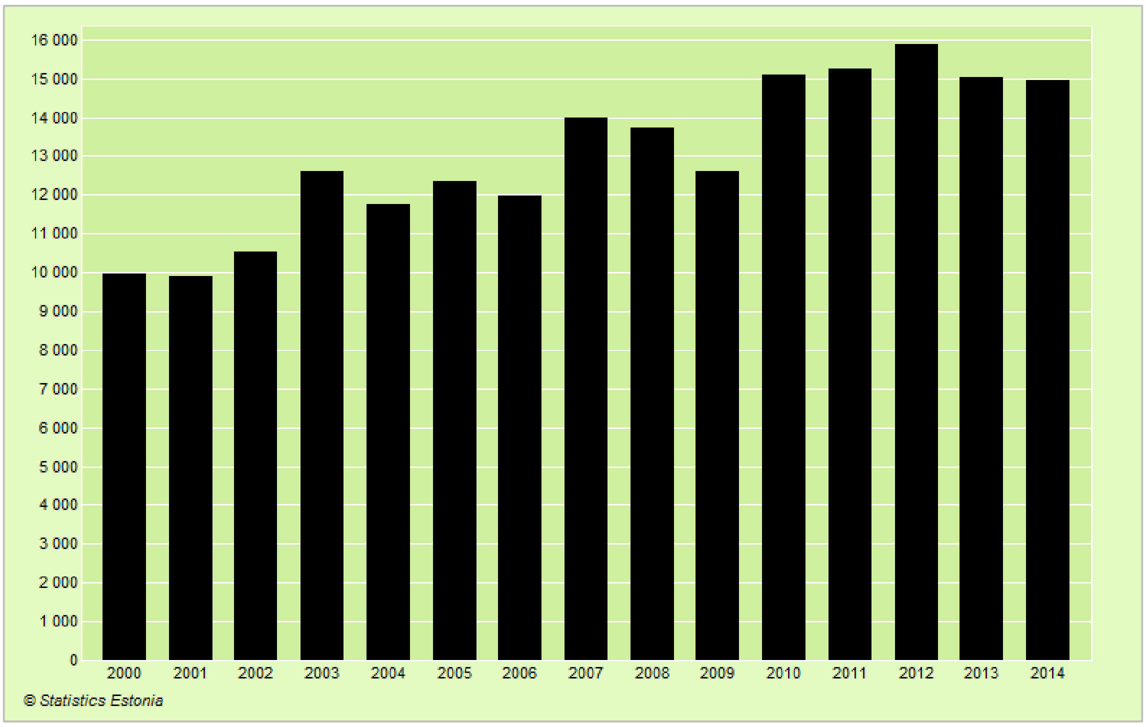

Figure 2. Oil shale production in Estonia in 2000-2014, thousand tons [3].

Oil shale always was the main source for electricity production in Estonia making it almost energy independent country and the net exporter of electricity. Energy dependency rate of Estonia is the lowest in EU second lowest in the European Economic Area after Norway which is having abundant water, oil and gas resources (Figure 3). Low energy dependency is certainly a positive aspect for any country but as it will be shown in the next chapters can also bring some problems.

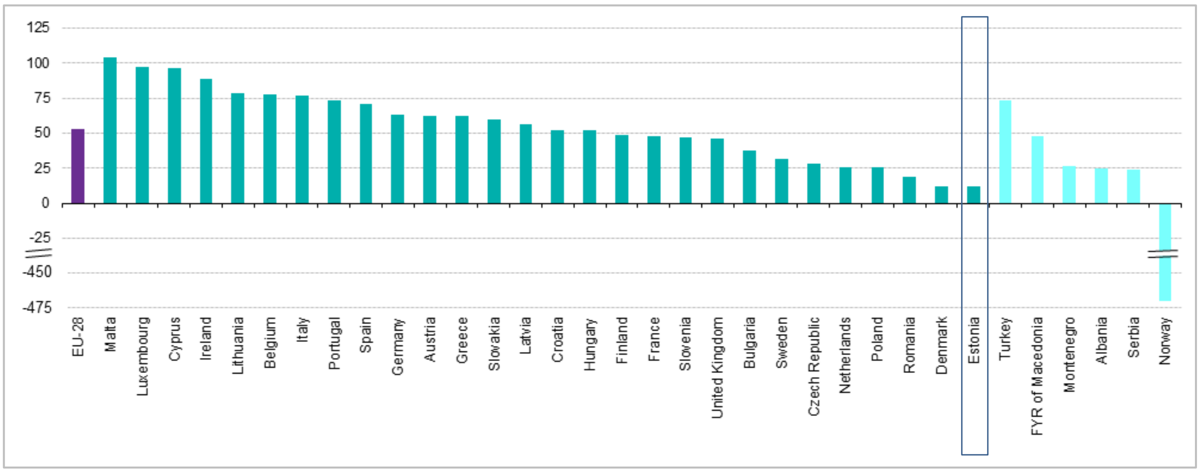

Figure 3. Energy dependency rates in Europe as of 2013 [4].

2.1.2. The position of Estonia in the European energy system

Nowadays Estonia has enough generation to cover its consumption peaks. Nevertheless it has also good interconnection with neighboring countries. Until 2016 when NordBalt connection was put into the operation, Estonia was basically acting as a corridor between Nordic and Baltic electricity markets. This was especially important for Latvia since this country in contrast to Estonia has the energy deficit. The map of Nordic power system can be seen in the Figure 4 (numbers on the map are representing lines capacities at 00:00 on the 9th of October 2016).

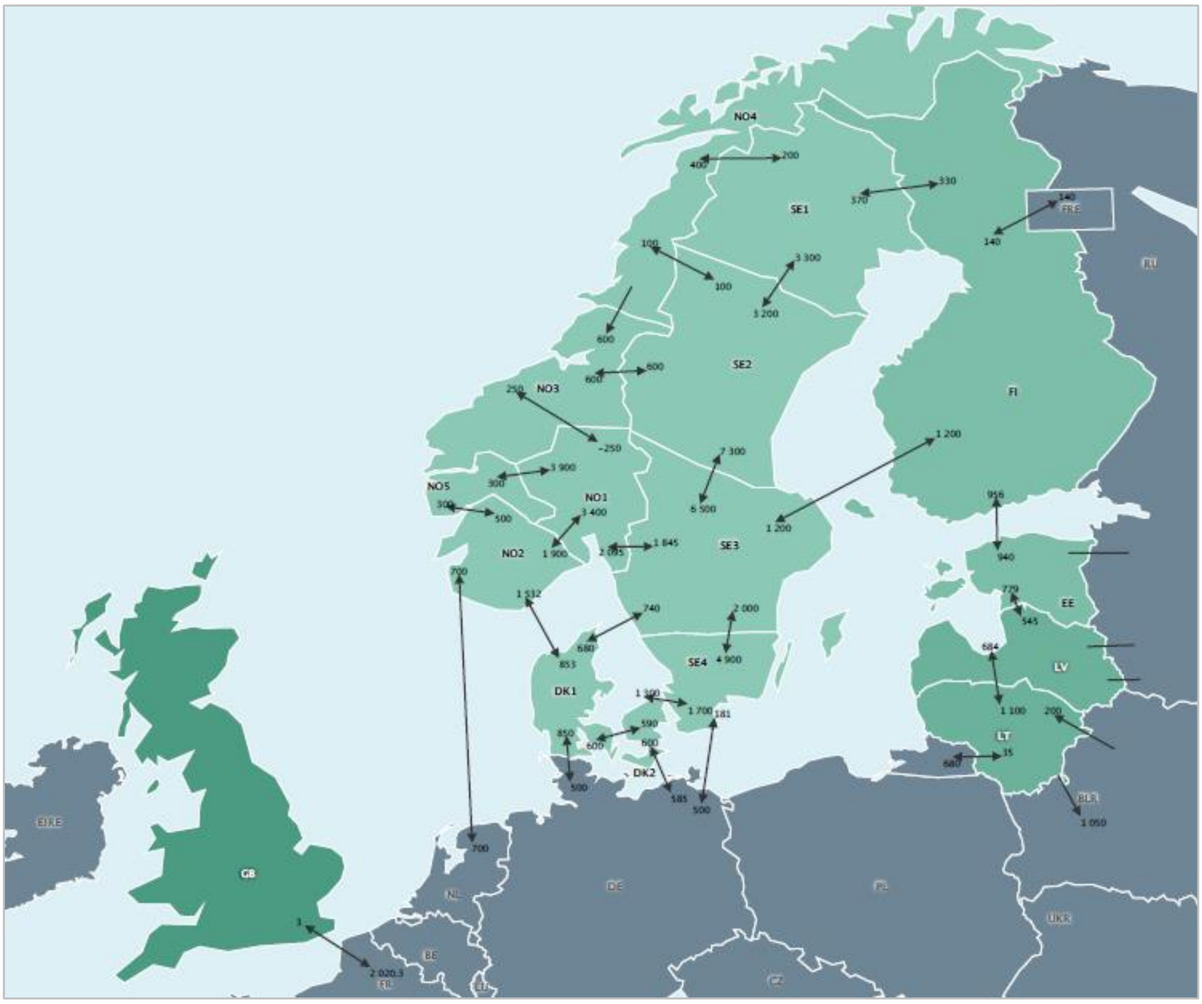
Figure 4. Nord Pool market map [5].

2.1.3. The development of RES in Estonia

As it was mentioned before, oil shale is a corner stone of Estonian energy system and this situation didn't change during recent years when most of the developed countries started implementing measures to fight with global warming. Starting from 1990 the share of solid fuels in gross inland consumption in Estonia was varying in the range between 55% in 2005 and 2006 and 66% 1992. Starting from 2005 it started to grow reaching 65% in 2014 (Figure 5).

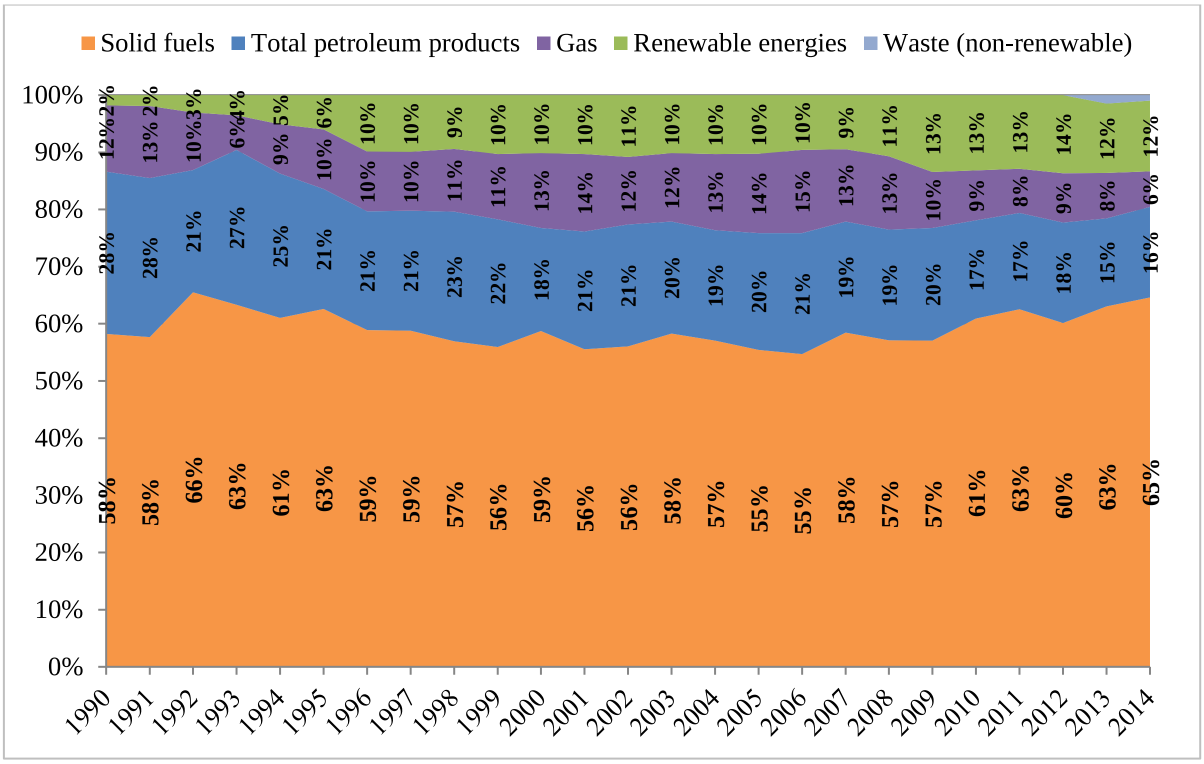

Figure 5. Dynamics of gross inland consumption by fuel type in Estonia (without electricity export) [6].

As it's possible to see from the figure above, renewable energy share in Estonia is growing although this growth happens not by cutting solid fuels but rather petroleum products and gas consumption. This is another interesting characteristic of Estonian energy system development which was possible due to a large number of CO_2 quotes delegated to Estonia by EU. This aspect is important for the future analysis and will be discussed more in the upcoming sections of this thesis.

Generation from the renewable energy sources in Estonia is showing a steady growth during the recent years as it is possible to see from the Figure 6. First wind turbines were installed in 2002 and this can be clearly be seen at the graph – before this year almost all renewable energy produced in Estonia was also consumed inside. Starting from 2002 export of renewable energy started to grow because of the intermittent nature of wind energy generation. In the modern wind turbines there is a possibility to curtail the production if it's needed but this wasn't possible before. It means that all wind energy produced should be settled in the market and when local demand is low it's possible to trade it to other countries.

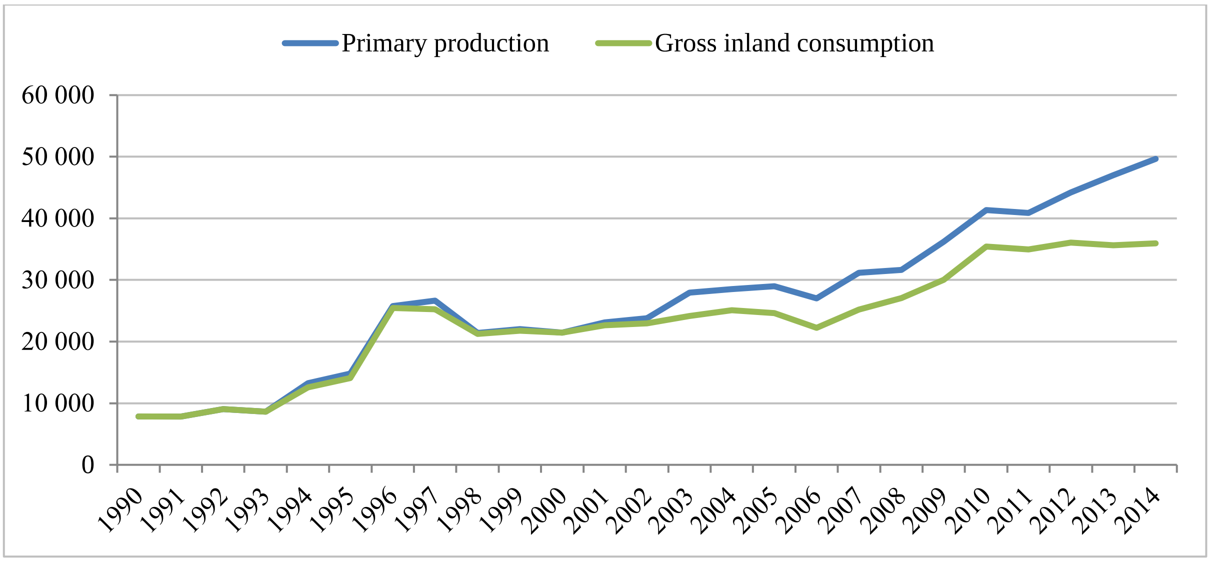

Figure 6. Energy production and inland consumption from renewable energy sources in Estonia, TJ [7]

It is interesting to observe that in fact starting from 2010 consumption of renewable energy in Estonia is not growing despite of increasing production and plateaued at ca. 35 600 TJ. The reason behind this is that Estonia joined Nord Pool Spot market in October 2010, first of Baltic countries. Being a part of a bigger energy market increased the liquidity and made cross-border trade simpler.

According to the Renewable Energy Directive by 2020 at least 20% of total energy consumption in EU should come from renewables. For every country in EU there was a national action plan created ensuring that targets will be reached. For Estonia the target was set at 25% of gross energy consumption. This objective was already met in 2011 and by 2014 the share raised to 26.5%. As of 2014 Estonia was one of just 9 EU countries already achieved their targets alongside with Bulgaria, Czech Republic, Croatia, Italy, Lithuania, Romania, Finland and Sweden [8].

In electricity generation the share of renewable sources in Estonia in 2014 was 14.8% with the largest share of biomass (8.3% of total generation) and wind (6.2% of the total generation) as it is possible to see from the figure below.

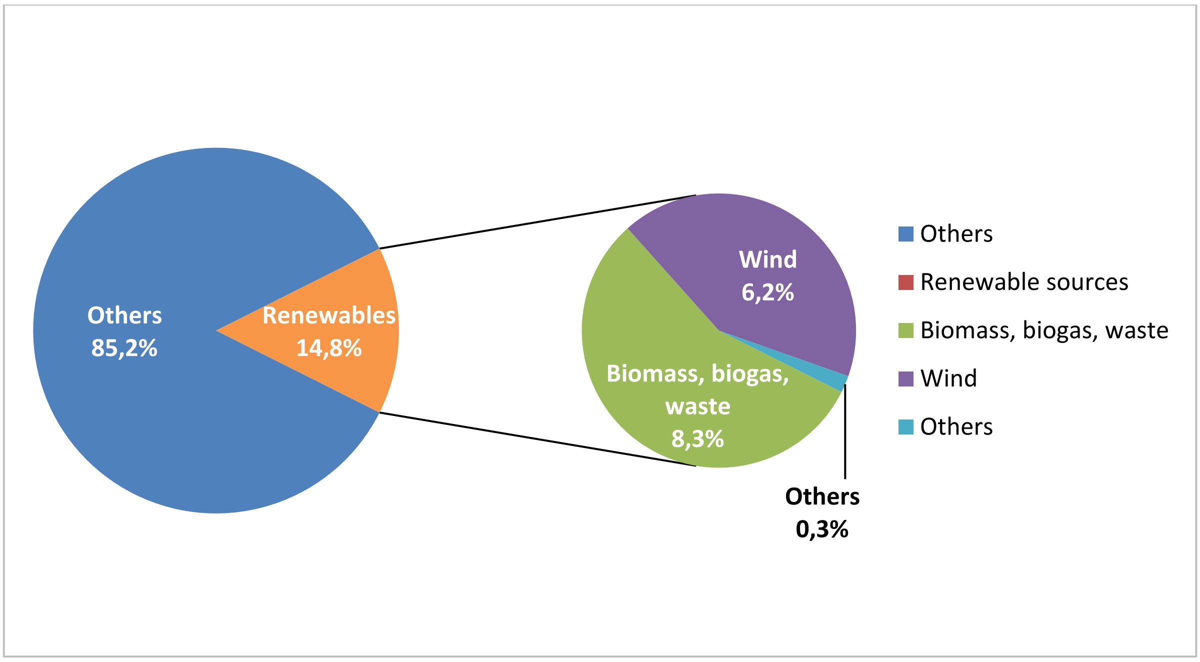

Figure 7. Energy production from renewable energy sources in Estonia, TJ [9]

2.1.4. Electricity and heat consumption

The general development trend is different for electricity and heat consumption in Estonia. Figure 8 shows the dynamics of energy consumption starting from 1960.

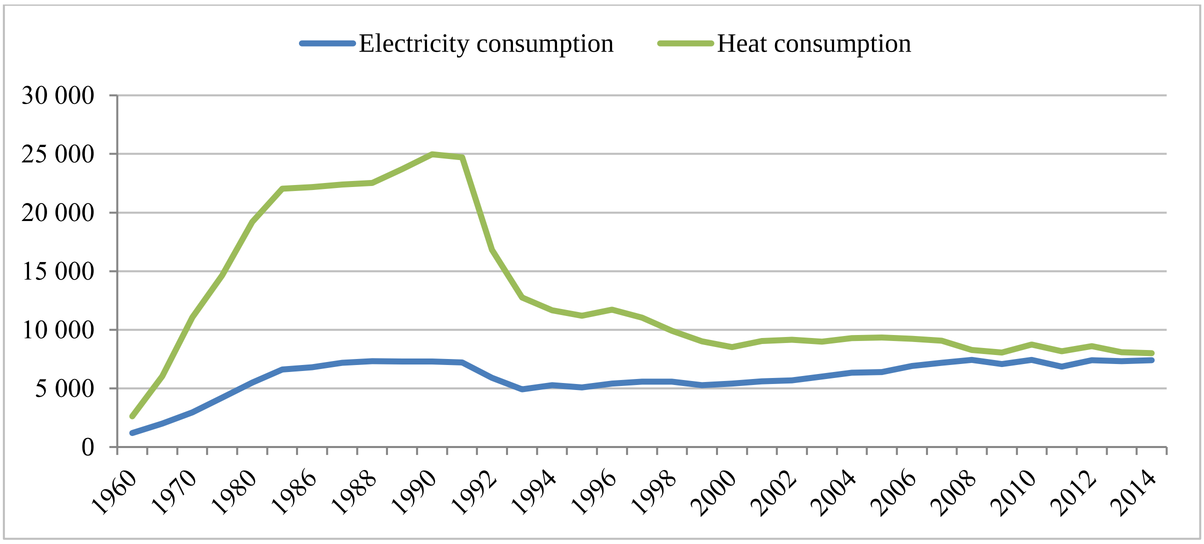

Figure 8. Electricity and heat consumption in Estonia, TWh [10,11]

After the collapse of the USSR many energy consuming facilities were closed and both electricity and heat consumption experienced a major drop. Heat consumption continued to gradually decrease after this moment having its minimum in 2014 at 8 015 GWh. This reduction is caused by energy saving measures and renovation of buildings in residential sector where Estonia is having a major problem with energy efficiency. Old buildings which were built during Soviet era are poorly insulated and in need for renovation. Another big problem was hot water consumption. In the 70s and 80s it was about 95L per person per day [12]. In 90s a major renovation of domestic hot water network was conducted and water meters were installed. These measures lead to a dramatic decrease in hot water consumption (more than three times between 1974 and 2004 [12]) and as a consequence to the total reduction of heat consumption.

In contrary electricity consumption was growing starting from 1993 and in 2014 was 7 414 GWh - higher than in the USSR era. Starting from 2008 electricity consumption finished the period of stable growth and is fluctuating around 7 277 TWh.

2.2. Challenges for Estonian energy system

As it was mentioned before, oil shale is a main source of energy for Estonia and this sector is developed better than any other because of rich history of oil shale mining. Although big resources of oil shale are ensuring Estonian energy system independency from other countries, it is also causing certain problems especially in the light of raising awareness about global warming.

Oil shale is not an optimal source of energy because of its low calorific value (8.6 – 11.5 GJ/t), which is more than three times lower than the one of coal. At the same time oil shale has higher CO_2 emissions per TJ of energy produced [13]. As a consequence energy production from oil shale has low efficiency and leads to extensive mining. Inefficiency of the current system can clearly be seen from Sankey diagram (Appendix VII). More than 26% of total energy inputs (2 156 ktoe from 8 173 ktoe) are being lost.

According to World Bank statistics, Estonia is at the second place in the world in CO_2 emissions from solid fuel consumption share in total country CO_2 emissions after North Korea (Figure 9). In 2011 86% of CO_2 emissions in Estonia were due to burning of oil shale. The average European level during the same year was 25%.

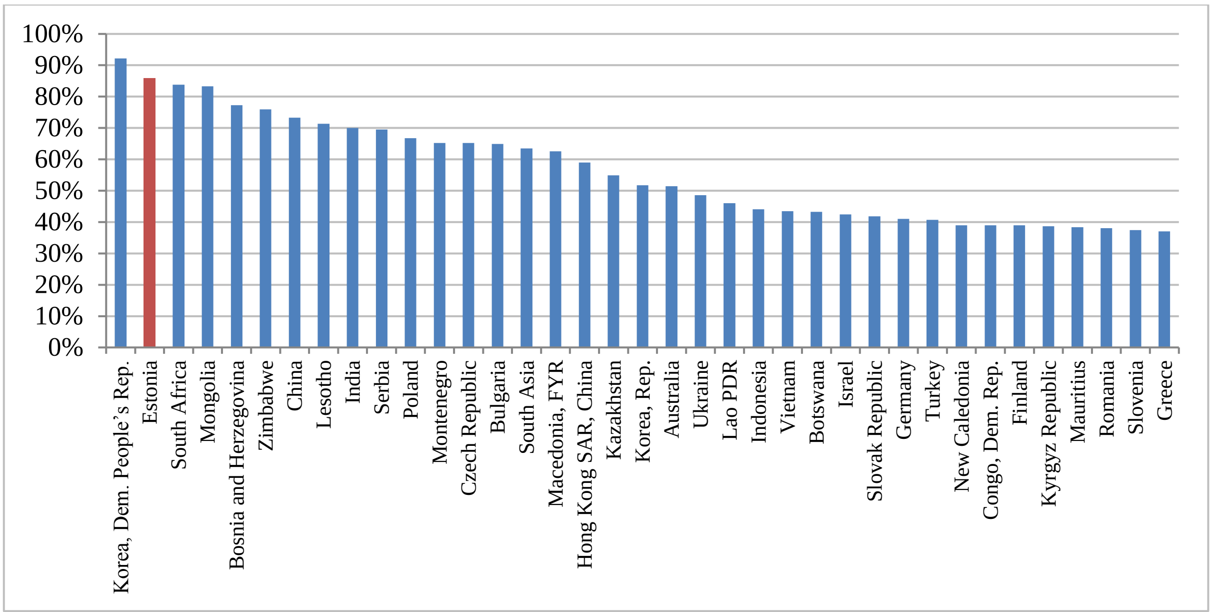

Figure 9. CO_2 emissions from solid fuel consumption (% of total) [15]

Estonia also has the second biggest CO_2 emissions level per capita in EU after Luxembourg with – 15.1 tonns CO_2 per capita in 2013 (Figure 10). Only fifteen countries in the world for which the data is available were generating more CO_2 per capita than Estonia.

Figure 10. Map of CO_2 emissions per capita in Europe (metric tons) [85]

Currently CO_2 prices are really low and Estonia had big CO_2 quotas and thus the stimulus to improve the situation wasn't strong enough. During the next years, though, it is expected CO_2 price to go up reaching double digits in 2018 [16]. It is also possible to expect new measures from EU in order to keep climate change under 1.5 °C above pre-industrial levels as defined by the Paris Agreement [17]. Above mentioned facts are suggesting that oil shale generation will be phased out in upcoming years. Forecasts from Estonian long-term energy strategy are supporting this suggestion showing that the generation from oil shale will steadily decrease in all scenarios (Figure 11).

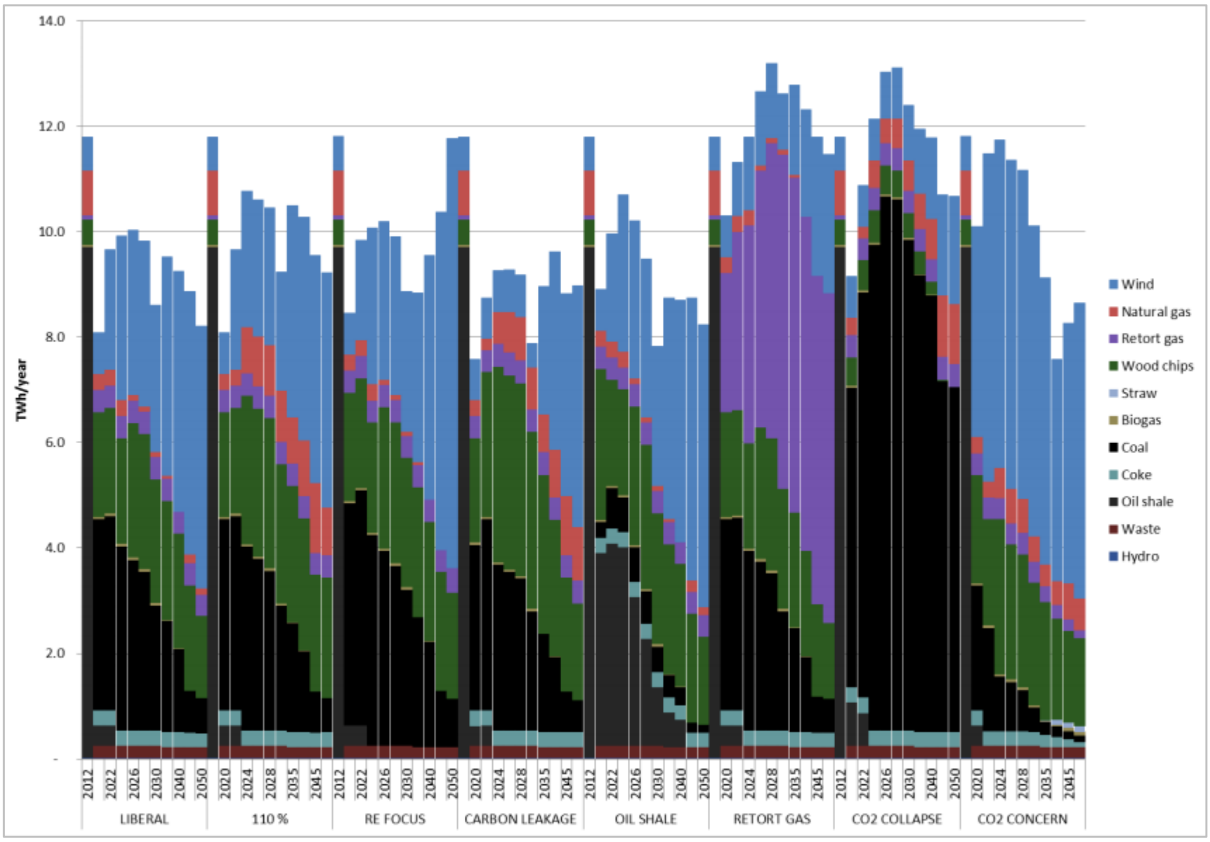

Figure 11. Long-term energy scenarios for Estonia [18]

These scenarios were developed as a part of Estonian long-term energy strategy developed by joint effort of Ministry of the Economic and Communication, Ministry of Environment, Elering, Enterprise Estonia, and Estonian Development Fund. The scenarios are describing the different ways of Estonian energy system development until 2050 and were simulated using BALMOREL model. The eight scenarios under consideration are:

- Liberal market: perfect electricity market, medium-level CO_2 prices, investments in generation and transmission from 2020 and 2026 respectively

- 110%: liberal market but there is always a local capacity which is enough to cover peak demand of Estonia
- Renewable energy: transition to 100% RES in Estonia by 2050
- Oil shale: oil shale is available at minimal (mining) costs. Other scenarios are using higher price levels (opportunity costs) for oil shale.
- Retort gas: gas from oil shale production is used for generation
- CO_2 market collapse: zero CO_2 price
- CO_2 concern: high CO_2 price – 100 EUR/ton in 2050
- CO_2 leakage: zero CO_2 price in Russia

In most of the scenarios oil shale consumption will be cut to zero by 2025 (Figure 12). Even in the scenario where oil shale is available at mining costs, the oil shale will be phased out by 2045.

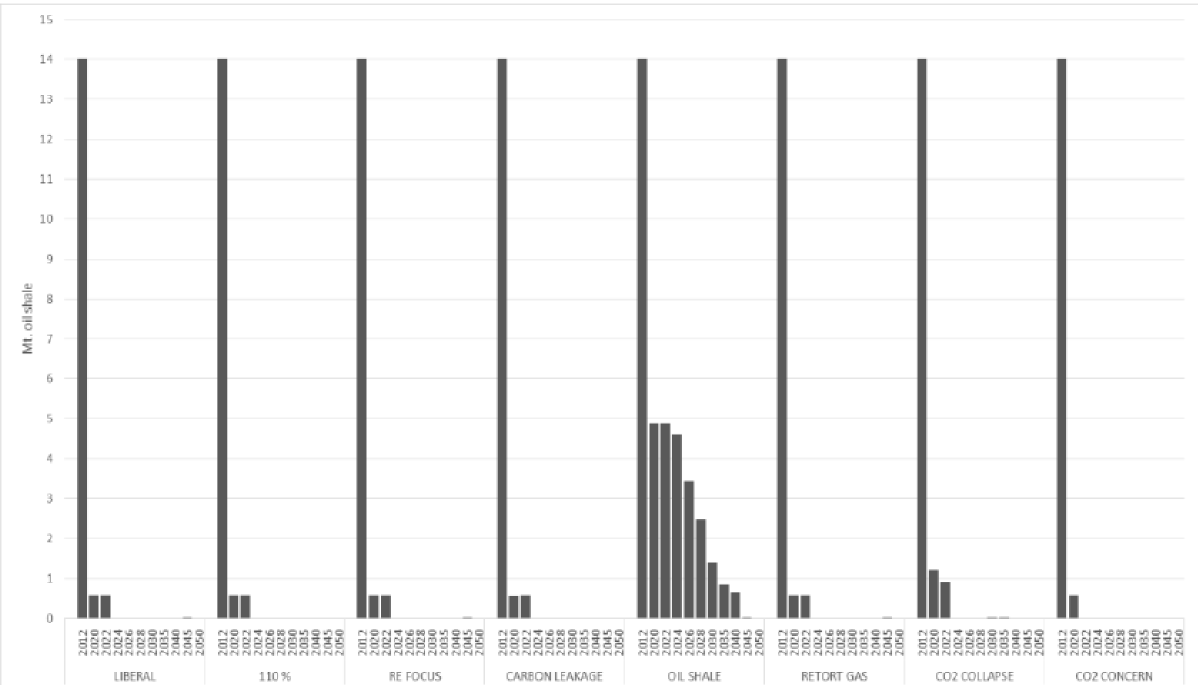

Figure 12. Oil shale consumption for electricity and heat generation in long-term energy scenarios for Estonia (million ton) [18]

Phasing out of oil shale is a big challenge for Estonia. Oil share generation is a major contributor to Estonian energy balance and has many developments due to the reach and long history. Another problem is that oil shale is very important for economics of some areas of Estonia where it creates many jobs. In particular this is a concern for Ida-Viru County. The average income level in this county is one of the lowest in Estonia thus there should be some measures ensuring that changes in energy system won't cause sufficient damage.

One of alternative ways to use oil shale is producing of oil and gas from it which will help to cut emissions while keeping mines in operation. This way is also more energy efficient compared to burning in power plants making it possible to utilize about 66% of primary energy (Figure 13) of oil shale. One of the drawbacks of this method is that it's very sensitive to oil prices and can hardly be feasible with the current level in the market.

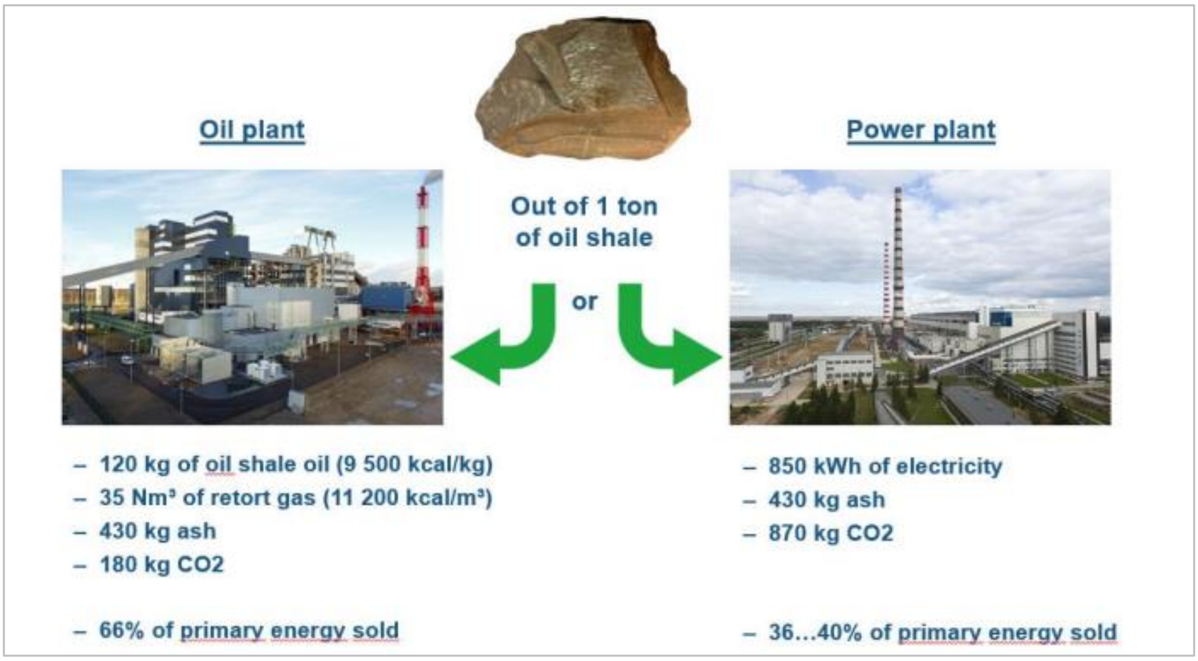

Figure 13. Different ways of oil shale use [19]

Switching to gas generation is another possibility of cutting CO_2 emissions and replacing oil shale. Gas turbines are also more effective and can change output quickly – an important fact for energy systems with a large share of renewable sources. The problem in this scenario is that 100% of gas consumed by Estonia is coming from Russia [19]. Sufficient increase in generation from gas will lead to increase in prices and energy dependency from Russia putting Estonia in the situation many countries are trying to avoid nowadays. It might also be hard to find investors willing to spend money on new gas power plants. The price of gas is relatively high compared to coal or oil shale. The carbon prices are also fluctuating near the minimum values. In such conditions gas-powered power plants are struggling with finding free money to cover their fixed costs.

As it was shown before, the share of RES in energy mix of Estonia is growing each year and will continue to develop. There are several problems associated with integration of renewables as it will be explained in the next section.

2.3. Additional requirements to energy system raising from renewable energy integration

Some of renewable energy sources such as solar, wind, wave are intermittent by the nature. Integration of these sources in any energy system is a challenge and the larger the share, the bigger is this challenge. There are many aspects needed to be taken into account when RES are introduced:

- Renewable energy sources need balancing
  Output of renewable energy sources is inconsistent and sometimes cannot be well predicted. In order to maintain stability of the system it is necessary to have generation with a quick response. Balancing needs are also raising price of energy.
- Energy market should have a right design
  Not all market designs are equally good integration of renewables. Market should give right signs to participants and equality should be ensured. For renewable energy sources there should also be some incentives.
- There should be enough interconnection capacity/storage capacity
  Electricity production from intermittent energy sources and demand cannot be synchronized. There will be some periods when there will be really low demand and high production from renewables. Curtailing will mean loosing of energy and should be avoided which could be done by using different types of energy storages or by external balancing if system has good interconnection.
- Top-notch forecast tools are needed
  Errors in forecasts are increasing energy prices and put additional stress on the system and thus should be minimized.

All above mentioned concerns are attracting a big attention from research community around the world. Literature review section of this thesis is aimed to present some of the recent developments in this field.

3. Literature review

The importance of renewable energy is evident. In the light of increasing concerns about climate change and global pollution, installation of RES is one of the main ways to change the situation. Wind energy reduces CO_2 [20], SO_2 and NO_x [22] emissions. Another positive effect is a decrease of system's operational costs though forecast errors can lower this effect [23]. Many studies has shown negative relation between wind energy share and system prices e.g. [24,25,26] although some authors were arguing that exact effect will depend on the structure of the market and prices are more likely to decrease in case if there are many firms and/or if ownership of wind turbines is diversified and not concentrated in the hands of one company [27]. Among other positive effects can be mentioned decreasing of energy dependency [28] and increase in system reliability [29].

Intermittent nature of RES is one of the main technological and economic challenges for integration into the system. Need of balancing reserves is increasing system costs as it showed in e.g. Ref. [30]. Exact numerical effects of RES integration costs are varying in different studies because there is still no single framework for calculating them. Hirth et al. [31] made an outstanding work analyzing results of more than 100 different integration studies and created a new framework for costs estimation. Their finding was that at wind penetration levels around 20-30% integration costs might be around 15-25 €/MWh with about two thirds of these coming from wind profile costs representing marginal costs of variability of RES output. The reason behind this is that with the increasing share of RES, the utilization rate of the thermal capacity is declining which leads to the increase of the specific capital costs. Moreover, the increasing share of VRE leads to curtailment during negative residual load and the capital costs of VRE generation are increasing.

Introduction of intermittent energy to the system has a great impact on conventional generators operating there. Because of lower price, renewable energy sources are displacing more expensive non-VRE plants leading to reduced utilization of the latter [49,50]. Although due to the change of the load profile caused by variability of VRE sources, some of flexible units as for example gas turbines might experience increased utilization [51]. While the utilization of conventional plants is decreasing, it's not possible to replace a large amount of generation by it due to the low capacity credit [50]. Increased variability is also leading to increasing costs of cycling and start-ups of power plants and increase emissions [49,52]. Cycling growth could lead to increased outages and depreciation of conventional plants [53].

The influence on cycling of power plants can be reduced by increasing interconnection availability [53].

Market design has a great influence on how system with a large share of RES is operating and on total costs. Chaves-Ávila et al. [32] compared different designs of balancing markets in Belgium, Denmark, Germany and Netherlands. It was shown that Dutch market design where wind power producers are fully responsible for their imbalances and single pricing imbalance settlement is used is "more robust" compared to other countries. Other authors are also considering one-price system as an optimal [33]. In this article there are also several recommendations for optimal design of balancing market: "the imbalance settlement should not contain penalties or power exchange prices, capacity payments should be allocated to imbalanced BRPs via an additive component in the imbalance price and a cap should be imposed on the amount of reserves" [33]. As forecast errors of wind generation are decreasing with prediction horizon [34], moving gate closure time closer to the actual delivery time would improve market operation and reduce balancing costs [25]. Intraday markets can also reduce integration costs of intermittent energy sources [32] although at the current moment liquidity of these markets is low [35]. Two-price system for imbalance pricing (currently used in Estonia) is considered to be one of the reasons causing low liquidity of intraday market [35]. Higher scheduling resolution is another possible change in market design which can help to reduce regulation reserves need [48].

Forecast tools question is closely connected to the market. Better forecast quality improves market operation and reduces costs [23]. Improving existent tools and creating new ones is one of the possible approaches to the problem. There is a wide body of literature suggesting different forecasting models for short-term e.g. Refs. [36-41] to mid-term e.g. Refs. [36, 42-44]. Some studies made an attempt to combine and review available methods e.g. Refs. [45-47]. Apart of improvements in models themselves there several other possibilities to decrease forecast errors. As Luickx et al. [23] stated in their article, moving gate closure time from 36h ahead to 3h ahead would improve the prediction accuracy by 100%. Increasing forecast area would also lead to sufficient improvement in forecast accuracy [34].

Energy storage is playing a big role in the integration of renewables and attracting more interest as share of RES is increasing. There are many energy storage technologies available: pumped hydro, flywheels, compressed air, batteries, hydrogen, superconductors and supercapacitors. There are many article reviewing these technologies and their characteristics available e.g. Refs. [54,55]. Among other possibilities for energy storage it should be mentioned that electric vehicles could also act as a distributed energy storage. Although at the moment this technology is not developed enough. Increase of transmission capacity could be an alternative to energy storage [56] but the choice of optimal solution is varying for every particular case.

Modeling of energy systems can help to understand how they're operating in the light of described above challenges, how flexible it is, find bottlenecks, estimate a potential for RES integration and more. The number of products for energy system modeling is vast. Connoly et al. [57] made a good overview of 37 tools. Based on this overview it's possible to say that EnergyPLAN [58] tool is a suitable candidate for the purposes of this thesis. EnergyPLAN was widely used for modeling of RES integration in different energy systems including Italy [59], Finland [60], Norway [61], Ireland [62], UK [63] and many others. There are also some country models available for free download although there is no Estonian model existent. EnergyPLAN was used before to model RES integration into Estonian energy system and possibilities of CHP balancing as a part of DESIRE project [64] but the model created was not made publicly available and the project itself took place about 10 years ago therefore both the tool and the system under consideration has changed dramatically.

4. Methodology

This chapter is aimed to provide the necessary information regarding tools and methods used in the thesis. First part of the chapter is a description of different modeling options available and the one which was chosen for this work. The next part is describes two cornerstone parameters for the modeling of energy systems with the large share of RES: CEEP and MREI. These parameters are vital for the understanding of the modeling scenarios and sensitivity analysis in this thesis. The last part of the chapter describes the methodology used to model the heating demand of Estonia – heating degree days methodology.

4.1. Comparison of modeling tools

The comparison of different modeling tools is presented in Appendix I. EnergyPLAN software was selected for the purposes of this thesis.

4.2. EnergyPLAN description

EnergyPLAN energy system modeling software continuously developing from 1999 and currently having version 12 made available in January 2015. It is free software and both the tool and documentation are freely available for download at www. Energyplan.eu. It was developed by prof. Henrik Lund in Aalborg University.

EnergyPLAN is a tool providing hour-by-hour simulation energy system for a period of 1 year or 8784 hours. The high resolution makes it a proper tool for analysis of fluctuating energy sources and enables it to observe seasonal changes in the system. It's important to mention here that EnergyPLAN is a deterministic model opposed to some stochastic models. It means that it will give the same results with the same input all the time. For analysis of renewable energy sources it means that some effects couldn't be estimated using this tool (e.g. increasing costs of balancing) although there are many study cases showing that this is not a big limitation.

There are two different optimization strategies implemented in EnergyPLAN – technical and market-economic. If technical strategy is used, EnergyPLAN seeks to minimize total fuel consumption and as a consequence CO_2 emissions. In market-economic strategy implies that all market parties are trying to maximize their profit and the tool is looking for the least expensive configuration. If market-economic strategy is enabled, there is a possibility to introduce external energy market and make EnergyPLAN to calculate the interaction between it and system under consideration. The one limitation here is that there is no possibility to create more than one energy exchange corridor while in reality in most of the cases there are several. Market-economic strategy also implies that costs should be specified in order to estimate marginal prices of energy.

The energy model used in EnergyPLAN is a very complex one. EnergyPLAN is using aggregated numbers as inputs instead of describing every plant separately. The structure of used energy model is shown in Figure 14.

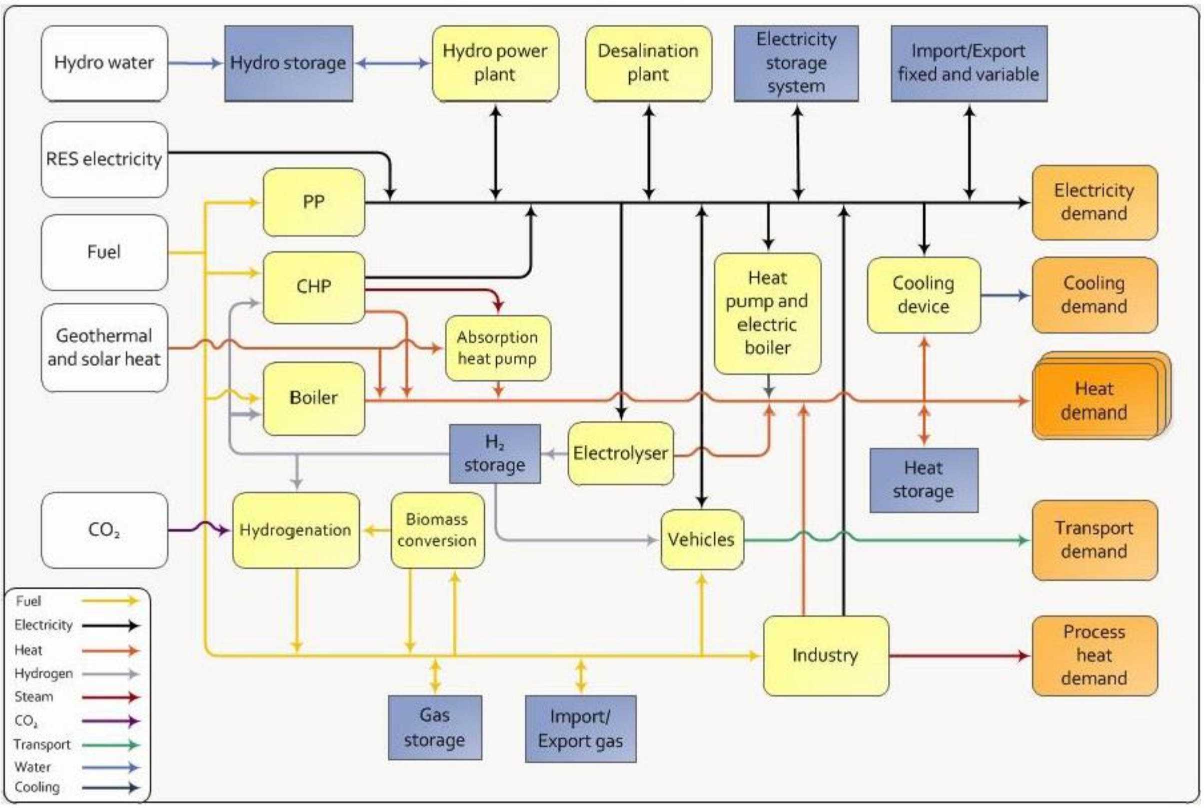

Figure 14. Energy system as it is described in EnergyPLAN model [58]

EnergyPLAN is an analytic programming tool which makes it very fast compared to other tools based on dynamic programming, iterations etc. A calculation of an energy system of a whole country takes just some seconds.

EnergyPLAN is a step-by-step tool. First all necessary inputs should be specified based on the strategy used for analysis. At this step EnergyPLAN is already doing some small calculations e.g. production from RES based on their distribution profile and capacity and some others. At the second step calculations not involving balancing are being made. The next step depends on which strategy is used and will either be technical energy system optimization or market-economic energy system optimization. The last step includes final outputs calculation: critical excess in electricity production (will be described in details in the next sections), CO_2 emissions, fuels and costs. This structure is presented in Figure 15.

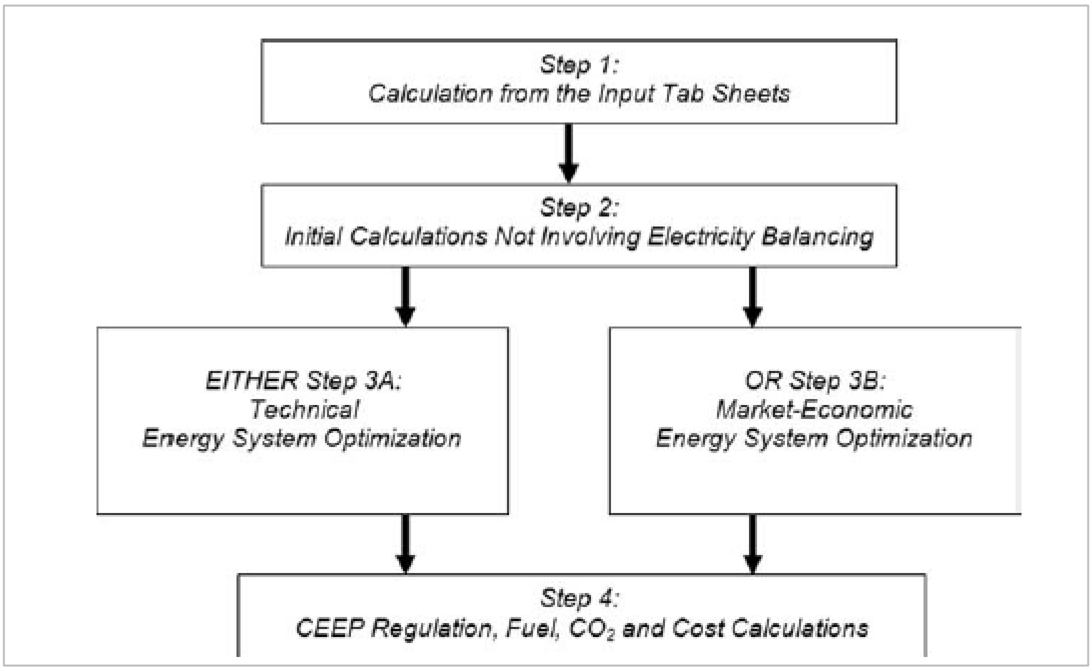

Figure 15. EnergyPLAN energy system analysis steps [58]

4.3. Critical excess electricity production (CEEP)

One of the key parameters defined in EnergyPLAN tool is so called critical excess electricity production or CEEP. This parameter was introduced in 2001 by the expert group formed by the Danish Energy Agency for the project aimed to create strategies for managing of excess electricity production from RES and CHP in Denmark [86]. CEEP is a software-specific parameter and is used in studies which utilizing EnergyPLAN software for the modeling purposes.

CEEP is amount of produced electricity which cannot be exported under current limitations on interconnection capacity. In reality this situation is impossible and will lead to the collapse of the system. Although in real life this will never happen, the magnitude of the effect is a good indicator of RES sources' influence. There are different strategies of dealing with CEEP implemented in EnergyPLAN:

1. Reducing RES in first two specified groups (in total EnergyPLAN allowing up to four different RES sources groups)
2. Replacing CHP in group 2[1] with boilers
3. Replacing CHP in group 3 with boilers
4. Replacing conventional boilers in group 2 with electric boilers

[1] In EnergyPLAN group 2 represents the systems with small CHP plants which are always operating with a heat load and group 3 - systems with large CHP which can generate electricity without the need to produce heat.

5. Replacing conventional boilers in group 3 with electric boilers
6. Reducing RES in third and fourth groups specified
7. Reducing power plants production together with RES sources
8. Increasing of CO_2 hydrogeneration (in case if it's applicable)

All these options can be implemented together in a consequence defined by user. In the case of Estonia, the main way the energy system managing possible excess electricity production is reducing RES sources and/or reducing of power plants production.

Here is a small thought experiment to show how CEEP works. Let's say we have a simple system consisting of a 50 MW power plant operating as a base load and wind turbines with a total installed capacity of 50 MW. The system is connected to the neighboring one with a line of 20 MW capacity. The demand during some hour is 70 MW. In such system with a large share of VRE there always will be some uncertainty connected to the wind generation. If during this hour wind turbines will produce 20 MW of electricity, then together with the base load they will cover the demand. If we will have 20 to 40 MW of electricity from wind, part of it will cover the demand and the extra amounts can be exported (for the simplicity we assume that the neighboring system is always buying the excess electricity up to capacity of the interconnecting lines). But if it will be a very windy hour and wind turbines will produce more than 40 MW, we will have the excess which cannot be consumed or exported – CEEP. In this case the system will be forced to curtail some of wind energy or power plant production which will lead to operational challenges, decreasing profits and increasing costs. From this simple example it is possible to see why CEEP is a good and important indicator of the performance of systems with a large or increasing share of RES.

4.4. The maximum share of RES in the system

There are different methods of calculating the maximum share of RES in energy system used by different authors. Henrik Lund – the creator of EnergyPLAN tool – suggests described above parameter of CEEP as the main indicator of energy system's flexibility and adaptability. Although one important moment here is that CEEP itself doesn't show the interplay between external market and system under consideration. It's important to have a parameter which will show the influence of excess electricity on the system. In case if market-economic strategy is chosen the most important aspect is a total costs. For the purposes of this thesis the methodology introduced by Zakeri et al. [60] was adapted. This methodology is based on the indicator named MREI (Maximum Renewable Energy Integration) [60]. The way of calculating it is presented in the equation below:

$$MREI = \frac{total\ benefits\ of\ added\ RES}{total\ production\ of\ added\ RES} = \frac{\Delta PFC + \Delta NPE}{\Delta RES} \left[\frac{TWh/a}{TWh/a}\right] \quad (1)$$

Where total benefits of added RES are calculated as a sum of reduction in fuel consumption (ΔPFC) and changes in power exchange (ΔNPE) divided by increase in RES production (ΔRES) [60]. Levels of MREI ≥1 are considered to be acceptable levels of RES integration and MREI = 1 is considered to represent a maximum level of RES integration [60].

4.5. Heating degree days methodology

EnegryPLAN is using hourly data for heat and electricity consumption on a country scale and while electricity consumption is monitored and available online, hourly heat data is not easy to estimate. The method used in this thesis is called "heating degree days".

The main idea of the method is that when outside temperature is below some particular number, there is no need for space heating in the building. This temperature is a base temperature and is connected to comfortable inside temperature. The temperature inside of a building is always some degrees higher than outside due to free heat. This difference is varying from building to building but on average is around 3 degrees. European Energy Agency (EEA) has a methodology for calculating heating degree days (HDD) and using the next equation [66]:

$$HDD = \begin{cases} (18℃ - T_m) * d, if\ T_m \leq 15 \\ 0, if\ T_m > 15 \end{cases} \quad (2)$$

Where T_m is an average temperature during a giving period of days. The heating consumption will be proportional to heating degree days. EEA is monitoring this value only at monthly and yearly scale. In order to use it in EnergyPLAN, hourly data is needed. For the purposes of this thesis HDD days were calculated using Eq. 2 but on hourly scale. The local climate and thus heating degree days value is different for different parts of Estonia. The research conducted by Loigu et al. [67] in Tallinn University of Technology in 2006 showed that Tallinn's HDD numbers can be seen as average for Estonia. Hourly temperature data was obtained from Estonian Weather Service web page [68] using a macros[2] specially written for this purpose. It was assumed that during summer months there is no need for space heating regardless the outside temperature. Additional information on heating demand calculation will be given in the next section describing EnergyPLAN model's inputs.

[2] Excel macro is a computer code written using the Visual Basic for Applications language

5. Estonian energy system model for EnergyPLAN

This chapter describes the creation and validation of the EnergyPLAN model for Estonia which was later used in this work for the analysis of different RES integration scenarios.

5.1. The model creation

As it was mentioned before, there is no model for Estonia available for download in open sources. For the purposes of this thesis it was created from the scratch using available data. The last year for which Statistics Estonia is providing full data is the year 2014 (at the moment when works on this thesis were conducted). This year was chosen as a base year for model creation.

The detailed explanation of all inputs necessary to create the model is provided in Appendix II. The order of the chapters there is the same as EnergyPLAN software uses which is making it easier to follow the logic of this work. All the sources and necessary links are provided there as well.

5.2. Validation of the model

In order to validate the model created, the outputs from it were compared to official data provided by Statistics Estonia. Table 1 shows a breakdown of different components of the electricity balance.

Source	Electricity production, TWh		Difference, TWh	Error, %
	Statistics Estonia	EnergyPLAN model		
Electricity only power plants	10.56	10.23	-0.33	3.1%
CHP	1.127	1.09	-0.037	3.3%
Energy from waste incineration	0.112	0.11	-0.002	1.8%
Renewable	0.63	0.61	-0.02	3.2%
Net export to Finland	-3.53	-3.53	0	0.0%
Net export to Latvia	6.28	5.88	-0.4	6.4%

Table 1. Comparison of the EnergyPLAN model output and Statistics Estonia data

Most of the outputs are below 4% and only net export to Latvia has a higher error. There are several different factors contributing to this error:

- The interconnection capacity between counties is not fixed and varies from hour to hour. This behavior cannot be implemented in EnergyPLAN.
- There is an interaction between the interconnection with Finland and the interconnection with Latvia which is cannot be modeled in EnergyPLAN

Consumption of different types of fuels in the model was also compared with official numbers of Statistics Estonia (Table 2).

Energy source	Annual consumption, TWh		Difference, TWh	Error, %
	Statistics Estonia	EnergyPLAN model		
Coal	35.12	34.42	-0.7	2.0%
Oil	11.56	11.72	0.16	1.4%
Natural gas	6.84	7.07	0.23	3.4%
Biomass	10.02	10.24	0.22	2.2%
Hydro	0.02	0.02	0	0.0%
Wind	0.6	0.59	-0.01	1.7%
CO_2 emissions*	19.237	17.99	-1.247	6.5%

Table 2. Comparison of fuel consumption in the EnergyPLAN model and Statistics Estonia data

For all fuels the error is well below 5%. It's possible to see that the model tends to decrease the consumption of coal (as it was mentioned before, category "Coal" for Estonia is mostly represented by oil shale). The possible explanation for this is that it tries to minimize CO_2 emissions.

CO_2 emissions were also compared. The number here was taken from [79] and not from Statistics Estonia because the last year available there is 2013. The reason behind this difference is that in this analysis the conversion of fuels in other types was not included. For Estonia it means that shale oil production was excluded from the analysis. The fuels conversion feature is not available in EnergyPLAN. Another possible reason is that emission factors used for calculations are different from the factual ones. The fact that consumption of oil shale was 2% lower than in reality also contributed to the described difference.

Overall the model produces good results and can be used for the further analysis.

6. Integration of larger share of renewable energy sources in Estonia

The purpose of this section is to analyze the possibility of integration of a larger share of renewable energy in Estonia, performance of the energy system under the new conditions and find an optimal share of RES. There will be six different scenarios analyzed – 4 dealing with wind energy and two analyzing increase in solar energy share.

6.1. Increasing share of onshore wind energy

For this scenario was assumed that installation of new turbines are scattered around Estonia and thus the distribution of hourly production will stay the same as described in Section 5 of Appendix II. This means that up scaling in energyPLAN is possible just by increasing existent input.

In order to find an optimal share, the methodology described in Section 3.4 was used. The production of wind energy gradually increased with 250 MW step. Figure 16 shows effects of the integration.

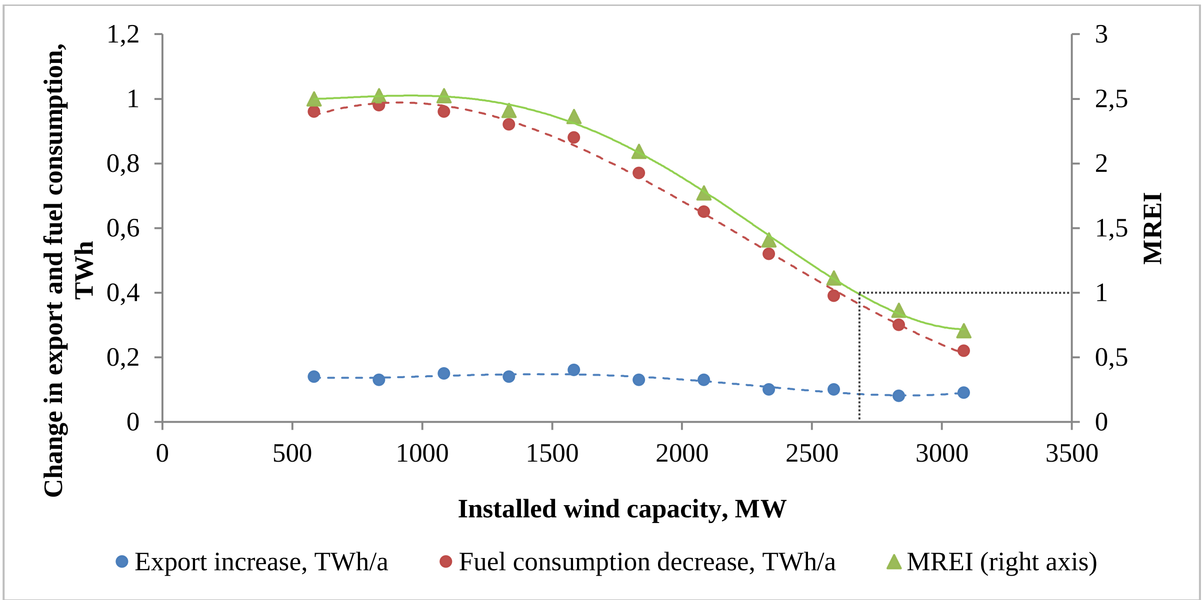

Figure 16. MREI and change in export of electricity and fuel consumption at different levels of installed wind capacity

The maximum installed capacity of wind energy in Estonia according to the methodology used in this thesis is approximately 2670 MW and corresponds to MREI index equal to one. Further increase of wind energy share won't lead to a proportional increase of benefits.

A decline of MREI after the installed capacity of wind energy reaches 1000 MW is caused by the fact that after this level some of wind energy will be curtailed due to low demand and/or insufficient interconnection lines capacity with Latvia. At 2670 MW of wind energy installed, 0.74 TWh/a of energy will be lost due to curtailment. This is approximately 15.3% from the total electricity production from wind – 4.85 TWh. The maximum level of hourly curtailment during the year is 1651 MW or 60% from the total installed capacity. The average hourly curtailment is 84 MW.

Installation of additional 2336 MW of wind energy will increase the total system operation costs[3] by €234 million per year. The fuel consumption will decrease and export of electricity will increase leading to reduction of the total costs although relatively cheap oil shale will be replaced by wind energy leading to higher investments and O&M costs. The price of CO_2 emissions is another factor influencing total costs. At the moment the price per ton of CO_2 is very small and predicted to grow. If we consider that it will grow from 6 EUR/t to 20 EUR/t, the total system operation costs will show slower growth rate with introduction of higher shares of wind energy. At this level of CO_2 prices, installation of additional 2336 MW of wind energy will lead to €203 million increase in total costs – €31 million lower than in the original scenario.

The total annual CO_2 emissions at the installed wind capacity of 2336 MW will decrease by 2.68 million ton while the share of electricity produced from wind will increase to 34.6%.

6.2. Increasing share of offshore wind energy

This scenario is different from the described above because here installed capacity won't be scattered along a big territory but concentrated in some specific spots. As it was mentioned before, distributed wind generation leads to a smoother electricity production profile. Introduction of a large offshore wind farm in Estonian energy system will mean that the amplitude of the wind energy variation will be higher. On the other hand, offshore wind farms have a higher capacity factor. The overall effect of these factors will be examined in this section.

Two different locations for an offshore wind farm will be considered – Gulf of Riga and a territory near Hiiumaa Island. These spots are being considered as potential offshore wind farm building locations by Eesti Energia and 4Energia.

First of all it's necessary to describe how inputs for offshore wind farm in EnergyPLAN were constructed.

[3] EnergyPLAN is using the following types of costs:

- Fuel costs: purchasing, handling and associated CO_2 costs
- Investment costs: capital costs and the interest rate
- Operation costs: operation and maintenance cost for the each technological unit in the system
- External electricity market: cost of electricity traded with the external market

6.2.1. Methodology of determining an offshore wind farm output distribution

In contrast to onshore wind energy, where EnergyPLAN inputs were taken from statistics, there are no currently operating offshore wind farms in Estonia and an hourly distribution of electricity output should be constructed using raw wind speed data.

In order to approximate an output of an offshore wind farm, hourly wind speed distributions for the year 2014 for the closest onshore weather stations were obtained through Estonian Weather Service archive [68]. For Gulf of Riga wind farm location the nearest weather station is Kihnu. For Hiiumaa the planned wind farm which will be located at several shallows, the data was obtained for two separate weather stations – Ristna and Osmussaare. Figure 17 shows two weather stations mentioned and considered locations for offshore wind farm building.

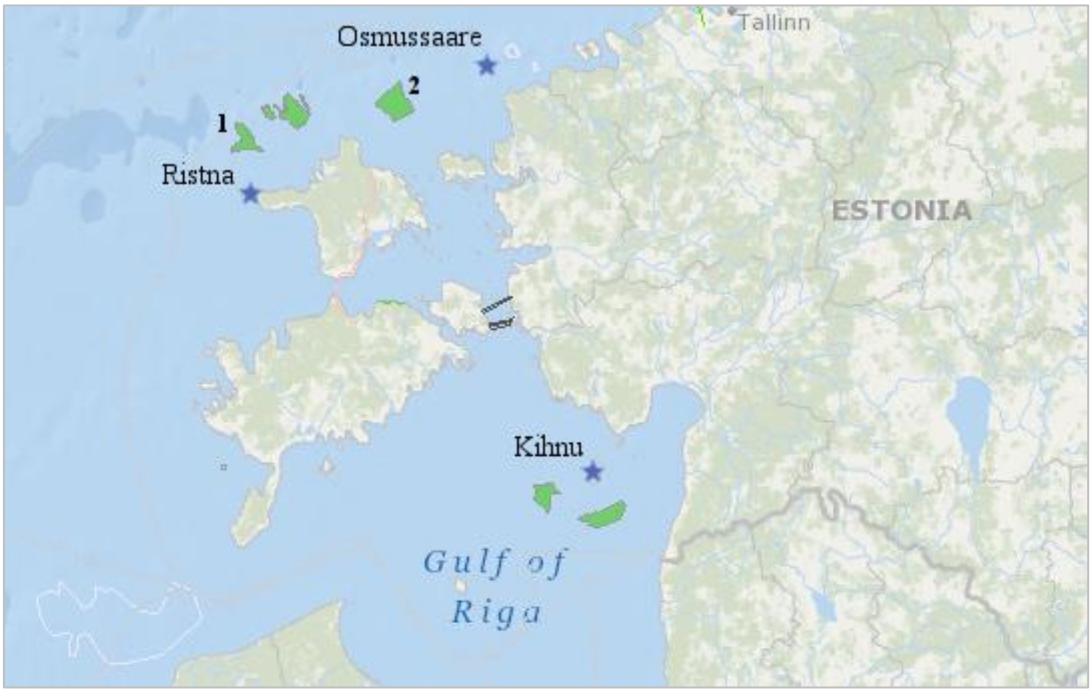

Figure 17. A map of potential offshore wind farms locations (filled green) [81] and nearest weather stations (marked with blue stars).

It's possible to see that weather stations are located close to locations of projected offshore wind farms. There will definitely be a difference from the wind parameters in exact locations but estimation of these is beyond the scope of this work.

The relation between the wind speed and the output of a wind turbine is described by wind turbine's power profile. Modern wind turbines are operating in a range of wind speeds. Cut-in wind speed is a minimal wind speed starting from which a wind turbine starts producing energy. Rated wind speed – the speed at which wind turbine is achieving its rated (maximal) output. Cut-out wind speed is a maximum wind speed at which turbine still can operate. If the wind speed is higher than a cut-out speed, a wind turbine will be stopped in order to eliminate a possibility of breakage.

Measurements of the wind speed at weather stations are conducted at the height of 10 meters. All modern large scale turbines are higher than this and thus the wind speed should be corrected to their height. The dependence of the wind speed from height is described by Hellemann law:

$$v = v_0 \left(\frac{H}{H_0}\right)^{\alpha}, \qquad (3)$$

where υ is the wind speed at the height H, υ_0 is the wind at the height H_0 and α is the friction coefficient [80]. The friction coefficient is highly dependent of the surface parameters. Weather stations used for calculations in this thesis are located in areas with noticeably different terrain conditions. The Ossmussaare weather station is located on a very small island and has no forest or any other obstacles and open to the wind. In this case the friction coefficient was assumed to be equal to 0.08 – the same as for the open water [80]. Kihnu is a bigger island which is partially covered by forest. These conditions are influencing the wind at low altitudes. In this case the friction coefficient was assumed to be equal to 0.2. The last weather station used in this work is located near Ristna on the Hiiumaa Island. Compared to two islands mentioned above, Hiiumaa is a big island mostly covered with forest. The weather station under consideration is located further from the shore compared to previous two cases and surrounded by trees. These conditions are influencing the configuration of the wind measured at the site and the friction coefficient was assumed to be equal to 0.3.

The wind speed is changing with the distance from the shore. As the data provided by Estonian Weather Service is measured on land, it is necessary to correct it. The dependence between the wind speed and distance from the coast can be described in the form of the following equation [93]:

$$v = v_0 \left(2 - \sqrt{\frac{x_0}{x + x_0}}\right), \qquad (4)$$

where υ is the wind speed at a distance x, υ_0 is the wind speed near the shore, x_0 is a distance scale. From [93] the a distance scale coefficient was assumed to be equal to 17.2.

For two different offshore wind farm projects this adjustment will be conducted differently. For Hiiumaa wind farm it is important to take into account a fact that turbines will be scattered over a large area with different wind configurations. To simulate this, the wind farm was assumed to be located at two sites – one North from Ristna weather station and another – South-West from Osmussaare weather station. These locations are marked as number 1 and number 2 in Figure 17 respectively. The installed capacity was assumed to be evenly distributed between these sites. For the first location the distance to the shore is equal to 20 km and equation (5) can be used without any adjustments. For the second location the wind speed at Osmussaare Island located 10 km from the shore was recalculated using equation (4) to obtain the wind speed υ_0 near the shore. Later it was used to calculate wind speed at the second location 25 km from the shore. The final equation is presented below:

$$v = v_0\left(2 - \sqrt{\frac{x_0}{x_1 + x_0}}\right) / \left(2 - \sqrt{\frac{x_0}{x_2 + x_0}}\right), \qquad (5)$$

where x_1 is the distance from the shore to the wind farm (25 km) and x_2 – the distance from the shore to Osmussaare Island (10 km).

For an offshore wind farm near Kihnu Island calculations are similar to the second site of Hiiumaa wind farm described above. The wind speed at the location under consideration was calculated using the equation below:

$$v = v_0\left(2 - \sqrt{\frac{x_0}{x_3 + x_0}}\right) / \left(2 - \sqrt{\frac{x_0}{x_4 + x_0}}\right), \qquad (6)$$

where x_3 is the distance from the shore to the wind farm (25 km) and x_4 – the distance from the shore to Kihnu Island (15 km).

Generally the dependence between power output of a wind turbine and the wind speed is described by the following equation:

$$P = \frac{1}{2}\rho A v^3 c_p\,, \qquad (7)$$

where P [W] is the output of a wind turbine, ρ [kg/m^3] is the air density, A [m^2] is the area covered by a rotor, υ [m/s] is the wind speed and c_p is the power coefficient [80]. The equation above is used to describe the performance of a wind turbine operating at wind speeds between cut-in and rated.

It was assumed that modern offshore wind turbines will be used. The parameters can vary from one turbine to another and are also dependent on the site. For this study next parameters are used:

- Cut-in speed – 3 m/s
- Rated speed – 11.4 m/s
- Cut-out speed – 25 m/s
- Rated output – 5 MW
- Hub height – 90 m

These parameters of so called “5 MW Baseline Wind Turbine” are taken from the study by NREL [82]. A power curve for the considered wind turbine can be seen in Figure 18.

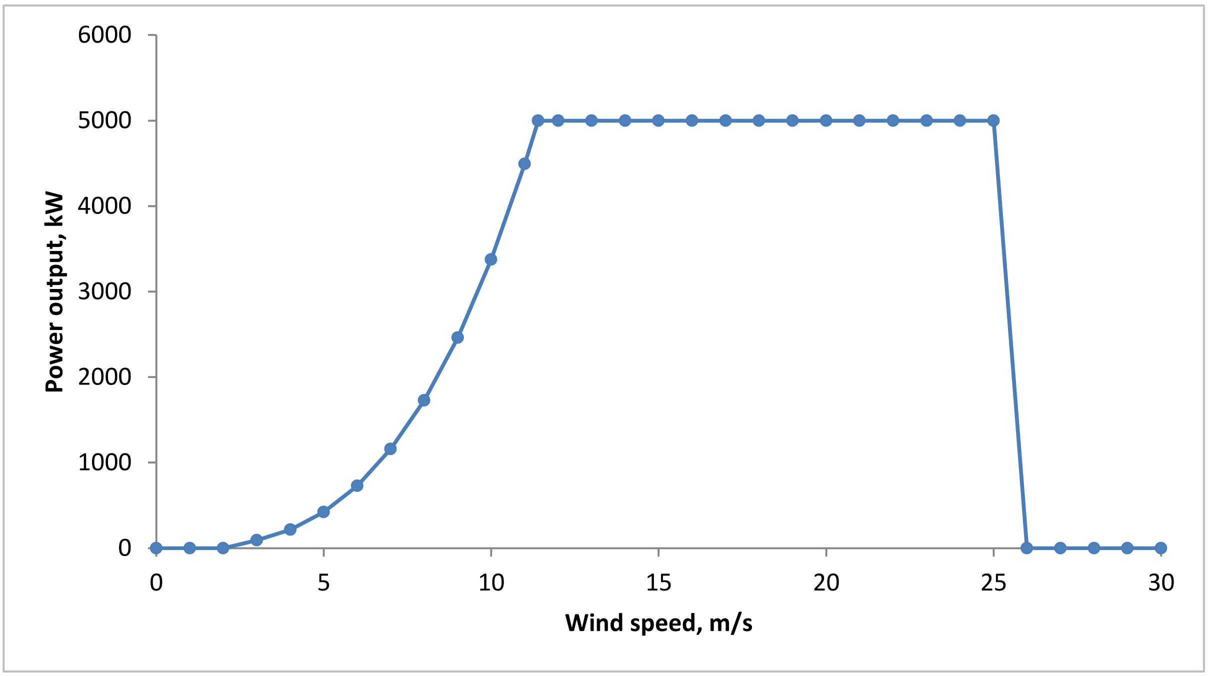

Figure 18. A power curve for the considered wind turbine

The final algorithm of obtaining the distribution of wind energy output in this scenario is as follows:

1. Obtaining hourly data from the Estonian Weather Service archive using an Excel macros
2. Recalculating wind speeds for 100 meters height using Eq. (3)
3. Adjusting the wind speed using Eq. (4) - (6)
4. Calculating the power output in accordance to the power curve and Eq. (7)

As it was mentioned before, EnergyPLAN is automatically normalizes hourly distributions so there is no need to do it manually. Final distributions will be provided in corresponding sections below.

6.2.2. Gulf of Riga offshore wind farm

An hourly distribution of energy produced by one turbine located in the described above position was created using a methodology described in 5.2.1 and is presented in Figure 19. Figure 20 shows the exceedence probability curve for the same turbine.

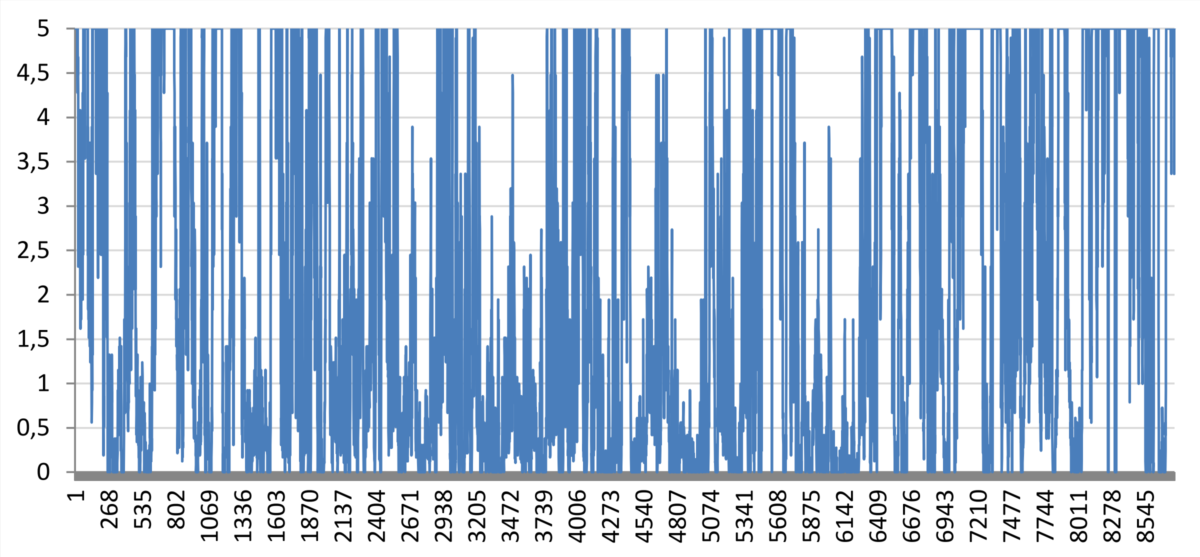

Figure 19. Hourly energy production of a 5 MW turbine in the Gulf of Riga offshore wind farm

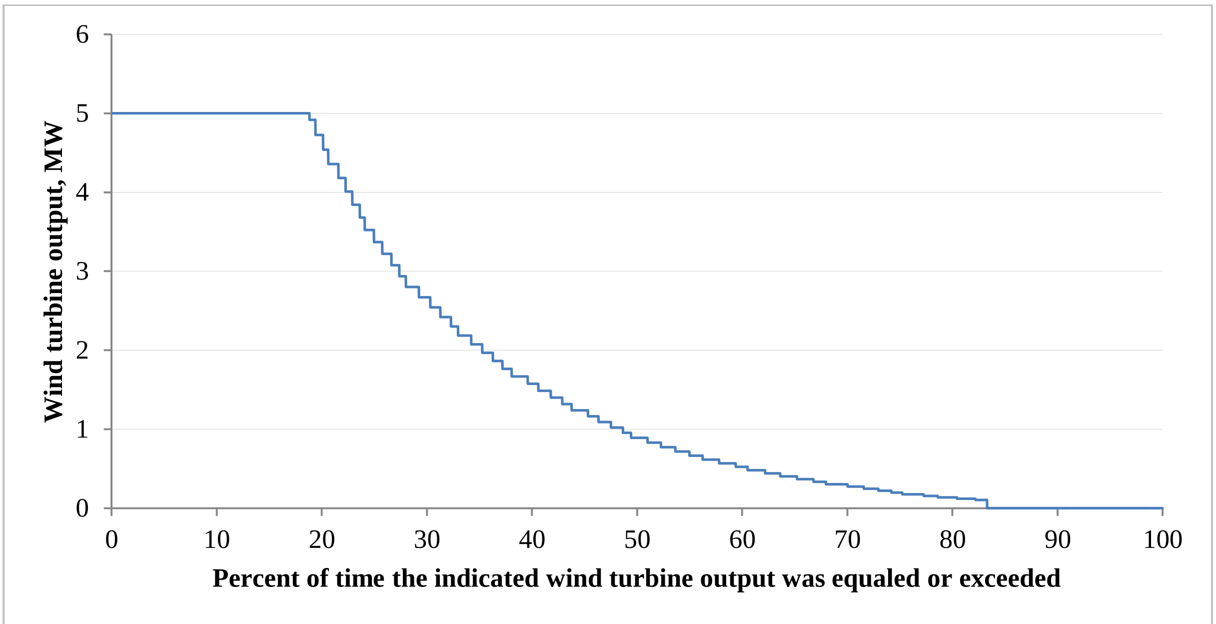

Figure 20. The exceedence probability curve for a 5 MW turbine in the Gulf of Riga offshore wind farm

The average wind speed at the 90 meters height is equal to 8.3 m/s and a capacity factor for a turbine during the year is equal to 0.42. Throughout the year there are 1163 hours in total when the wind speed was below the cut-in speed. A modeled turbine would operate at its rated capacity 2101 hour in the year. Occurrence of extreme wind speeds is low and there are only 25 hours in the year when the wind speed exceeds cut-out speed.

The distribution showed above was used as an input in EnergyPLAN. There is a possibility to create separate inputs for offshore and onshore wind energy and see separate numbers both technologies. Similarly as in the case of onshore wind energy, the new capacity was added with 250 MW step. The following figure shows how additional offshore wind capacity is influencing Estonian energy system.

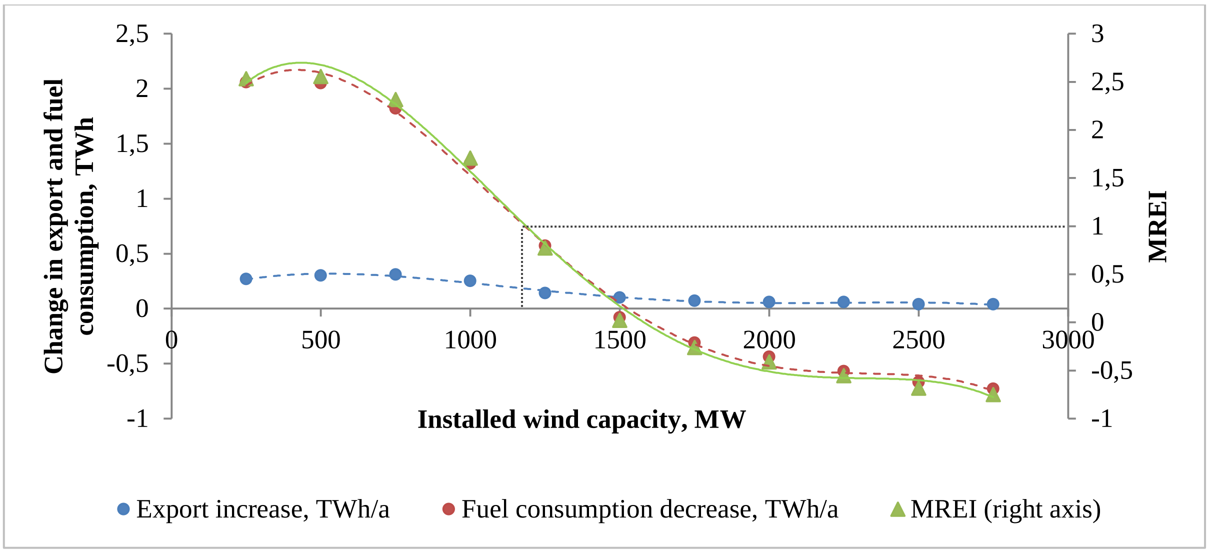

Figure 21. MREI and change in export of electricity and fuel consumption at different capacity levels of the Gulf of Riga offshore wind farm

The maximum beneficial level of added wind energy in the system is about 1190 MW which is about two times less than in the first scenario. This fact illustrates the difference between offshore and onshore wind energy integration mentioned above. Due to higher capacity factor of offshore energy, every MW of installed offshore wind capacity generates more energy than 1 MW of onshore wind capacity. This leads to higher savings in the fuel consumption. Although because the variation of the wind speed for a big offshore installation is not compensated by other variable energy source located in the area with a different wind configuration, offshore this scenario is associated with a higher level of curtailment. Already at the level of 500 MW installed during some hours wind energy will be curtailed. At the maximum level of 1190 MW installed the total curtailment during the year will be equal to 0.68 TWh which means that 13.7% of all wind energy produced will be lost. During some hours curtailment will achieve 960 MW or 63% of total installed wind capacity. On average 78 MW of wind energy per hour will be curtailed throughout the year.

In total, 4.37 TWh (or 31% from total electricity production) of wind energy will be produced at the maximum level of offshore wind energy capacity – 0.47 TWh less than in the first scenario. The total annual costs will grow €102 million which is less than in the first scenario but only due to the fact that fewer turbines will be installed. In the case of CO_2 price level of 20 EUR/t, total costs increase will be €35 million lower.

The total annual CO_2 emissions will be cut by nearly 2.88 million ton – 0.2 million ton more than in the first scenario.

In its current configuration, the Gulf of Riga offshore wind farm project implies installation of 600 MW of new capacity which is an acceptable level for the system under its current configuration.

6.2.3. Hiiumaa Island offshore wind farm

As it was mentioned before, for Hiiumaa offshore wind farm it was assumed that it is will be built at two sites – North from Ristna (Ristna site) weather station and South-West from Osmussaare (Osmussaare site) weather station. Hourly generation profiles for a 5 MW turbine located in these locations is shown in Figure 22 and Figure 24. The exceedence probability curves for the same locations are shown in Figures 23 and 25.

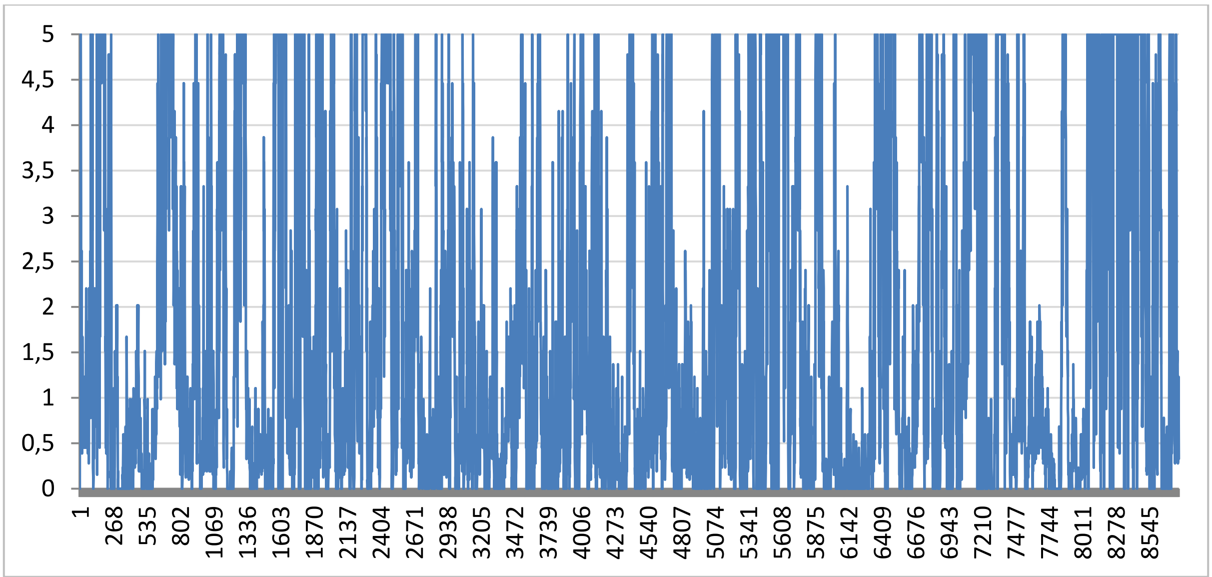

Figure 22. Hourly energy production of a 5 MW turbine on the Ristna site

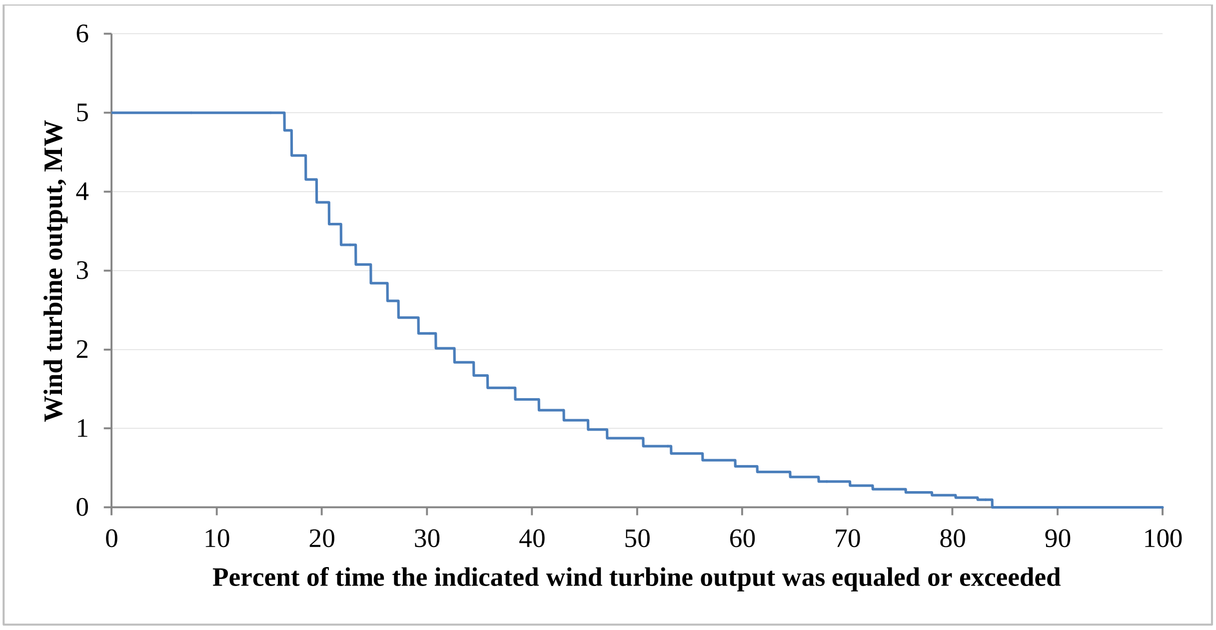

Figure 23. The exceedence probability curve for a 5 MW turbine on the Ristna site

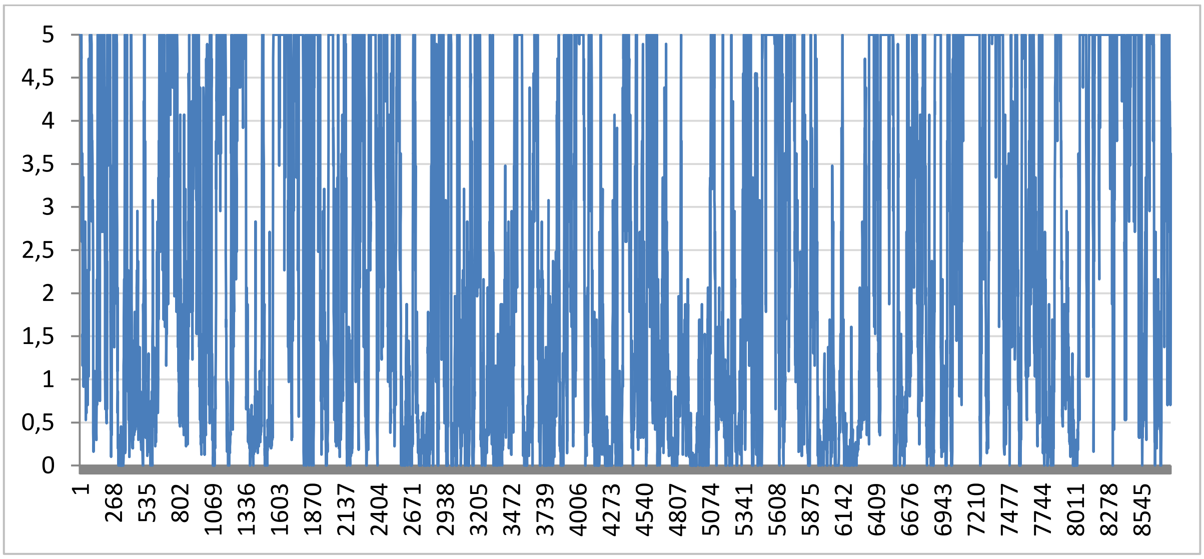

Figure 24. Hourly energy production of a 5 MW turbine on the Osmussaare site

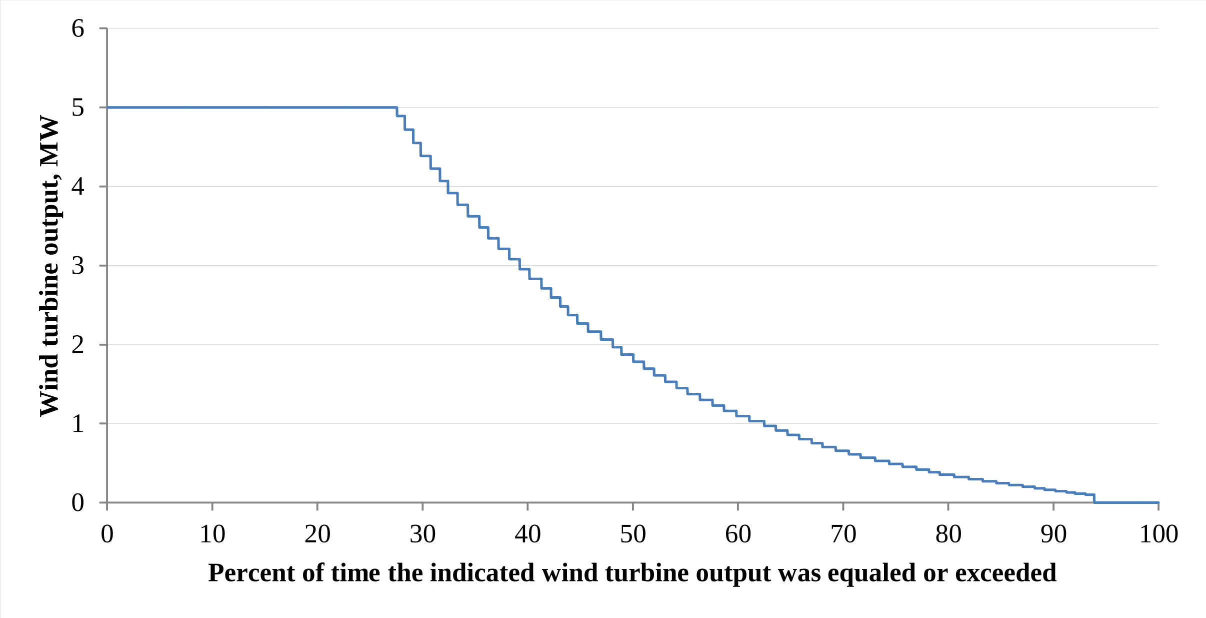

Figure 25. The exceedence probability curve for a 5 MW turbine on the Osmussaare site

It is possible to see that distributions are quite different and the Ristna site has lower wind speeds. The correlation coefficient between these distributions is equal to 0.7 meaning that there will be some smoothing of a resulting profile of a wind farm.

These distributions were used as inputs in EnergyPLAN. The only difference from previous scenarios is that this wind farm will be represented by two separate inputs and installed capacity will be evenly distributed between these. Otherwise, the approach is the same. Figure 26 shows the effect of increasing capacity of the farm.

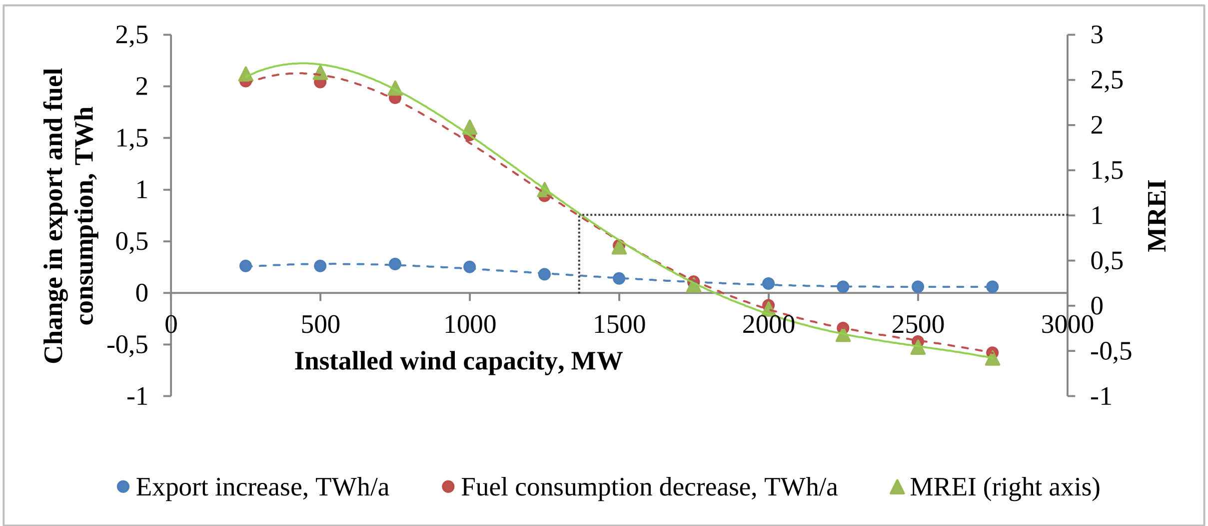

Figure 26. MREI and change in export of electricity and fuel consumption at different capacity levels of the Hiiumaa offshore wind farm

In this scenario the maximum profitable capacity for a wind farm is higher than in the Gulf of Riga scenario – 1375 MW. This fact clearly illustrates the effect of distributed generation. At this level of installed wind capacity, Hiiumaa offshore wind farm will produce 4.93 TWh of energy in a year. The total wind energy production including already installed onshore wind turbines will account for 34.7% of the system's total production. About 0.88 TWh from the total wind production will be lost due to curtailment – 15.9% from the total electricity production from wind. The maximum hourly level of curtailment is equal to 1227 MW (72% from the total installed wind capacity) while the average hourly curtailment is 100 MW. Even though curtailment is higher than in the previous scenario, the system can accommodate more wind energy because the capacity factor and consequently fuel savings are higher in this case.

The total production of electricity from wind at the maximum level of installed offshore wind energy is equal to 5.52 TWh/year. It is more than in both previously described scenarios. The total increase in system costs will be about €128 million – €25 million more than in the second scenario but €107 million less than in the first scenario.

6.2.4. Simultaneous operation of Gulf of Riga and Hiiumaa offshore wind farms

At the present moment two offshore wind farms mentioned above have the highest possibility of being built and it is important to know how the system will react in case these two will work at the same time. In this scenario we assume that Gulf of Riga wind farm has the capacity of 600 MW and already installed. Then the capacity of Hiiumaa wind farm was gradually increased with the step of 250 MW. Figure 27 shows how the system will react to the increasing capacity of Hiiumaa offshore wind farm.

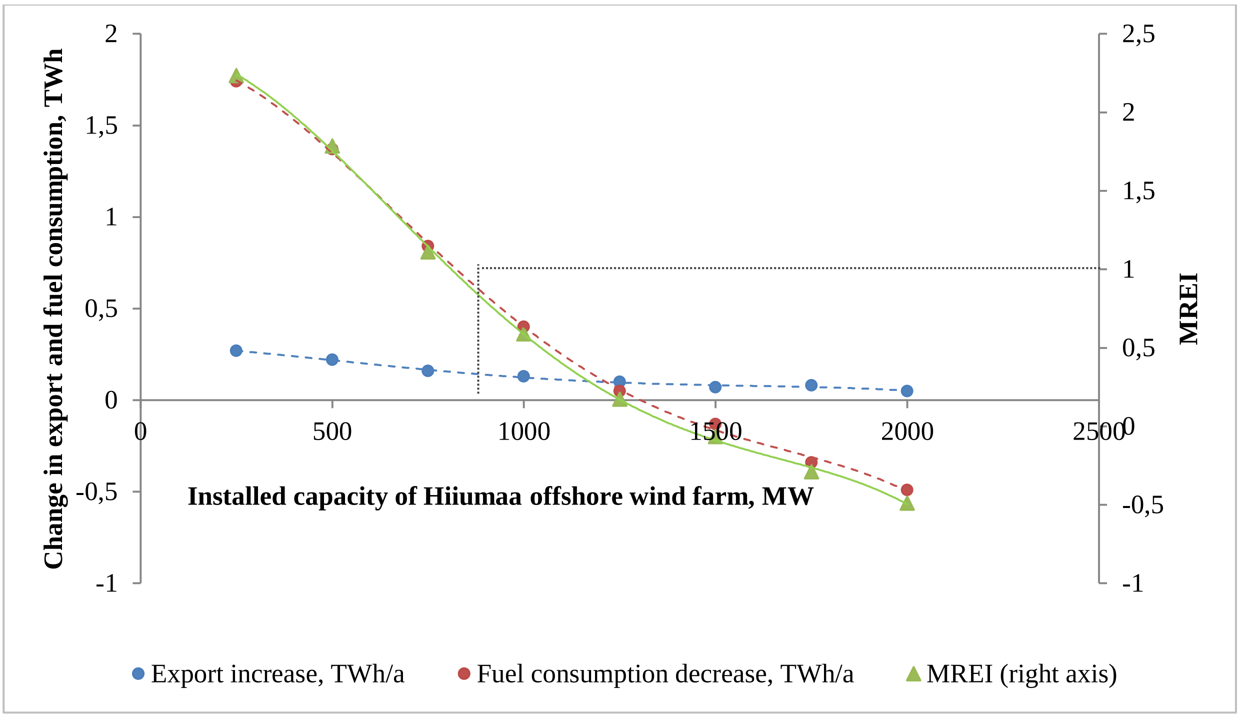

Figure 27. MREI and the change in export of electricity and fuel consumption at different capacity of Hiiumaa offshore wind farm

The current project implies that the capacity of Hiiumaa wind farm will be up to 1100 MW although the level at which MREI is becoming equal to one is 810 MW. This level can be considered as the optimal maximum for the Hiiumaa project.

The maximum installed capacity of offshore wind energy in this scenario is 35 MW higher than in the Hiiumaa case described above. At the same time, amount of electricity produced at offshore wind farms is 0.19 TWh higher – 5.12 TWh/year. In this scenario positive aspects of distributed generation outweigh the negative effects of lower capacity factor for Gulf of Riga offshore wind farm making higher levels of RES integration possible. It is worth mention though that wind distribution used in this work was constructed based on available data. For the more precise analysis the wind data measured directly at proposed sites should be used.

6.3. Increasing share of solar energy

6.3.1. Methodology and data processing

Here and in all following chapters when talking about the capacity of solar panels, it means peak power. It is also assumed that solar arrays are built using panels tested under standard test conditions (STC):

- Cell temperature of 25°C
- Irradiance of 1000 W/m^2

- Air mass 1.5 spectrum

The output of solar panel was assumed to be dependent of irradiance and the air temperature. The difference between a solar module's temperature and ambient temperature was not considered for simplicity. In the modern solar modules the coefficient between peak power and temperature lays somewhere in the range of -0.5%/°C to -0.3%/°C. For this thesis this coefficient was assumed to be equal to -0.4%/°C as for SunPower SPR-315 solar panel taken as an example [84]. It means that with the temperature increasing 1°C, the peak power of solar module is decreasing by 0.4%.

The temperature and irradiance data was obtained through a written request to Estonian Weather Service. The data provided is a time series for temperature and irradiance for four Estonian weather stations located in the different parts of the country: Tallinn, Narva, Pärnu and Tõravere. Unfortunately, the data provided had some hours missing. For Tallinn, Pärnu and Tõravere missing parts were short and values for these hours were restored using the following equations:

$$I_i = I_{i-1} + (I_{i-24} - I_{i-25}) \qquad (8)$$

$$T_i = T_{i-1} + (T_{i-24} - T_{i-25}), \qquad (9)$$

where I_i and T_i are missing irradiance and temperature, I_{i-1} and T_{i-1} are the values for the previous hour, I_{i-24} and T_{i-24} are values one day before and I_{i-25} and T_{i-25} are values 25 hours before.

In the case of data from Narva weather station, missing parts were longer – up to several days in a row. The equations above were adjusted to use a longer time intervals:

$$I_i = I_{i-1} + (I_{i-72} - I_{i-73}) \qquad (10)$$

$$T_i = T_{i-1} + (T_{i-72} - T_{i-73}), \qquad (11)$$

where I_i and T_i are missing irradiance and temperature, I_{i-1} and T_{i-1} are the values for the previous hour, I_{i-72} and T_{i-73} are values three days before and I_{i-73} and T_{i-73} are values 73 hours before.

The overall procedure of creating the input for EnergyPLAN is as follows:

1. Obtaining data from Estonian Weather Service
2. Filling the missing hours using Eq. (8)-(11)
3. Calculating the output of a reference panel using irradiance data
4. Correcting the output using the temperature coefficient
5. Normalizing the output to the peak power of the reference panel

The last step is important here. Even though it was mentioned before, that EnergyPLAN will normalize any hourly distribution for energy output you put there, in this case automatic normalization will lead to the error. This is due to the fact that in Estonian conditions in 2014 the panel will never reach its peak output. The maximum irradiance level reached during 2014 is equal to 925 W/m^2 – 75 W/m^2 less than in standard test conditions. After temperature correction and averaging of data from four weather stations, the maximum normalized production during the year will be equal to 84% from its peak capacity measured under standard conditions. For Pärnu this number will be higher since irradiance levels there are higher than Estonian average – 87% from peak capacity of a solar panel. If normalization will be conducted inside of EnergyPLAN, it will assume that normalized maximum is equal to 100% from installed capacity of solar panels and total electricity production from them will be overestimated.

6.3.2. Distributed increase of solar energy share

This scenario assumes that increase in solar energy share will take place country wide. In order to simulate this, the irradiance and temperature data from four weather stations was converted to energy production of a reference solar module and then averaged. The distribution used as an input in EnergyPLAN was obtained using methodology above and presented in Figure 28.

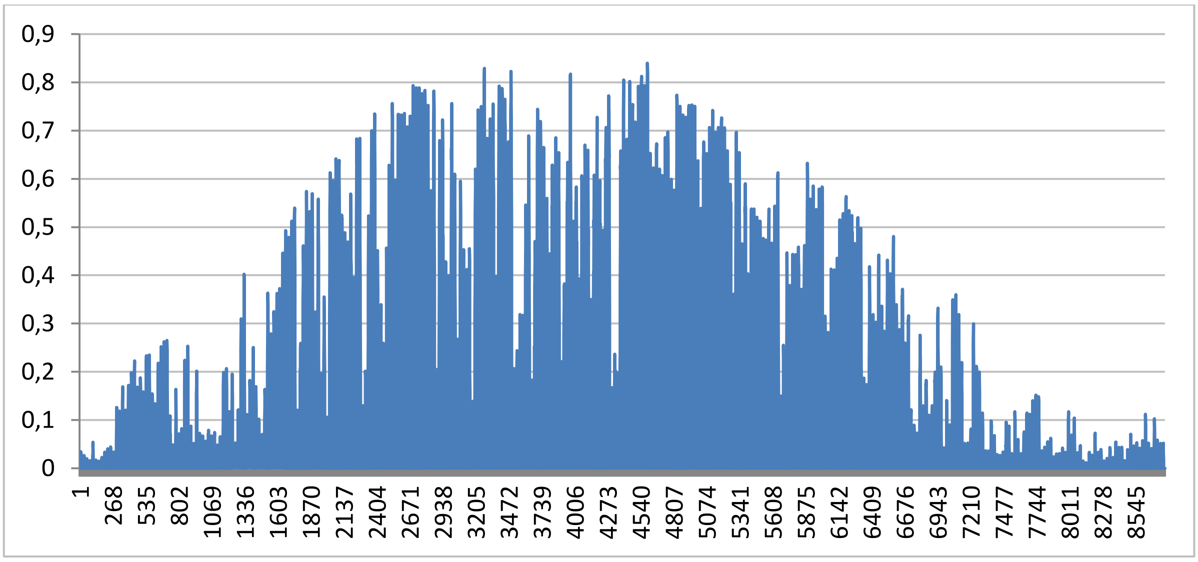

Figure 28. Hourly normalized energy production of solar panels in the scenario of a distributed increase of solar energy share

As in previous scenarios, the installed capacity of solar panels was increasing with a 250 MW step. Figure 29 shows how system's parameters changing with increasing share of solar energy.

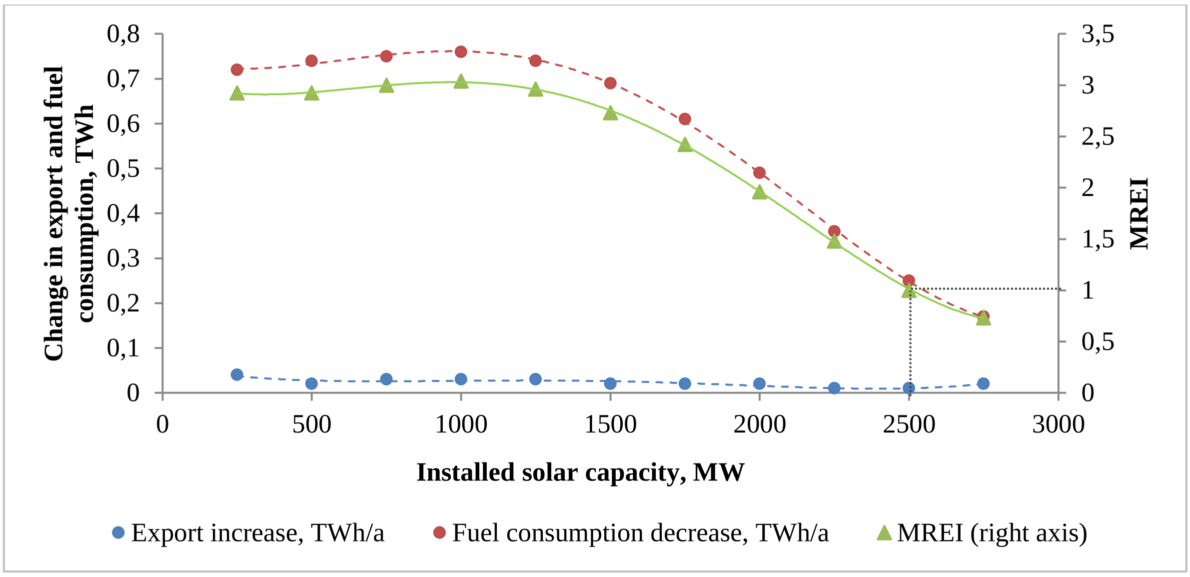

Figure 29. MREI and the change in export of electricity and fuel consumption at different levels of installed solar capacity

As it can be seen from the figure above, the system can efficiently accommodate 2500 MW of solar energy. It is the highest value among all scenarios. Nevertheless, the production of electricity from solar is lower than in all wind scenarios – 2.59 TWh per year. At the same time, the total system costs will increase by €212 million. Only in the first scenario total costs were higher but production from newly installed capacity was higher too. This fact shows that integration of solar energy in this scenario has very high costs per kWh of energy produced compared to all investigated wind integration scenarios.

The amount of energy that will be curtailed is the lowest among all previous scenarios – 0.45 TWh. This is due to the fact that solar energy is produced only during day hours when the consumption is also high.

The total CO_2 emissions in this scenario will be reduced by 2.29 million ton.

6.3.3. Centralized increase of solar energy share

In this scenario it is assumed that new solar capacity will be added in the area of Estonia which has the highest yearly irradiation among four locations available for this analysis – Pärnu. The overall procedure of data preparation is the same as in the previous scenario with the exception of averaging which is not needed here. The hourly energy production for this scenario is shown in the figure below.

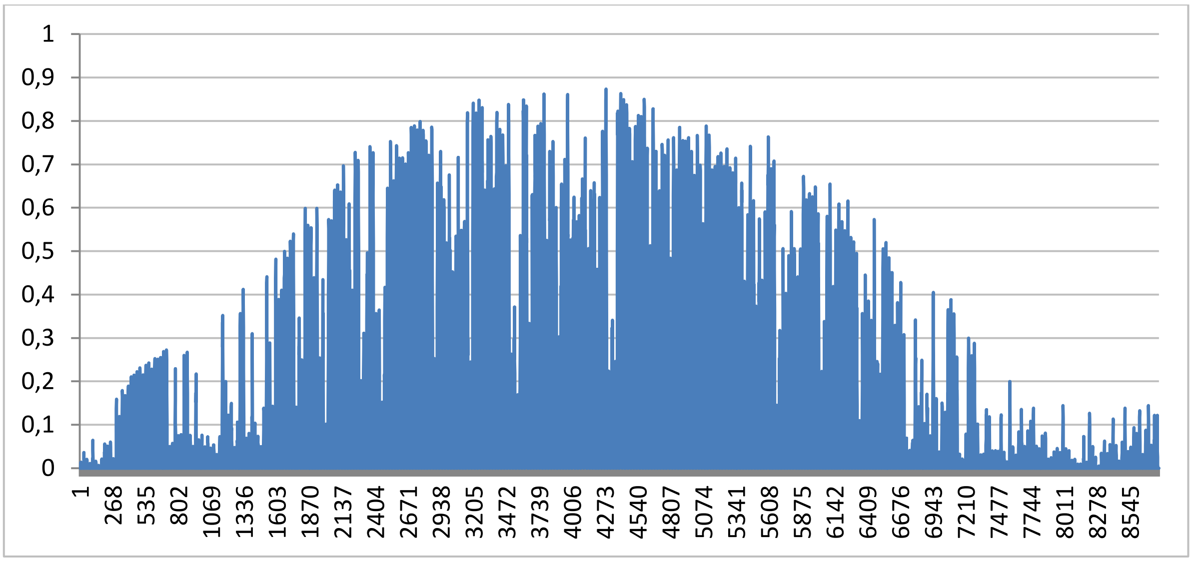

Figure 30. Hourly normalized energy production of solar panels in the scenario of an increasing solar capacity in Pärnu region

The distribution looks very similar to the one presented in the previous scenario although average and maximum production levels are higher. From the other hand, the changes in production from one hour to another will be higher too. Figure 31 shows how fuel consumption, net export and MREI are changing with increasing solar capacity.

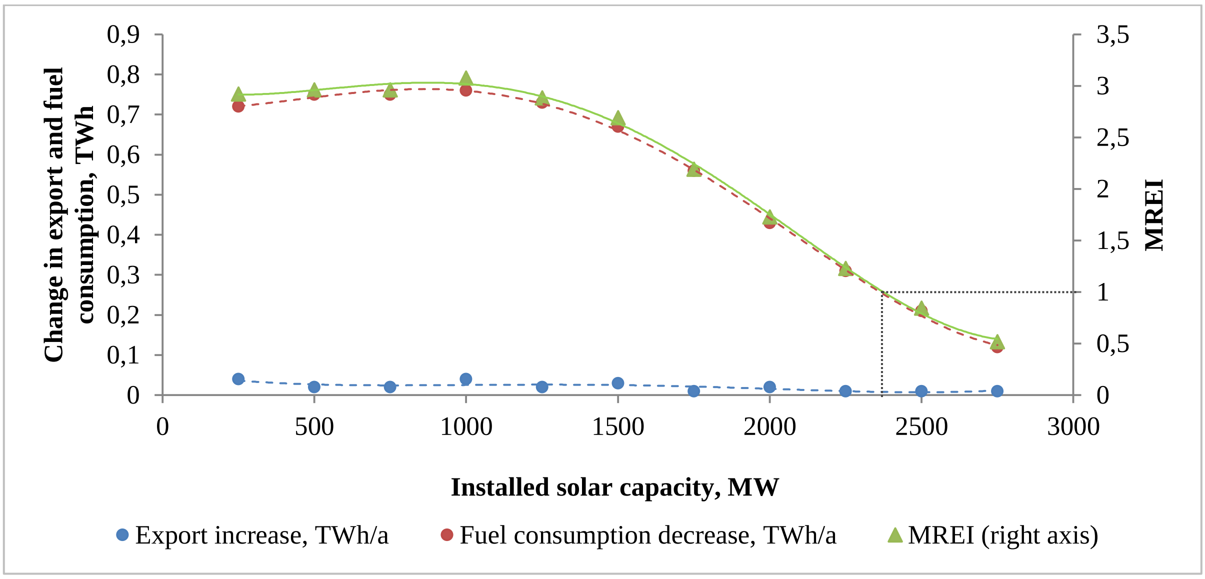

Figure 31. MREI and the change in export of electricity and fuel consumption at different levels of installed solar capacity in Pärnu region

Although the shape of the curves looks very similar to the previous scenario, the maximum capacity the system can accommodate in this case is 150 MW lower – 2350 MW. It means that positive effects of higher production levels in this scenario are being outweighed by the negative ones coming from a higher hour-to-hour generation variation. This scenario shows the importance of distributed solar energy integration in the current state of Estonian energy system. The difference in irradiance levels between different locations in fact is not that big but short term weather changes at these locations are independent and thus making the generation profile smoother.

6.4. Comparison of the scenarios

This section is dedicated to the comparison of the scenarios studied above. Figure 32 shows how MREI index changes with added capacity of renewable energy in scenarios described above.

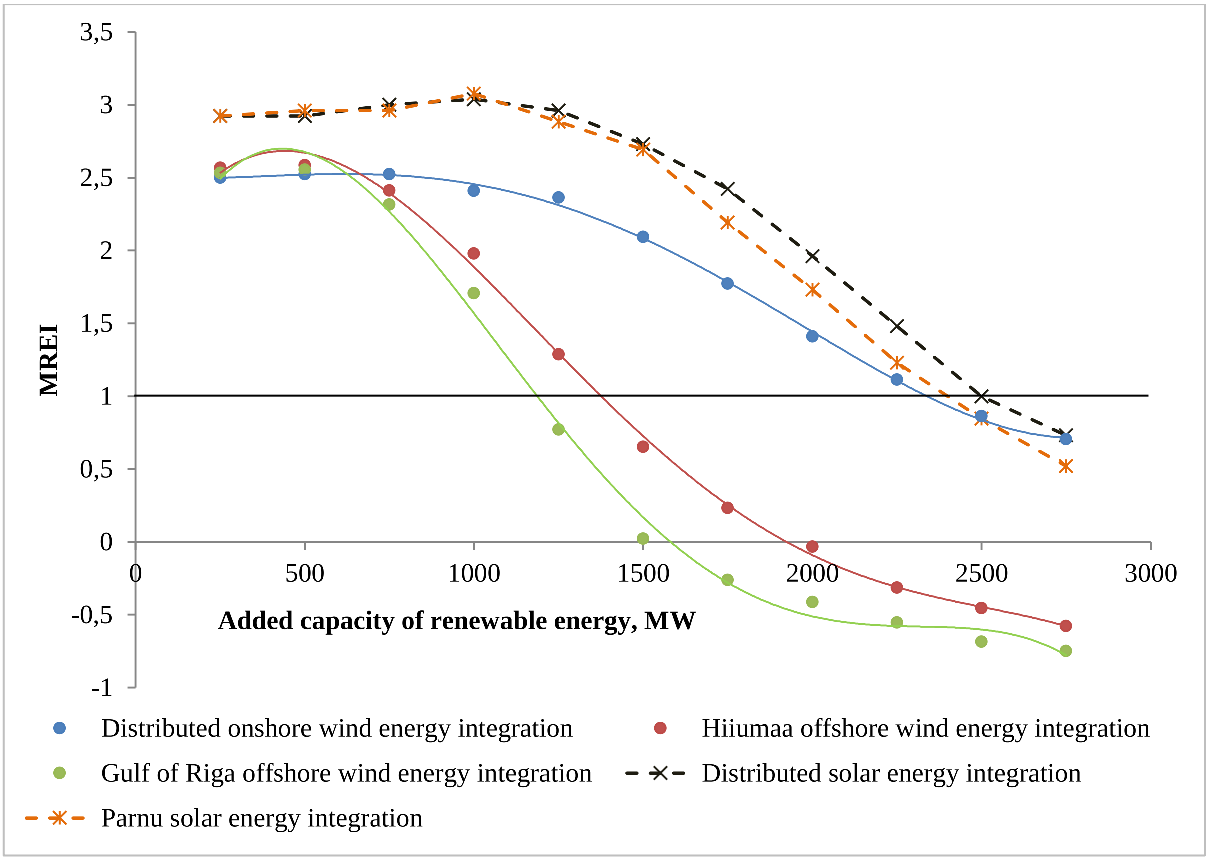

Figure 32. Comparison of MREI behavior in different scenarios of renewable energy integration

It is possible to see that all wind scenarios are starting somewhere around MREI=2.5 while graphs for solar energy scenarios are lying above. This is happens because solar energy replaces more fuel per kWh of energy produced. In other words it is possible to say that it is utilized better. And while the slope of curves for solar energy scenarios is steeper than for the scenario of distributed onshore wind energy integration, this difference in the starting levels makes possible higher levels of solar energy integration.

As it can be seen above, in the case of Estonian energy system MREI index is mostly influenced by changing fuels consumption. Figure 33 shows how consumption of primary fuels is changing with introduction of higher levels of intermittent energy in the system.

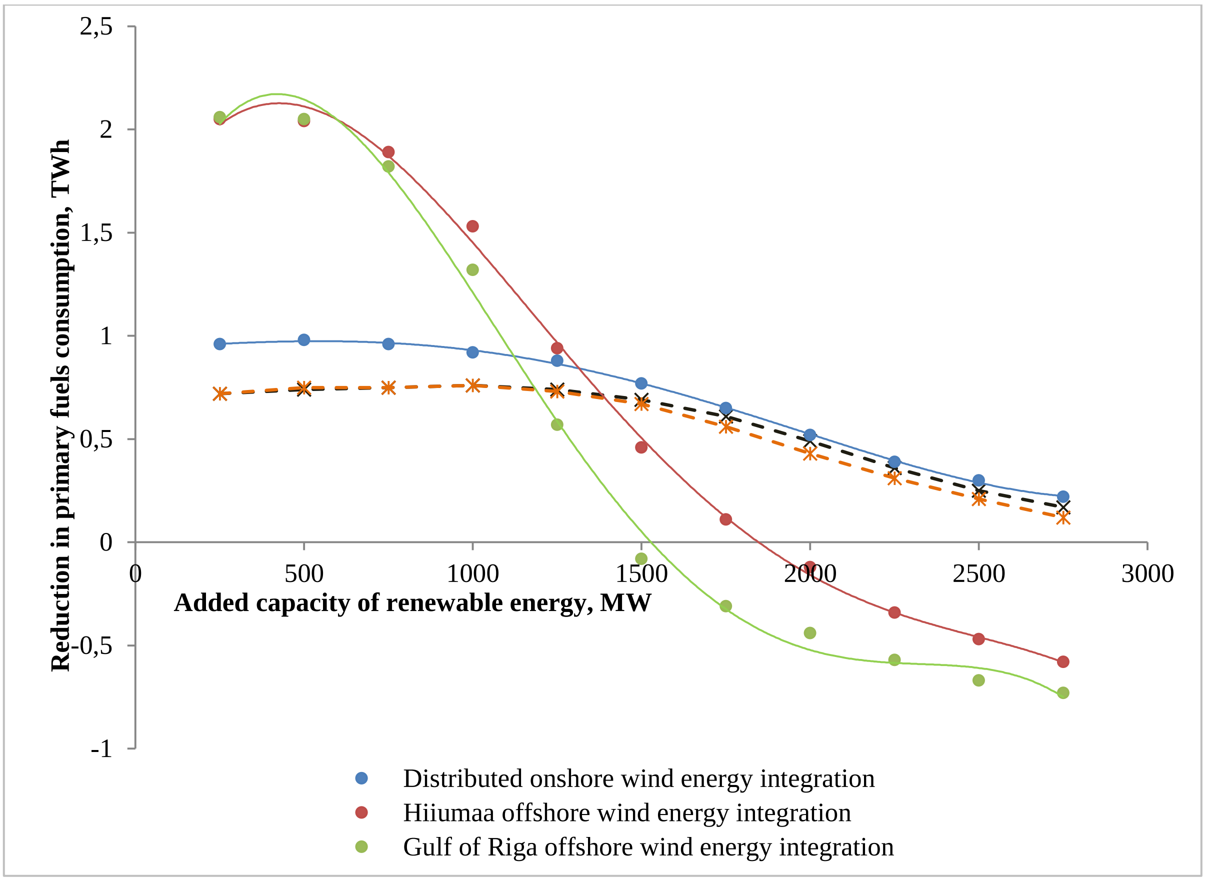

Figure 33. Comparison of fuel consumption reduction in different scenarios of renewable energy integration

Offshore wind energy at low penetration levels replaces sufficiently more fossil fuels that solar energy or onshore wind energy. This is the effect of higher penetration levels. Although higher production levels also bringing up a problem with system flexibility. With installation of additional capacity, fuel reduction is starting to decline quickly as some part of the energy is being curtailed and hourly fluctuations are increasing too. Figure 34 shows only how fuel consumption is changing from one level of installed RES to another. The following figure illustrates how accumulated values of total fuel consumption reduction are changing.

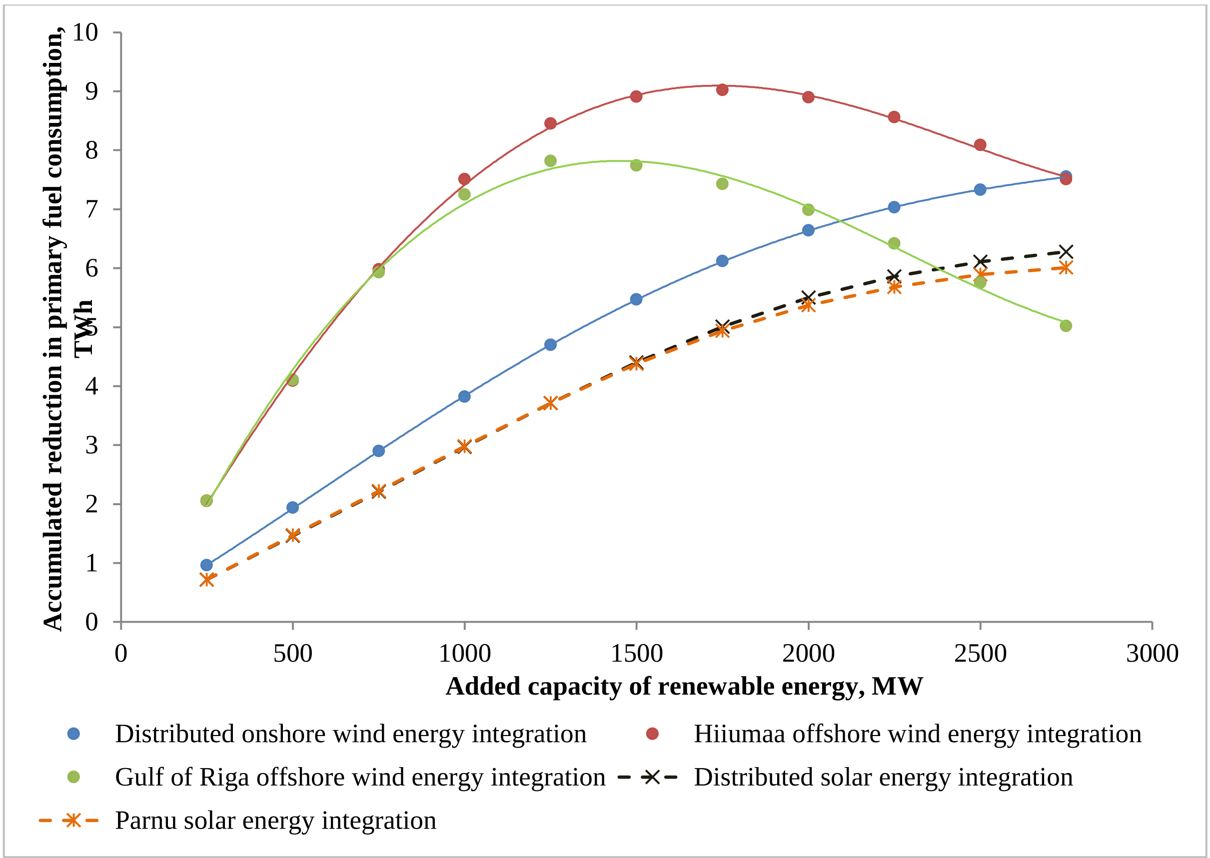

Figure 34. Accumulated reduction in fuel consumption in different scenarios of renewable energy integration

Figure above shows that after some point total fuel savings will in fact start decreasing as the system will need more fuel to balance very high hourly variations of RES output. It illustrates the importance of proper system planning and usefulness of MREI index, as negative effects are starting to appear after maximum levels calculated in sections above. Offshore energy looks better but only up to certain level which should be carefully estimated.

The table below represents the main parameters for each scenario analyzed. In each row the best result among all scenarios is highlighted in green colour.

	Scenario					
	Onshore wind energy	Gulf of Riga offshore wind farm	Hiiumaa offshore wind farm	Simultaneous installation of Hiiumaa and Gulf of Riga wind farms	Distrib uted solar energy	Pärnu region solar energy increase
Maximum level of added RES capacity, MW	2336	1187	1375	1410	2500	2350
Electricity produced by RES, TWh	4.87	4.98	5.54	5.72	3.2	3.05
Electricity curtailed, TWh	0.74	0.69	0.88	0.91	0.45	0.42
Curtailment as a fraction from RES production, %	15%	14%	16%	16%	14%	14%
Share of RES in total electricity production, %	35%	36%	39%	40%	25%	24%
Share of not curtailed RES in total electricity production, %	29%	31%	33%	34%	22%	21%
System costs increase, million EUR	234	102	127	129	212	200
Change in system costs per MWh of energy produced by newly installed RES[4], EUR/MWh	54.9	23.3	25.8	25.2	81.9	82.0
Net export increase, TWh	1.24	1.25	1.31	1.38	0.38	0.22
CO_2 emissions reduction, ton	2.68	2.88	3.24	3.32	2.29	2.16

Table 3. The main parameters for the scenarios analyzed in this thesis

The table above shows that while the system can accommodate more solar than wind energy, all wind scenarios are showing better production rates and lower costs. Simultaneous installation of Hiiumaa and Gulf of Riga offshore wind farms is the best option in terms of

[4] This parameter shouldn't be confused with the cost of energy produced by newly installed RES. Alongside with investments, rate of return and O&M costs EnergyPLAN is also taking into account change in cost of consumed fuel and exchange with the external market so in some cases this parameter can even be negative. Although it's a good economic indicator of overall system benefits in different scenarios of energy system development.

maximum possible level of RES integration. From the economical point of view, the Gulf of Riga offshore wind farm is the most cost-effective option.

6.5. Simultaneous integration of higher shares of wind and solar energy

The last important moment will be studied in this thesis is the influence of solar energy share on the maximum possible wind capacity. It can happen that in case of correlated production from wind and solar energy, the curtailment will be higher leading to stricter limitations for maximum possible share of wind energy. The methodology for this section is exactly the same as in all scenarios above. Solar capacity is added with 500 MW step. At each step the maximum capacity for wind energy is being found as the point in which MREI is becoming equal to one. Two different cases are investigated here – distributed growth of onshore wind energy (as in Section 6.1) and the case of the Gulf of Riga offshore wind farm (as in Section 6.2.2). The figure below shows how the maximum level of installed capacity is changing for these two cases.

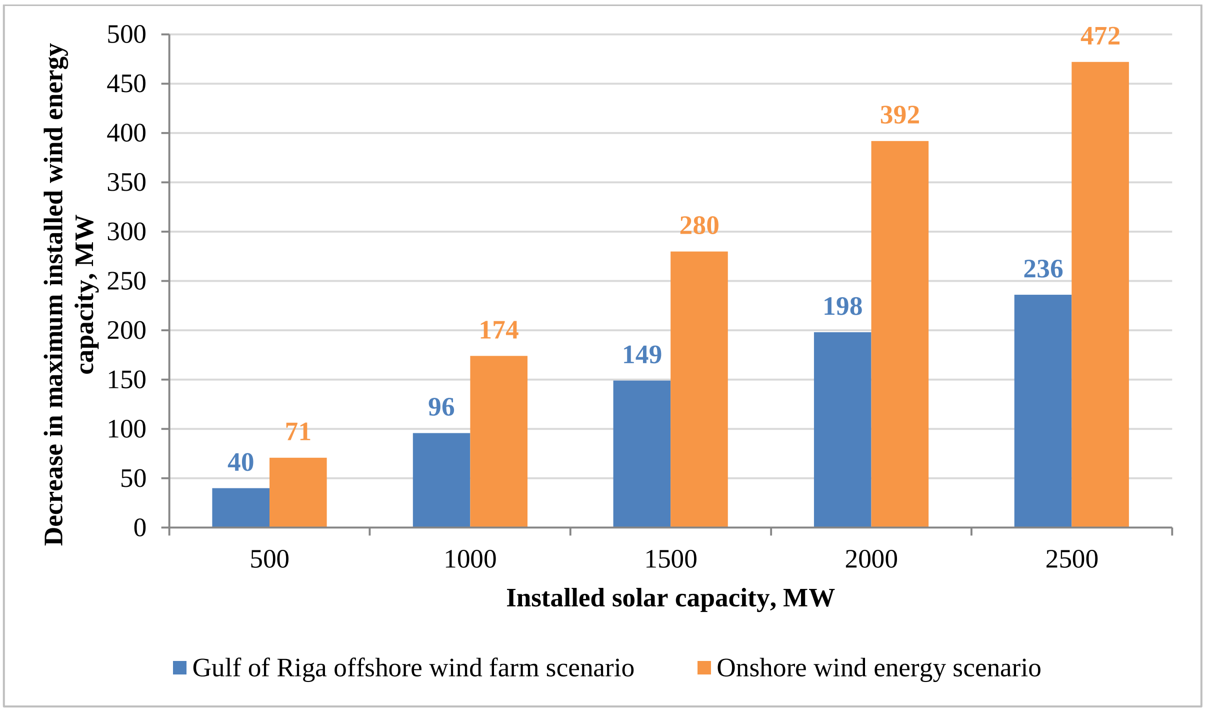

Figure 35. Changes in the maximum wind energy capacity at different levels of installed solar energy capacity

As it is possible to see, the additional solar capacity is influencing onshore wind energy more than offshore wind energy but in both cases is leading to a decrease of the maximum wind energy capacity. Figure 35 confirms a hypothesis in the beginning of this section. During some hours solar and wind energy are increasing each own fluctuations and it becomes harder for the system to balance these. If local maximums of solar and wind energy production are happening when consumption in the system is relatively low, curtailment levels are growing. Table 4 shows how the main system parameters are changing with increasing share of RES.

Simultaneous increase of solar energy and onshore wind energy						
	Installed capacity of solar panels					
	0	500	1000	1500	2000	2500
Maximum level of added RES capacity, MW	2336	2765	3162	3556	3944	4364
Electricity produced by RES, TWh	4.3	4.5	4.8	5.2	5.5	5.9
CO_2 emissions reduction, ton	2.7	3.1	3.5	3.9	4.0	4.1
System costs increase, million EUR	234	257	287	319	354	400
Cost of energy produced by newly installed RES, EUR/MWh	54.9	57.1	59.3	61.7	64.4	68.1
Simultaneous increase of solar energy and offshore wind energy						
	Installed capacity of solar panels					
	0	500	1000	1500	2000	2500
Maximum level of added RES capacity, MW	1187	1647	2091	2538	2989	3451
Electricity produced by RES, TWh	4.4	4.8	5.1	5.5	5.8	6.2
CO_2 emissions reduction, ton	2.9	3.4	3.8	4.1	4.2	4.2
System costs increase, million EUR	102	136	171	210	254	305
Cost of energy produced by newly installed RES, EUR/MWh	23.3	28.2	33.3	38.5	43.9	49.5

Table 4. The main parameters of the energy system with increased shares of solar and wind energy

The table above shows that even though the maximum possible level of wind energy integration is decreasing with installation of solar panels, the overall effects of simultaneous integration of these two technologies is positive. The share of RES in the energy balance is increasing even though some part of energy is being curtailed. The negative aspect here is that cost of the energy produced is increasing with the increasing share of solar energy due to higher investments costs and lower capacity factor compared to wind energy in Estonian conditions.

Another interesting aspect worth mention here is that CO_2 emissions reduction is not decreasing linearly with introduction of RES. Figure 36 illustrates this thesis.

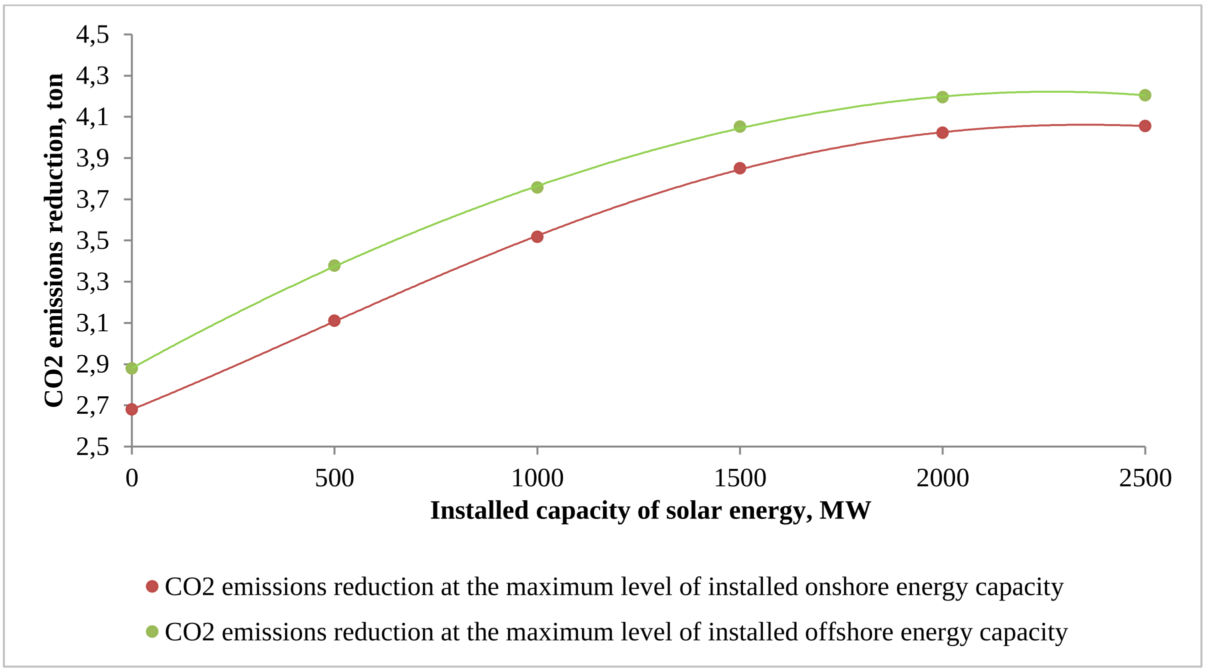

Figure 36. CO_2 emissions reduction at different levels of installed RES capacity

After some level of installed RES capacity the reduction in CO_2 emissions is reaching its maximum and the future increase of renewable energy share is not leading to any substantial changes in the resulting pollution intensity. The possible reason behind this effect is that at very high penetration levels of intermittent energy sources, there is also a need in balancing during hours with low production from RES. At the same time, when the energy production from solar panels and wind turbines is very high, a substantial amount of energy will be curtailed. These factors are limiting positive effects of RES integration.

7. Conclusions

This thesis was exploring the Estonian energy system with the accent on the questions of renewable energy sources integration. For this purpose, the model of the system was created using the latest fully available data. As some of the statistical tables presented by Statistics Estonia for the year 2015 were not available, 2014 was chosen as the base year for this thesis. The model was created using EnergyPLAN software. The model outputs were compared to the actual data and it was shown, that the model produces accurate results with error levels for not exceeding 5% for the most of the output parameters. The occurrences where the error was exceeding 5% mark are most probably caused by functional limitations of the software, as there is no possibility to take into account an interaction between two interconnection corridors – Finland-Estonia and Estonia-Latvia. Overall, the model produced good results making it possible to use it for the further analysis of different developing scenarios.

Currently, all Estonian wind farms are located onshore and spread over the country. If wind energy sector will continue this decentralized onshore growth, the energy system under its current design will be able to accommodate up to 2336 MW of new onshore installations. As the result, CO_2 emissions will be reduced by 2.7 ton annually. Although, since the main Estonian energy source – oil shale – is very cheap, the yearly system's costs will increase by 234 million EUR. In this scenario, RES will produce 4.9 TWh of electricity per year or 35% of total production.

Two biggest Estonian offshore projects – the Hiiumaa offshore wind farm and the Gulf of Riga offshore wind farm – were shown to produce sufficiently better results compared to onshore wind energy. Although the maximum installed capacity in these scenarios is lower than in the onshore scenario, both wind farms are expected to produce more energy due to higher capacity factors. The Hiiumaa offshore wind farm is able to produce about 4.9 TWh of clean energy per year at its peak capacity of 1375 MW, while for the Gulf of Riga these values are lower – 4.4 TWh and 1187 MW correspondingly. At the same time, the second of above mentioned offshore wind farms has sufficiently lower costs. In fact, from all scenarios analyzed in this thesis, the Gulf of Riga offshore wind farm is the most cost effective option.

Both projected offshore wind farms can be accommodated separately by the energy system at their maximum planned capacities – 600 MW for the Gulf of Riga offshore wind farm and 700-1100 MW for the Hiiumaa offshore wind farm. If both projects will be developed together, the maximum possible capacity for the Hiiumaa wind farm should be limited by 810

MW. From all scenarios, simultaneous integration of two offshore wind farms is promising the highest level of energy production from RES – 5.1 TWh/year – and as a consequence, the biggest reduction of CO_2 emissions – 3.3 million ton per year.

The scenarios of solar energy integration are featuring sufficiently lower capacity factors compared to any of wind energy scenarios. In Estonian conditions, solar panels are never working at their rated capacity which leads to a lower production per MW installed. Even though solar panels are requiring lower investments, the resulting change in the system costs per MWh of energy produced are more than three times higher than in the case of Gulf of Riga offshore wind farm – 82 EUR/MWh.

Comparing two scenarios of distributed solar energy integration and centralized growth in the area with high irradiance levels it is possible to see that with generation spread around the country, its energy system can accommodate more RES but the relative level of curtailment (total curtailment as a fraction of energy produced) is lower for the scenario in which all solar panels are concentrated in Pärnu area.

It was shown that solar energy is reducing the maximum level of wind energy integration. Onshore wind energy is being influenced more than offshore wind energy. At the same time, the total maximum RES capacity (solar and wind) is growing sufficiently. The cost efficiency of the mixed technology scenarios is lower compared to “wind only” cases. Another interesting effect found here is that with growing capacity of RES, the reduction in CO_2 emissions becomes lower and after some point the positive effects of newly added renewable energy are disappearing completely.

8. Résumé

With the increasing share of renewable energy sources share in the world, the modeling of energy systems becomes more and more important. Each country's energy system is unique and requires an individual approach since the way it responds to the introduction of RES is based on many factors such as the fuel and generation mix, the structure of consumption, geographical and weather characteristics and many more. Country scale studies are extremely important for the evaluation of the direction of energy system's development, analysis of possible obstacles and future planning. These models should be frequently updated in order to reflect the changes and current trends and give a picture as close to real time as possible.

The number of studies analyzing energy systems of different countries and RES integration in these systems was written over the last years. Unfortunately, there are just several studies of this type are available for Estonia and none of these is using the latest available statistical data. This thesis was created in order to cover this gap and create a model of Estonian energy system, analyze several development scenarios and find limits for RES integration. The model created is based on the latest available data and might be used in future studies.

Firstly, the development path and the present state of Estonian energy system were analyzed. This analysis and a literature review formed a foundation for the model. From many different modeling tools, EnergyPLAN was chosen. It is free and well-documented software with an intuitive user interface. It was used for an analysis of energy systems of many different countries and especially for Denmark – a country famous for its dedication to RES development.

All needed data for the model was obtained from open sources such as Statistics Estonia, Nord Pool, Elering, Estonian Weather Service and others. The year 2014 was taken as a base year in this thesis since at the moment of writing some of necessary records for 2015 were not available. Hourly heat demand is a specific input which is required for the model but is not being measured. It was constructed using so-called heating degree days methodology. The model created was validated and showed the results close to the real measurements.

Several scenarios of renewable energy development in Estonia were created in order to evaluate the performance of different technologies, analyze the system's response to increasing share of RES and find the limits for the integration of clean energy sources. For offshore wind energy scenarios, the wind parameters for the chosen sites were not available.

The hourly distribution was modeled using the data from several closest weather stations located at Kihnu, Osmussaare and Hiiumaa islands. For the solar panels, their output was constructed using the hourly irradiation data for several locations in Estonia obtained on request from Estonian Weather Service.

For every scenario, the system costs, energy production from RES, CO_2 emissions reduction, export/import values, the maximum level of RES installation (based on MREI methodology) and many other parameters were found and compared. It was shown, that in Estonia offshore wind energy is the most cost-effective option compared to onshore wind energy and solar generation. On the other hand, the system in its current state can accommodate more solar energy than wind energy. The electricity consumption profile is closer to the solar panels generation profile and this leads to lower levels of curtailment. In Estonia, solar panels tested under standard testing conditions are almost never working at their rated capacity. In 2014 there was not a single hour when the irradiation level reached 1000 W/m^2 thus the capacity factor for solar installations is relatively low. There should be a great decrease in solar panels prices before it would be economically feasible to start investing in big solar projects in Estonia.

Two biggest Estonian energy projects – the Hiiumaa offshore wind farm and the Gulf of Riga offshore wind farm – are showing a good fit in the system already under its current design. Estonian energy system can even accommodate both of these projects at the same time if their total capacity will be less than 1410 MW. Although the production levels of these wind farms are very high, not all energy can be utilized. With the current limitations of interconnection capacity, some part of the energy will be curtailed and lost. At the maximum level of installed capacity of offshore wind farms, 14% to 16% of all wind energy produced will be lost. With the development of new interconnection capacity between Estonia and Latvia, the curtailment levels will go down.

An increasing share of solar energy was shown to reduce the maximum levels of installed wind capacity and onshore wind energy is influenced more. However, this effect was shown to be relatively small. Overall solar and wind energy are good to be combined and theoretically can account for up to 50% of Estonian electricity production without bringing negative effects to the system.

9. Resümee

Kasvava taastuva energia leviga maailmas, energiasüsteemide modelleerimine muutub üha olulisemaks. Iga riigi energia süsteem on unikaalne ja vajab individuaalset lähenemist, sest ta vastab TEA (Taastuva Energia Allikad) mis põhineb paljude teguritel, näiteks kütuse ja põlvkonna segu, tarbimist struktuurist, geograafiliste ja kliima omadustel ja paljudel muul. Riigi uuringud on äärmisel tähtsad selleks et hinnata riikliku energiasüsteemide arendamise suunda selleks, et analüüsida võimalikke takistusi ja planeerida tuleviku. Sellised mudelid tuleb tihti uuendada, et kajastada muudatusi ja praeguseid trende ja anda läheda ettekujutust reaalajast. Uuringute arv mis analüüsib erinevate riikide energia süsteemid ja TEA integratsiooni süsteemides on ümberkirjutatud viimastel aastatel. Kahjuks on ainult mõned uuringud mis on sellega seotud ja saadavad Eestis ja ükski neist ei kasuta viimased kättesaadavad statistika andmed. Antud Magistritöö oli loodud selleks, et katta moodustatud vahe ja luua Eesti energiasüsteemi mudel, analüüsida mitmeid arengustsenaariume ja leida piirid TEA integreerimises. Loodud mudel põhineb värsketel andmetel ja võib olla kasutatud järgmistel uuringutel.

Esiteks analüüsiti arengutee ja hetkeolukorda Eesti energiasüsteemis. See analüüs ja kirjanduse ülevaade moodustasid parema teadusliku baasi mudelit. Paljudest erinevatest simuleerimis vahenditest , EnergyPlan oli valitud. Antud vahend on tasuta ja hästi dokumenteeritud, tarkvara on intuitiivse kasutajaliidesega. Ta oli kasutatud erinevate riikide energia süsteemide analüüsimiseks eriti Taani jaoks- riik, mis on tuntud oma pühendumisega TEA arengusse. Kõik vajalikud andmed mudeli jaoks oli võetud avalikest allikatest, näiteks Statistikaamet, Nord Pool Elering, Eesti Weather Service ja teised. Aasta 2014 oli valitud baasaastana selle Magistritööks, kuna mõned andmed 2015 aasta kohta pole kättesaadavad. Tundide soojus nõudlus on kindel sisend, mis on nõutud mudeli jaoks, kuid ei ole mõõdetud. Mudel oli ehitatud kasutades nn soojuskraadi päeva metoodikat. Saadud mudel oli valideeritud ja näitas reaalse mõõtmisele lähedased tulemused. Mitmeid stsenaariumid Eesti taastuvenergia arendamist oli loodud selleks, et hinnata erinevate tehnoloogiate tulemuslikkust, analüüsida süsteemide vastust TEA osakaalu suurenemisele ja leida piirid keskkonnasäästliku energia allikate integreerimiseks. Avamere tuule energia stsenaariumi moodustamiseks, tuule andmetest valitud veebilehed ei olnud kättesaadavad. Tunni jaotus oli simuleeritud kasutades andmeid mitmest lähimatest ilmajaamadest, mis asuvad Kihnul, Osmusaarel ja Hiiumaa saartel. Päikestepaneelide toodangu arvutamise jaoks oli võetud tunni kiirutuse andmed mitmest Eesti ilmateenistusest.

Iga stsenaariumi jaoks, süsteemi kulud, energia tootmine taastuvatest energiaallikatest, CO_2 emisiooni vähendamine, ekspordi/impordi väärtused, maksimaalne TEA tase (põhineb MREI metoodikal) ja paljud teised parameetrid olid võrreldud. Selgus, et Eesti avamere tuuleenergia on kõige kulutasuvam lahendus võrreldes maismaal tuule ja päikeseenergia tootmisega. Teisest küljest , süsteem praeguses olekus võimaldab paigutada rohkem päikeseenergiat kui tuuleenergiat. Elektritarbimise profiil on lähemal päikesepaneelide põlvkonna profiilile ja see toob kaasa madalama kärpe. Eestis, päikesepaneelide katsetused standardsete tingimuste all näitasid, et peaaegu mitte kunagi päikesepaneelid ei tööta oma nimivõimsustel. Aastal 2014 ei olnud ühegi tunni, millal kiirituse tase ulataks 1000 W/m^2 selle pärast päikese võime tegur on suhteliselt madal. Peaks juhtuma päikestepaneelide suur hinna langus enne seda, kui alustakse investeerimist suurte päikeseenergia projektidesse Eestis ja see oleks majanduslikult otstarbekas.

Kaks Eesti suurima energia projekte – Hiiumaa avamere tuulepark ja Gulf of Riga lahe meretuulepark – näitavad hea süsteemi sobivust juba praegu nende oleva disainiga. Eesti energiasüsteem võib mahtuda mõlemad projektid samal ajal, juhul kui nende koguvõimsus on väiksem kui 1410MW. Vaatamata sellele, et nende tuulepargi tootmise tase on väga suured, mitte kõik energia võib olla kasutatud. Praeguste piirangutega sidumisvõimalustes, mingi osa energiast tuleb piirata ja kaotada. Maksimaalse avamere tuulepargi paigaldatud võimsusest 14% kuni 16% kaob. Uute sidumiste arendamisel Eesti ja Lätti vahel piiramise tase läheb alla. Oli näidatud, et kasvav päikeseenergia turuosa vähendab maksimaalse võimalikku tuuleenergia tase süsteemis. Samal ajal maismaa osa tuuletootmisest on suurema mõju all võrreldes avamerega. Kuid see toime oli suhteliselt väike. Üldiselt päikese-ja tuuleenergia kombineerimine on hea ja võib moodustada kuni 50% Eesti elektrienergia tootmist ilma negatiivse mõjuta süsteemile.

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The number of computer tools available for modeling of RES integration is very large. Table below shows types of the most popular tools available.

Tool	Type						
	Simulation	Scenario	Equilibrium	Top-down	Bottom-up	Operation optimisation	Investment optimisation
AEOLIUS	Yes	–	–	–	Yes	–	–
BALMOREL	Yes	Yes	Partial	–	Yes	Yes	Yes
BCHP Screening Tool	Yes	–	–	–	Yes	Yes	–
COMPOSE	–	–	–	–	Yes	Yes	Yes
E4cast	–	Yes	Yes	–	Yes	–	Yes
EMCAS	Yes	Yes	–	–	Yes	–	Yes
EMINENT	–	Yes	–	–	Yes	–	–
EMPS	–	–	–	–	–	Yes	–
EnergyPLAN	Yes	Yes	–	–	Yes	Yes	Yes
energyPRO	Yes	Yes	–	–	–	Yes	Yes
ENPEP-BALANCE	–	Yes	Yes	Yes	–	–	–
GTMax	Yes	–	–	–	–	Yes	–
H2RES	Yes	Yes	–	–	Yes	Yes	–
HOMER	Yes	–	–	–	Yes	Yes	Yes
HYDROGEMS	–	Yes	–	–	–	–	–
IKARUS	–	Yes	–	–	Yes	–	Yes
INFORSE	–	Yes	–	–	–	–	–
Invert	Yes	Yes	–	–	Yes	–	Yes
LEAP	Yes	Yes	–	Yes	Yes	–	–
MARKAL/TIMES	–	Yes	Yes	Partly	Yes	–	Yes
Mesap PlaNet	–	Yes	–	–	Yes	–	–
MESSAGE	–	Yes	Partial	–	Yes	Yes	Yes
MiniCAM	Yes	Yes	Partial	Yes	Yes	–	–
NEMS	–	Yes	Yes	–	–	–	–
ORCED	Yes	Yes	Yes	–	Yes	Yes	Yes
PERSEUS	–	Yes	Yes	–	Yes	–	Yes
PRIMES	–	–	Yes	–	–	–	–
ProdRisk	Yes	–	–	–	–	Yes	Yes
RAMSES	Yes	–	–	–	Yes	Yes	–
RETScreen	–	Yes	–	–	Yes	–	Yes
SimREN	–	–	–	–	–	–	–
SIVAEL	–	–	–	–	–	–	–
STREAM	Yes	–	–	–	–	–	–
TRNSYS16	Yes	Yes	–	–	Yes	Yes	Yes
UniSyD3.0	–	Yes	Yes	–	Yes	–	–
WASP	Yes	–	–	–	–	–	Yes
WILMAR Planning Tool	Yes	–	–	–	–	Yes	–

Table 1. Types of computer tools [57]

It's possible to see that most of the tools are using bottom-up approach and allowing using scenarios. The difference between bottom-up and top-down tools can be seen from the Table 2.

Top-Down Models	Bottom-Up Models
use an "economic approach"	use an "engineering approach"
give pessimistic estimates on "best" performance	give optimistic estimates on "best" performance
can not explicitly represent technologies	allow for detailed description of technologies
reflect available technologies adopted by the market	reflect technical potential
the "most efficient" technologies are given by the production frontier (which is set by market behavior)	efficient technologies can lie beyond the economic production frontier suggested by market behavior
use aggregated data for predicting purposes	use disaggregated data for exploring purposes
are based on observed market behavior	are independent of observed market behavior
disregard the technically most efficient technologies available, thus underestimate potential for efficiency improvements	disregard market thresholds (hidden costs and other constraints), thus overestimate the potential for efficiency improvements
determine energy demand through aggregate economic indices (GNP, price elasticities), but vary in addressing energy supply	represent supply technologies in detail using disaggregated data, but vary in addressing energy consumption
endogenize behavioral relationships	assess costs of technological options directly
assumes there are no discontinuities in historical trends	assumes interactions between energy sector and other sectors is negligible

Table 2. Types of computer tools [65]

All tools can be divided to the groups based on modeled geographical area (global, international, national, state, regional, local), timeframe (from 1 to 75 years, unlimited in case of some tools), time-step (from seconds to years). Tools with long timeframe and yearly resolution and short timeframe (1 year) and hourly resolution making up the majority of tools as it can be seen from Table 3.

Tool	Geographical area	Scenario timeframe	Time-step	Specific focus
			1. National energy-system tools	
			1.1. Time-step simulation tools	
Mesap PlaNet	National/state/regional	No limit	Any	–
TRNSYS16	Local/community	Multiple years	Seconds	–
HOMER	Local/community	1 year[a]	Minutes	–
SimREN	National/state/regional	No limit	Minutes	–
EnergyPLAN	National/state/regional	1 year[a]	Hourly	–
SIVAEL	National/state/regional	1 year[a]	Hourly	–
STREAM	National/state/regional	1 year[a]	Hourly	–
WILMAR Planning Tool	International	1 year[a]	Hourly	–
RAMSES	International	30 years	Hourly	–
BALMOREL	International	Max 50 years	Hourly	–
GTMax	National/state/regional	No limit	Hourly	–
H2RES	Island	No limit	Hourly	–
MARKAL/TIMES	National/state/regional	Max 50 years	Hourly, daily, monthly using user-defined time slices	–
			1.2. Sample periods within a year	
PERSEUS	International	Max 50 years	Based on typical days with 36–72 slots for 1 year	–
UniSyD3.0	National/state/regional	Max 50 years	Bi-weekly	–
RETScreen	User-defined	Max 50 years	monthly	–
			1.3. Scenario tools	
E4cast	National/state/regional	Max 50 years	Yearly	–
EMINENT	National/state/regional	1 year[a]	None/yearly	–
IKARUS	National/state/regional	Max 50 years	Yearly	–
PRIMES	National/state/regional	Max 50 years	Years	–
INFORSE	National/state/regional	50+ years	Yearly	–
ENPEP-BALANCE	National/state/regional	75 years	Yearly	–
LEAP	National/state/regional	No limit	Yearly	–
MESSAGE	Global	50+ years	5 years	–
MiniCAM	Global and regional	50+ years	15 years	–
			2. Tools with a specific focus	
			2.1. Time-step simulation tools	
AEOLIUS	National/state/regional	1 year[a]	Minutes	Effects of fluctuating renewable energy on conventional generation
HYDROGEMS	Single-project investigation	1 year[a]	Minutes	Renewable energy and hydrogen stand-alone systems
energyPRO	Single-project investigation	Max 40 years	Minutes	Single power-plant analysis
BCHP Screening Tool	Single-project investigation	1 year[a]	Hourly	Combined heat and power
ORCED	National/state/regional	1 year[a]	Hourly	Dispatch of electricity
EMCAS	National/state/regional	No limit	Hourly	Electricity markets
ProdRisk	National/state/regional	Multiple years	Hourly	Hydro power
COMPOSE	Single-project investigation	No limit	Hourly	CHP with electric boilers or heat pumps
			2.2. Sample periods within a year	
EMPS	International	25 years	Weekly (with a load duration curve representing fluctuations within the week)	Hydro power
WASP	National/state/regional	Max 50 years	12 load duration curves for a year	Power-plant expansion on the electric grid
			2.3. Scenario tools	
Invert	National/state/regional	Max 50 years	Yearly	Heat sector
NEMS	National/state/regional	Max 50 years	Yearly	US energy markets

Table 3. Characterization of tools' parameters [57]

Another important aspect is availability of tools. Some of presented software products are proprietary making their use for academic purposes less attractive. In case if university or faculty don't have purchased academic license it's in most of the cases too expensive to buy them for individual user. The number of users is important too because generally this parameter is straightly connected to availability of study materials, number of publications where the tool was used and professional forums activity making it's easier to learn. The comparison of tools based on these criteria is presented in Table 4.

Tool	Organisation (link)	Availability	Downloads/sales
	Very high number of users		
RETScreen	RETScreen International (http://www.retscreen.net/)	Free to Download	>200000
HOMER	National Renewable Energy Laboratory and HOMER Energy LLC (www.homerenergy.com)	Free to Download	>28000
LEAP	Stockholm Environment Institute (http://www.energycommunity.org/)	Commercial/free for developing countries and students	>5000
BCHP Screening Tool	Oak Ridge National Laboratory (http://www.ornl.gov/)	Free to Download	>2000
energyPRO	Energi-Og Mijødata (EMD) International A/S (http://www.emd.dk/)	Commercial	>1000
	High number of users		
EnergyPLAN	Aalborg University (http://www.energyplan.eu/)	Free to Download	100–1000
Invert	Energy Economics Group, Vienna University of Technology (http://www.invert.at/)	Free to Download	100–1000
MARKAL/TIMES	Energy Technology Systems Analysis Program, International Energy Agency (http://www.etsap.org/)	Commercial	100–1000
MESSAGE	International Institute for Applied Systems Analysis (http://www.iiasa.ac.at/)	Free/Simulators must be purchased	100–1000
ORCED	Oak Ridge National Laboratory (http://www.ornl.gov/)	Free to Download	100–1000
TRNSYS16	The University of Wisconsin Madison (http://sel.me.wisc.edu/trnsys/)	Commercial	100–1000
WASP	International Atomic Energy Agency (http://www.iaea.org/OurWork/ST/NE/Pess/PESSenergymodels.shtml)	Commercial/Free to IAEA member states	100–1000
	Medium number of users		
EMCAS	Argonne National Laboratory (http://www.dis.anl.gov/projects/emcas.html)	Commercial	20-50
EMPS	Stiftelsen for Industriell og Teknisk Forskning (SINTEF) (http://www.sintef.no/)	Commercial	20-50
ENPEP-BALANCE	Argonne National Laboratory (http://www.dis.anl.gov/projects/Enpepwin.html)	Free to Download	20-50
GTMax	Argonne National Laboratory (http://www.dis.anl.gov/projects/Gtmax.html)	Commercial	20-50
	Low number of users		
AEOLIUS	Institute for Industrial Production, Universität Karlsruhe (http://www-iip.wiwi.uni-karlsruhe.de/)	Commercial	1–20
COMPOSE	Aalborg University (http://www.socialtext.net/energyinteractivenet/index.cgi?compose)	Free to Download	1–20
IKARUS	Research Centre Jülich, Institute of Energy Research (http://www.fz-juelich.de/ief/ief-ste/index.php?index=3)	Commercial/Earlier versions are free	1–20
INFORSE	The International Network for Sustainable Energy (http://www.inforse.org/europe/Vision2050.htm)	Distributed to non-governmental organisations	1–20
Mesap PlaNet	seven2one (http://www.seven2one.de/de/technologie/mesap.html)	Commercial	1–20
NEMS	Office of Integrated Analysis and Forecasting, Energy Information Administration (http://www.eia.doe.gov/)	Free/Simulators must be purchased	1–20
PERSEUS	Institute for Industrial Production, Universität Karlsruhe (http://www-iip.wiwi.uni-karlsruhe.de/)	Commercial: only sold to large European utilities	1–20
ProdRisk	Stiftelsen for Industriell og Teknisk Forskning (SINTEF) (http://www.sintef.no/Home/)	Commercial	1–20
RAMSES	Danish Energy Agency (http://www.ens.dk/)	Projects completed for a fee	1–20
SIVAEL	Energinet.dk (http://www.energinet.dk/en/menu/Planning/Analysis+models/Sivael/SIVAEL.htm)	Free to Download	1–20
EMINENT	Instituto Superior Técnico, Technical University of Lisbon (http://carnot.ist.utl.pt/~eminent2/)	To be decided	0
PRIMES	National Technical University of Athens (http://www.e3mlab.ntua.gr/)	Projects completed for a fee	0
	Number of users is not specified as it is not monitored		
BALMOREL	Project Driven with a users network and forum around it (http://www.balmorel.com/)	Free to Download (Open Source)	Not specified
E4cast	Australian Bureau of Agricultural and Resource Economics (http://www.abare.gov.au/)	Commercial	Not specified
H2RES	Instituto Superior Técnico and the University of Zagreb (http://powerlab.fsb.hr/h2res/)	Internal use only	Not specified
HYDROGEMS	Institutt for energiteknikk (http://www.hydrogems.no/)	Commercial/free for TRNSYS Users	Not specified
MiniCAM	Pacific Northwest National Laboratory (http://www.globalchange.umd.edu/)	Free to Download Once Contacted	Not specified
SimREN	Institute of Sustainable Solutions and Innovations (http://www.isusi.de/theerjreport.html)	Projects completed for a fee	Not specified
STREAM	Ea Energy Analyses (http://www.ea-energianalyse.dk/)	Free to Download Once Contacted	Not specified
UniSyD3.0	Unitec New Zealand (http://www.unitec.ac.nz/)	Contact Prof. Jonathan Leaver: jleaver@unitec.ac.nz	Not specified
WILMAR Planning Tool	Risø DTU National Laboratory for Sustainable Energy (http://www.wilmar.risoe.dk/)	Commercial	Not specified

Table 4. Number of users and availability of tools [57]

EnergyPLAN tool was chosen based on criteria described above. The tool and documentation are freely available for download for all users and purposes, user base is relatively big and it was used in many studies investigating integration of RES in energy systems. It's one of just four tools which were used to simulate 100% RES systems with 1 hour time-step [57]. The geographical area which can be investigated can vary and in most of the studies this software was used at country scale. EnergyPLAN is taught in many Danish universities and was used many times to analyze Danish energy system both at the current moment and future scenarios. These factors are showing the potential of the tool for the purposes of this thesis.

In order to estimate maximum share of RES and show interplay between external market and Estonian energy system, market-economic strategy was chosen making it necessary to include prices and specify external market as well. In the current section all the data used as inputs will be described alongside with corresponding sources and assumptions.

As it was mentioned in the description of EnergyPLAN, it uses hourly distributions containing 8784 data points which is number of hours in a leap year. The year 2014 wasn't a leap year and in order to build proper inputs the last day of the year was copied and pasted in the end of actual observed distribution. This is a necessary measure in order to make EnergyPLAN to recognize input files.

1. Electricity demand

For the purposes of this thesis market-economic simulation was used. Estonia is connected to Finland, Latvia and Russia. It's possible to simulate only one interconnection with external market in EnergyPLAN and in this thesis Latvian market was chosen due to the fact that it's highly dependent from Estonian energy supply. Interconnection with Finland was used as a fixed import-export which means that it's not changing when inputs are changing. This is one of limitations of EnergyPLAN model but as Zakeri et al. [60] pointed out, the error originating from it is under 8%. The inputs for electricity demand section were taken from the table "FE03: ELECTRICITY BALANCE SHEET by Indicator and Year" of Statistics Estonia[5] (Table 1).

[5] Due to the design of the Statistics Estonia web site, there is no possibility to give a direct link to any particular statistical table. To make it possible to find relevant data, for each table used in this thesis its full name will be given. The search engine located at http://pub.stat.ee/px-web.2001/Dialog/statfile1.asp might be used to find any table by its name provided here and later in this work.

FE03: ELECTRICITY BALANCE SHEET by Indicator and Year	
	2014
Gross production*	12 444
Net production**	11 013
Imports	3 730
..imports from Russia***	0
..imports from Latvia	108
..imports from Lithuania	0
..imports from Finland	3 622
Consumption	7 417
..consumption in industry****	2 548
..consumption in construction	78
..consumption in agriculture	205
..consumption in transport	50
..consumption in households	1 739
..consumption in other branches	2 797
Own use by power plants	1 431
Losses****	842
Exports	6 484
..exports to Russia	0
..exports to Latvia	6 390
..exports to Lithuania	0
..exports to Finland	94

Table 1. Estonian electricity balance 2014, GWh [69]

Estonia has imported 3 622 GWh of electricity from Finland and exported 94 GWh. This means that fixed import-export input will be equal to -3.528 TWh as in EnergyPLAN it is calculated as export less import.

The total inland consumption is calculated as follows:

$$Total\ consumption = Gross\ production + Imports - Exports$$
$$= 12444 + 3730 - 6484 = 9690\ GWh \quad (1)$$

The distribution of electricity consumption for 2014 was taken from the data provided by Estonian TSO Elering [70] (Figure 1).

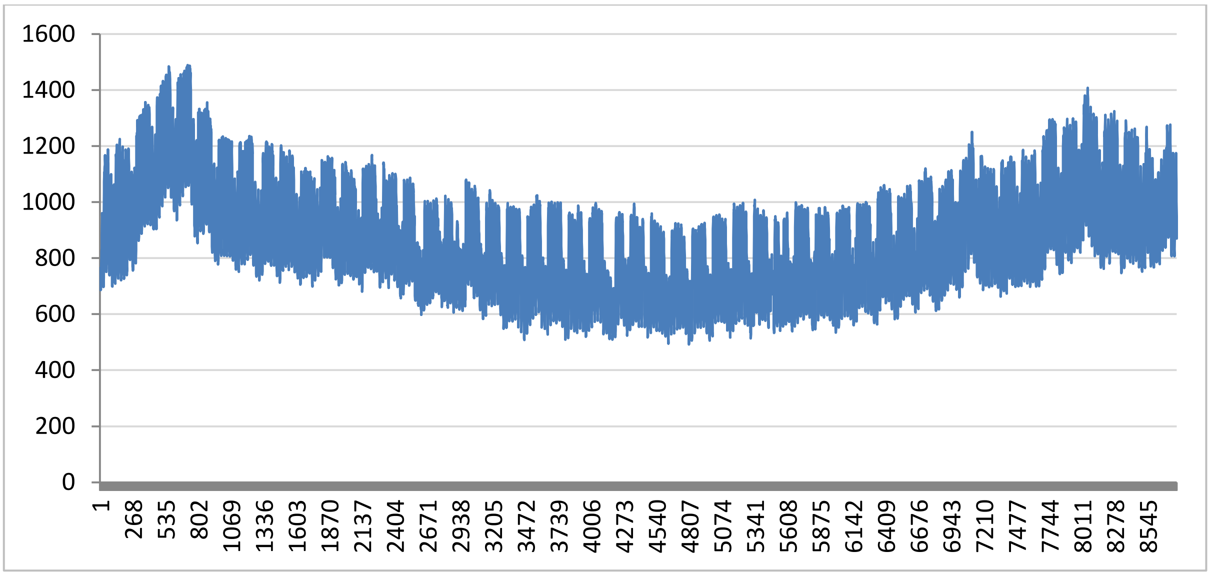


Figure 1. Electricity consumption in Estonia in 2014, MWh [70]

Hourly distribution of electricity exchange with Finland was obtained from Nord Pool historical market data [71] and shown on the figure below:

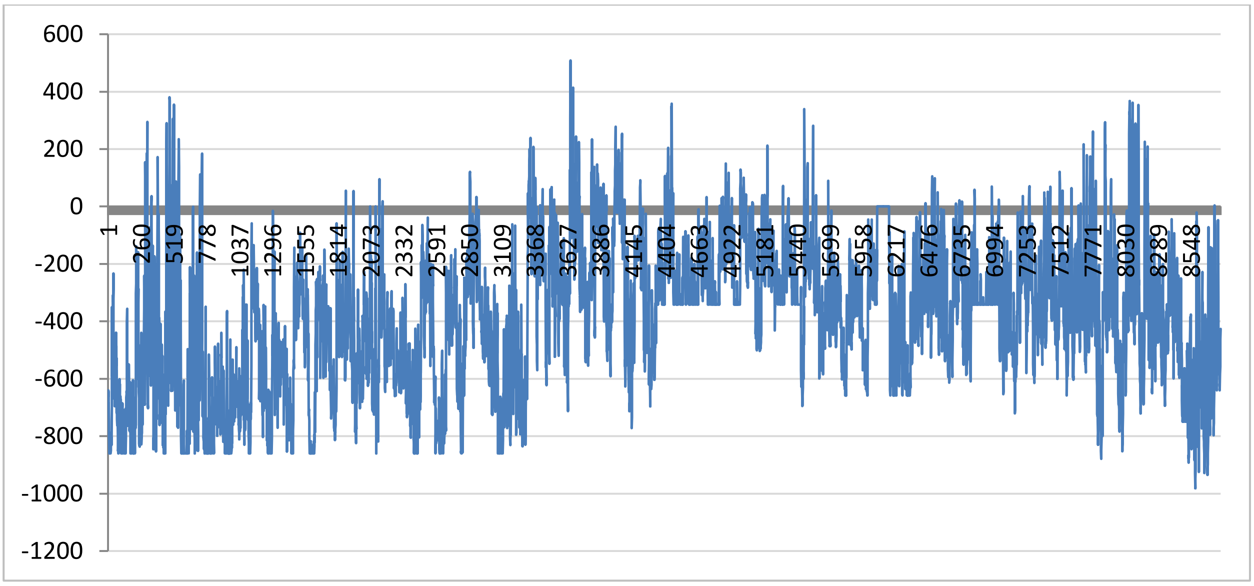


Figure 2. Electricity exchange between Estonia and Finland in 2014, MWh [71]

These distributions don't need to be normalized since EnergyPLAN is doing it internally. Figure 3 shows EnergyPLAN tab with all used inputs highlighted yellow.

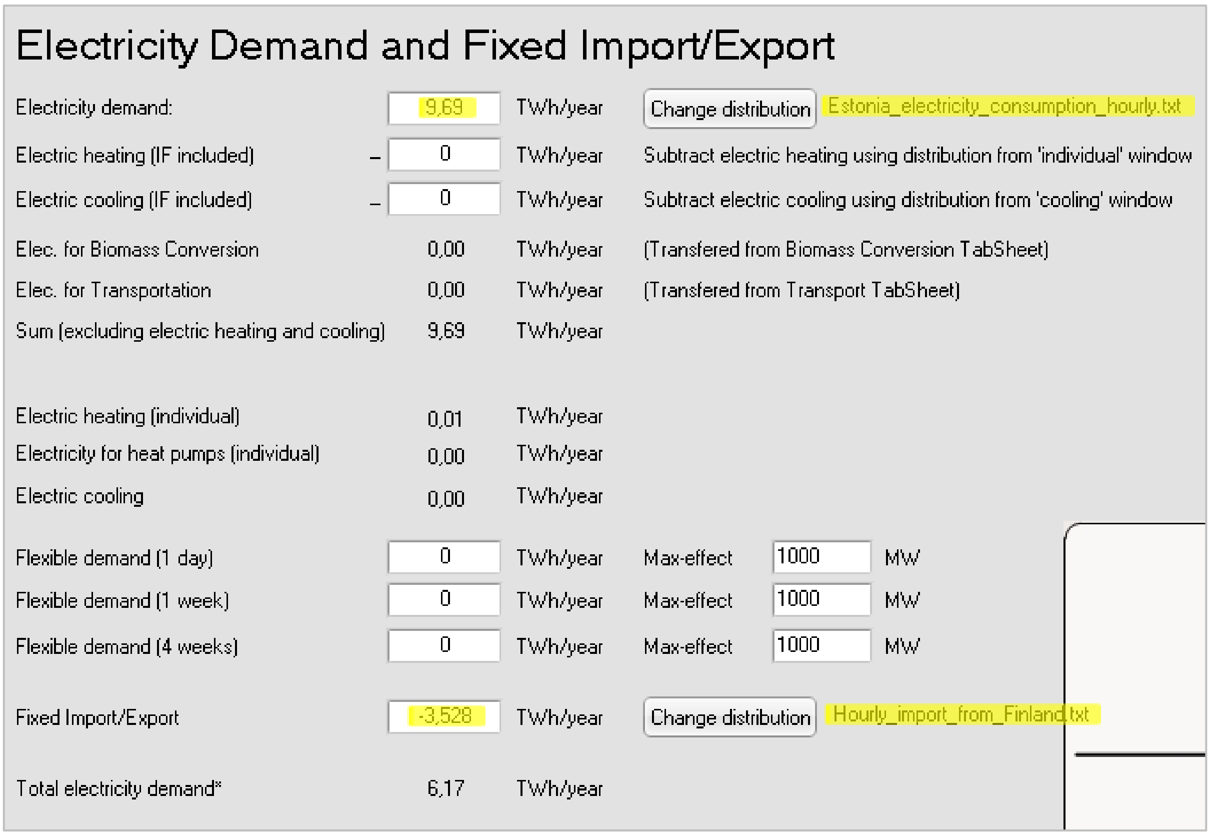


Figure 3. Electricity demand inputs

2. Heating demand

The distribution of heating demand for Estonia was built using "degree days" method described in "Methodology" section. As it was mentioned, it was assumed that there is no need for space heating during summer months. Although there is always some hot water demand and it is more or less constant over the year. According to research conducted by Koiv et al. [72] heat demand for water heating is making 24% of total yearly heat demand. This data was used to build the final distribution (Figure 4).

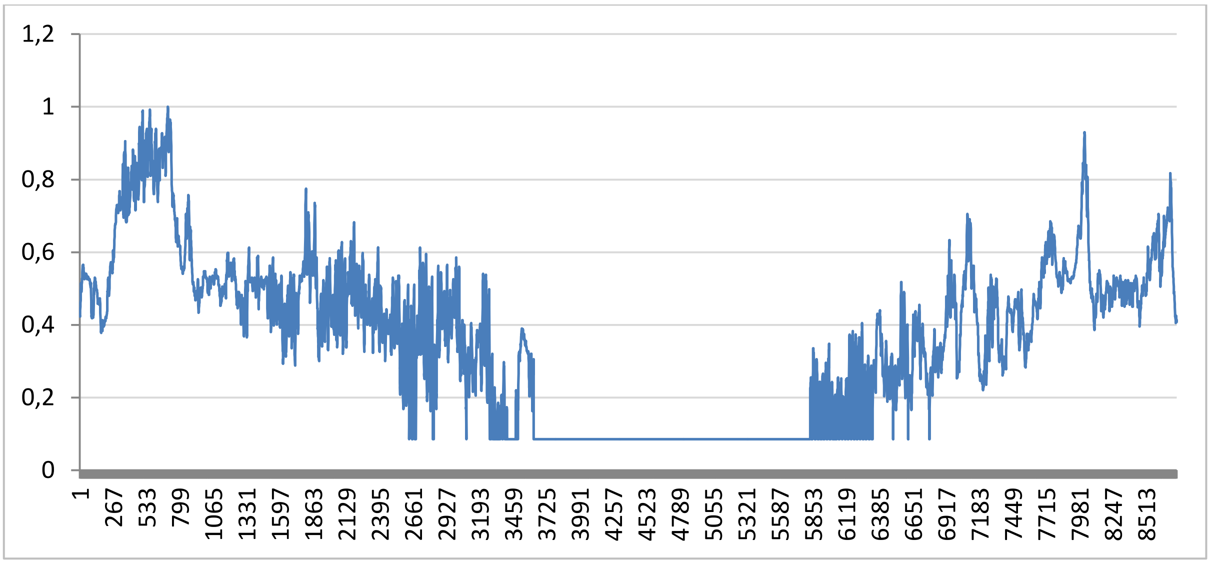


Figure 4. Normalized heating demand in Estonia in 2014

Heating demand section in EnergyPLAN consists from individual and district heating. According to Statistics Estonia "FE04: HEAT BALANCE SHEET by Indicator and Year" table in 2014 heat consumption in Estonia was 8913 GWh from which 6059 GWh came from district heating and 2854 GWh from individual heating [69] (Table 2).

FE04: HEAT BALANCE SHEET by Indicator and Year	
	2014
Production	8 913
..production in power plants*	4 077
..production in heating plants	4 836
District heating**	6 059
Consumption	8 015
..consumption in industry***	2 581
..consumption in construction	32
..consumption in agriculture	108
..consumption in households	3 470
..consumption in other branches	1 824
Losses****	898

Table 2. Heat balance in Estonia in 2014

Generation of heat from boilers was taken from the table "FE043: BOILERS by Year, Type of boiler and Indicator". EnergyPLAN fuels division is different from the one given by Statistics Estonia. All different types of fuels should be grouped into categories: coal, oil, natural gas and biomass. Electrical boilers are representing a separate category. The resulting distribution is presented in Table 3.

Boiler type	Generated heat	Share
Coal	141	3%
Oil	453	9%
Ngas	2572	53%
Biomass	1661	34%
Electricity	9	0%
Total	4836	100%

Table 3. Heat generation from boilers in Estonia in 2014, GWh

It was assumed that these shares are the same for individual and DH boilers. The share of electric heating is very small and was neglected.

Individual heating in EnergyPLAN is calculated from fuel consumption and boilers efficiencies ratings. This made in order to connect individual heating and fuel consumption for further calculations of CO_2 emissions and fuel costs. Since the data provided by Statistics Estonia is not representing fuel consumption by boilers, it was calculated using average boilers efficiencies (average load efficiency) provided by Vatopoulos et al. [73] (Table 4).

Fuel	Boiler Efficiency %	
	Min Load	Max Load
Coal	75%	85
Oil	72%	80
Gas	70%	75
Biomass	60%	70

Table 4. Boilers efficiency

Using the data provided above, final inputs for individual heating were calculated (Table 5).

Boiler type	Efficiency	Amount of individual heat produced, GWh	Fuel consumption, GWh
Coal	0.8	0.08	0.10
Oil	0.76	0.27	0.35
Ngas	0.725	1.52	2.09
Biomass	0.65	0.98	1.51
Total		2.85	4.06

Table 5. Individual boilers generation and fuel consumption

Final inputs in EnergyPLAN are presented in Figure 5.

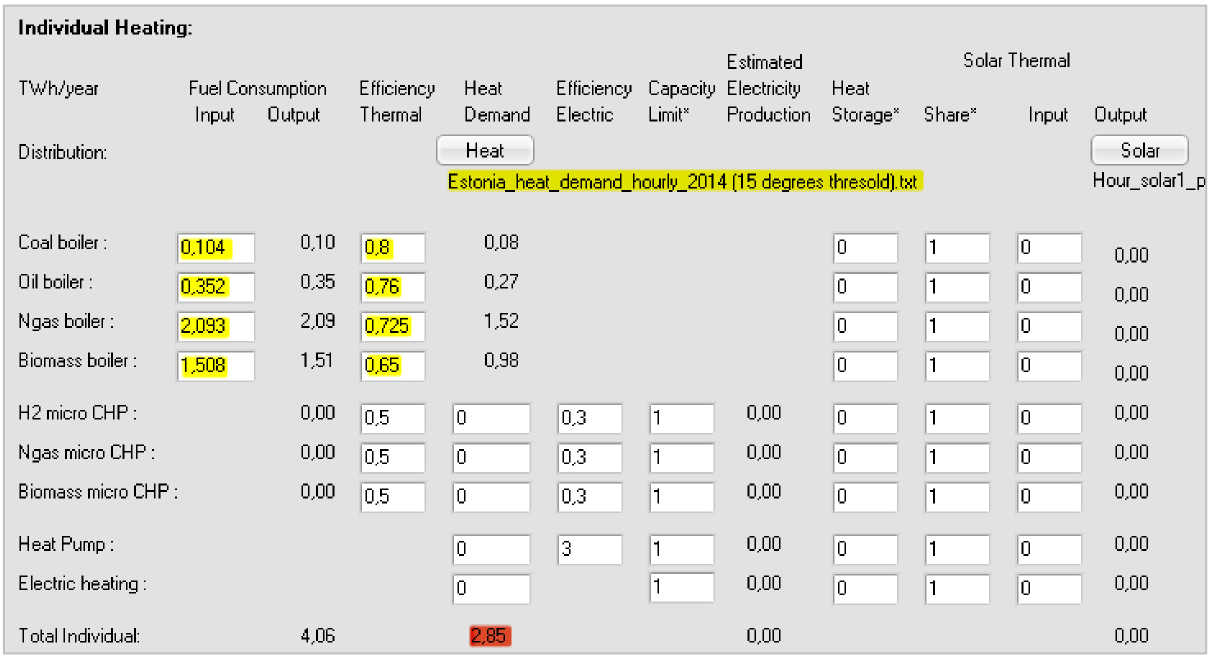


Figure 5. Individual heating demand inputs

Parts highlighted yellow are representing model inputs, the number highlighted red is a total individual heating demand calculated by EnergyPLAN from these inputs. All other values presented in the picture are either calculated by EnergyPLAN (gray background) or are default inputs not influencing the result (white background).

District heating plants in EnergyPLAN are divided to three groups:

- Group 1 – systems representing boilers without CHP plants
- Group 2 – systems with small CHP plants which are always operating with a heat load
- Group 3 – systems with large CHP which can generate electricity without the need to produce heat

As it is possible to see from Table 2, boilers generated 4836 GWh of heat in 2014 from which 2854 GWh came from small scale boilers. Remaining 1982 GWh were generated by large scale DH boilers. It was assumed that these boilers are located in areas with no access to CHP plants and thus representing Group 1.

Production of heat in Group 2 was found using assumption that this group is represented by backpressure CHP plants. Production of heat by these plants was found from the table “FE034: CHP PLANTS by Year, Indicator and Type of generator” of Statistics Estonia (Table 6). The corresponding value is 2477 GWh.

FE034: CHP PLANTS by Year, Indicator and Type of generator				
	Total	**Backpressure turbine**	**Steam condensing turbine**	**Internal combustion engine**
2014				
Number of turbines/internal combustion engines	46	13	14	19
Maximum electrical capacity, MW	466	223	220	23
Maximum useful heating capacity, MW	1 432	723	685	24
Electricity generation, GWh	1 239	819	328	92
Heat production, GWh	3 515	2 477	951	87
Consumption of coal, thousand t	1	1	0	0
Consumption of oil shale, thousand t	652	60	592	0
Consumption of peat, thousand t	66	65	1	0
Consumption of wood, thousand m^3 solid volume	1 170.0	1 141.0	29.0	0.0
Consumption of shale oil, thousand t	1	0	1	0
Consumption of natural gas, thousand t	27	10	0	17
Consumption of shale oil gas, TJ	2 028	815	1 213	0
Consumption of biogas and black liquor, TJ	1 544	1 331	0	213
Consumption of municipal waste, TJ	1 455	1 455	0	0
Consumption of coal, TJ	18	18	0	0
Consumption of oil shale, TJ	5 010	465	4 545	0
Consumption of peat, TJ	685	678	7	0
Consumption of wood, TJ	8 787	8 478	309	0
Consumption of shale oil, TJ	33	12	21	0
Consumption of natural gas, TJ	905	325	2	578

Table 6. CHP plants production in Estonia in 2014

The rest of heat production (1630 GWh) was assumed to represent Group 3 plants production. It is possible to see from Table 6 that total losses in transmission lines in 2014 were 898 GWh or 15% from DH heat production. The distribution for heat consumption was assumed to be the same for individual and district heating. It was assumed that the relative losses are the same in all groups. Described above values were used as inputs in the model (Figure 6).

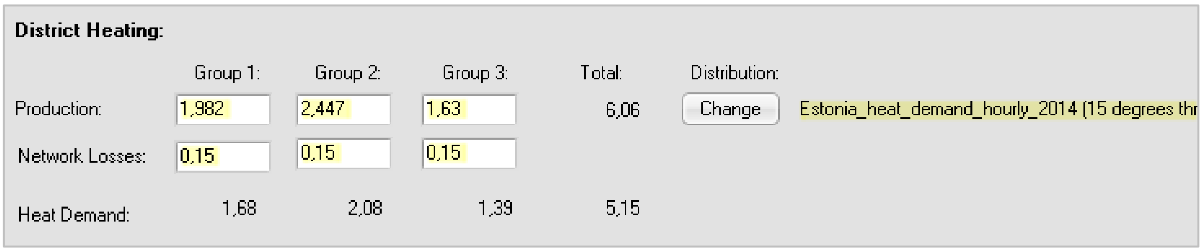


Figure 6. District heating inputs

3. Fuel consumption

Fuel consumption in EnergyPLAN is divided into three main categories: industry, transport and various. This data was obtained from the table "FE024: ENERGY BALANCE SHEET, TERAJOULES by Type of fuel/energy, Year and Indicator" [69] (The table is provided in TJ and TWh Annex III). This table has categories "Final consumption in industry" and "Final consumption in transport" which were used as a base for the corresponding inputs in EenrgyPLAN. Categories "Final consumption in commercial and public services", "Final consumption in households" and "Final consumption in agriculture and fishing" were grouped to the input "Various".

For "Industry and Other Fuel Consumption" tab EnergyPLAN is using the same four fuel categories as for individual boilers: coal, oil, natural gas and biomass. Statistics Estonia is providing more detailed decomposition into more than 20 fuel types. These fuel types were combined together in order to create the final inputs. The comparison of fuel categories in Statistics Estonia and EnergyPLAN is presented in Table 7.

Statistics Estonia category	EnergyPLAN category
Coal	Coal
Coke*	
Oil shale	
Milled peat	
Sod peat	
Peat briquette	
Wood*	Biomass
Briquette and pellets	
Biogas**	
Other biomass**	
Municipal waste	
Natural gas	Natural gas
Liquefied gas	
Shale oil gas**	
Heavy fuel oil	Oil
Shale oil (heavy fraction)	
Shale oil (light fraction)	
Light fuel oil and diesel**	
Motor gasoline	
Aviation gasoline	

Table 7. Comparison of fuel categories in Statistics Estonia and EnergyPLAN

The final inputs for “Industry” and “Various” are presented in Figure 7.

Industry and Other Fuel Consumption

TWh/year	Industry	Various*	Fuel Losses*
Coal	0,9	0,1	0
Oil	0,47	4,38	0
Ngas	0,46	0,95	0
Biomass	0,26	4,41	0

Figure 7. EnergyPLAN inputs for industry and other fuel consumption

In transport section the division of fuels into categories is different from industry and is presented by jet fuel, diesel, petrol, natural gas and LPG. These categories are connected to corresponding categories of energy balance provided by Statistics Estonia (Appendix III). The final inputs in “Transport section” of EnergyPLAN are shown in Figure 8.

TWh/year	Fossil	Biofuel	Waste*	Synthetic Fuel	Total
JP (Jet Fuel)	0,48	0		0	0,48
Diesel	4,84	0	0,00	0	4,84
Petrol	0,71	0		0	0,71
Ngas* (Grid Gas)	0,02				0,02
LPG	0				0,00
H2 (Produced by Electrolysers)					0
Electricity (Dump Charge)					0
Electricity (Smart Charge)					0

Figure 8. EnergyPLAN inputs for transport sector

4. Heat and electricity supply

The EnergyPLAN’s tab representing heat and electricity supply is divided into three sections:

- Boilers
- CHP
- Industrial CHP

In previous sections an assumption was made that all boilers are either used for individual heating or located in areas where no CHP plants are available (Group 1 of EnergyPLAN). This means that there will be no boilers in Group 2 and Group3 (more information on groups in EnergyPLAN is provided in Section 2. of this Appendix).

The classification of plants in EnergyPLAN and in Statistics Estonia is different and categories were matched in the next way:

- Industrial CHP in EnergyPLAN represents “Autoproducers power plants” from table “FE032: CAPACITY AND PRODUCTION OF POWER PLANTS by Year, Indicator and Type of power plant” of Statistics Estonia
- Group 2 CHP plants in EnergyPLAN are representing backpressure turbine plants from Table 10
- Group 3 CHP plants in EnergyPLAN – steam condensing turbines from Table 10

The final input for industrial CHP plants in EnergyPLAN is shown in Figure 9.

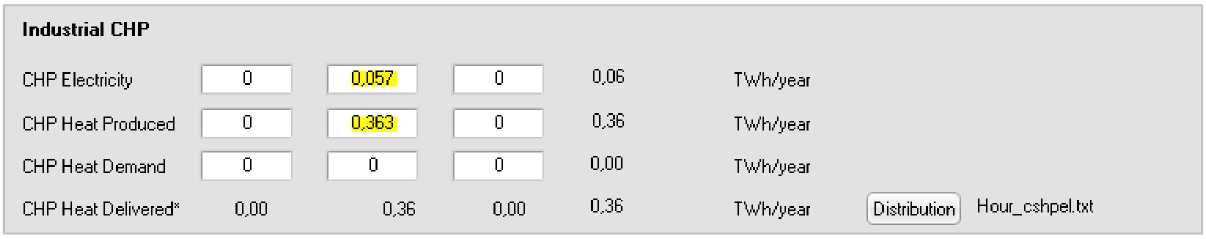


Figure 9. EnergyPLAN inputs for industrial CHP

Since distribution of industrial CHP’s is unknown, it was assumed to be constant.

Electric capacity of CHP plants was taken from table “FE034: CHP PLANTS by Year, Indicator and Type of generator” (Table 6) of Statistics Estonia. Electric and thermal efficiencies were first calculated from fuel consumption data and energy production from the same table but output results of model were higher than it was observed. It can be explained by the fact that in real life plants sometimes are operating in non-optimal mode, as well by possible outages or repairs. Efficiencies were corrected in order to obtain a correct output from the model.

The rest of capacity was placed in “CHP condensing mode operation” (plants producing no heat) and to “Waste” section (will be described in Section 7). The calculation of electric efficiency for “CHP Condensing Mode Operation” will be shown in Section 6 because it is connected to fuel balances for different types of generators. The final inputs for CHP plants section are shown in Figure 10.

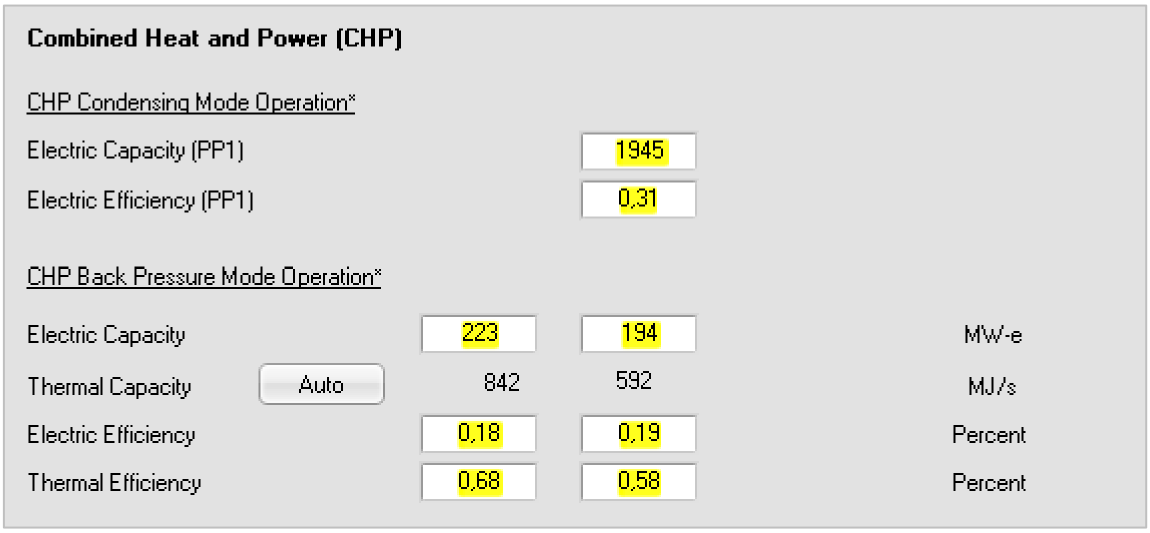


Figure 10. EnergyPLAN inputs for CHP plants

5. Electricity only supply

"Electricity Only" tab of EnergyPLAN contains inputs the following types of generators:

- Condensing power plants
- Nuclear power plants
- Geothermal power plants
- Damned hydro power
- Damned hydro storage
- Intermittent renewable energy sources

Condensing power plants were specified in previous section and from the list below only intermittent energy sources are presented in Estonia. According to Statistics Estonia, these sources namely are wind energy and river hydro energy. The installed capacities of hydro (5 MW) and wind energy (334 MW) were taken from "FE032: CAPACITY AND PRODUCTION OF POWER PLANTS by Year, Indicator and Type of power plant" [69] (This table can be seen in Appendix IV).

The distribution for generation from wind was obtained from Elering data archive [70]. The numbers for generation provided there are in MW and were normalized to the total installed capacity of wind turbines. In cases of missing data, the linear regression was used to fill blank fields based on nearest available observations. The final distribution used as an input is shown in Figure 11.

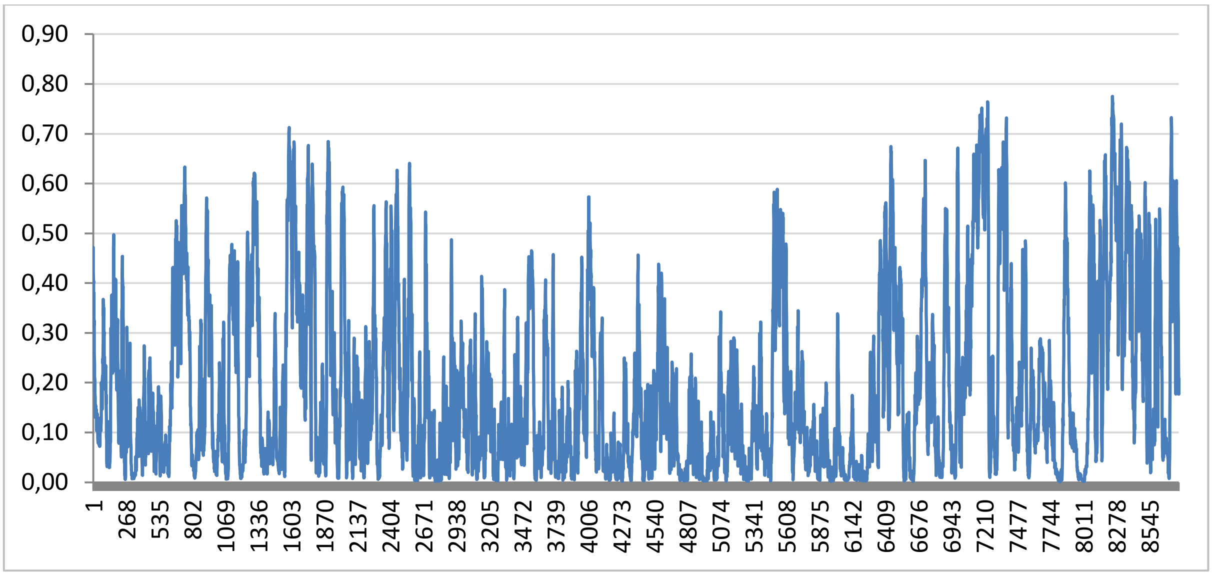
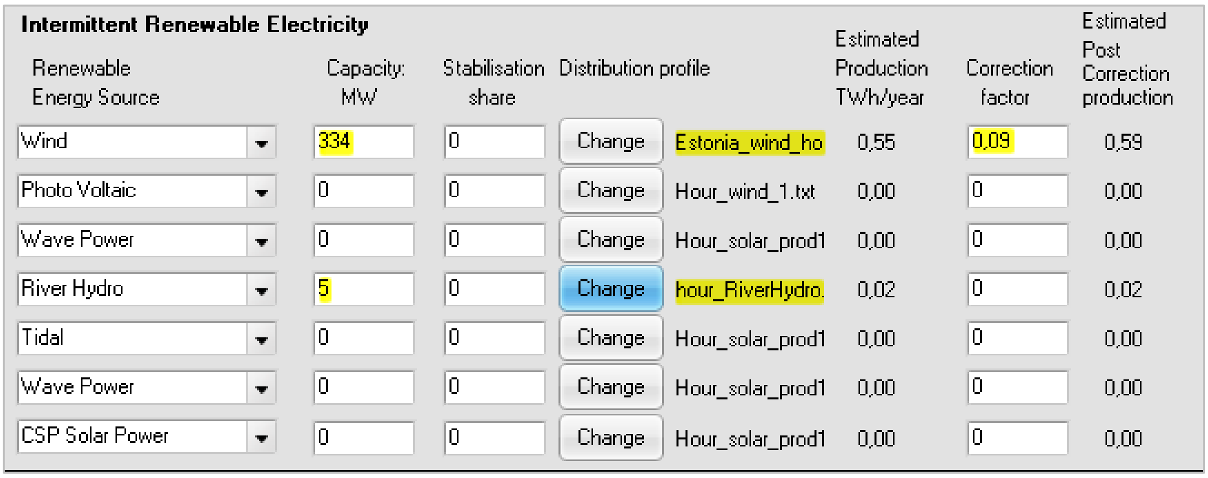


Figure 11. Wind energy load in Estonia in 2014

The maximum load during the year was 78% and minimum 0%. The resulting yearly output of wind farms in EnergyPLAN was slightly lower than the value provided by Statistics Estonia and was adjusted using the correction factor feature of EnergyPLAN. The final output of 0.61 GWh was achieved by using correction factor of 0.09.

There is no data for hourly hydro energy generation available and installed capacity of hydro plants is very low. The default distribution available in EnergyPLAN data was used in this thesis. Final inputs are shown in Figure 12.


Intermittent Renewable Electricity

Renewable Energy Source	Capacity: MW	Stabilisation share	Distribution profile		Estimated Production TWh/year	Correction factor	Estimated Post Correction production
Wind	334	0	Change	Estonia_wind_ho	0,55	0,09	0,59
Photo Voltaic	0	0	Change	Hour_wind_1.txt	0,00	0	0,00
Wave Power	0	0	Change	Hour_solar_prod1	0,00	0	0,00
River Hydro	5	0	Change	hour_RiverHydro.	0,02	0	0,02
Tidal	0	0	Change	Hour_solar_prod1	0,00	0	0,00
Wave Power	0	0	Change	Hour_solar_prod1	0,00	0	0,00
CSP Solar Power	0	0	Change	Hour_solar_prod1	0,00	0	0,00

Figure 12. Intermittent renewable energy sources input in EnergyPLAN

6. Thermal plant fuel distribution

Consumption of fuels in EnergyPLAN is divided to categories:

- DHP – district heating plants in Group 1

- CHP2 – CHP plants in Category 2
- CHP3 – CHP plants in Category 3
- Boiler2 – boilers in Category 2
- Boiler3 – boilers in Category 3
- PP1 – condensing power plants (first category)
- PP2 – condensing power plants (second category)

The division of power plants (PP) into two different categories is needed in case if in some system there will be plants with very different efficiencies. In this case it's possible to see outputs of high efficiency and low efficiency plants separately.

As it was assumed in Section 2, all district heating plants in Group 1 are represented by boilers. The fuel distribution for DHP was calculated from total consumption by boilers available from the table "FE043: BOILERS by Year, Type of boiler and Indicator" [69] after deduction of consumption by domestic boilers presented in Table 5. Efficiencies of boilers were assumed to be the same as provided in Table 4.

Consumption of fuels by CHP plants was taken from the table "FE034: CHP PLANTS by Year, Indicator and Type of generator" (Table 6) by converting TJ to TWh and grouping fuels into larger categories: Coal, Oil, Ngas and Biomass. Final consumption by fuels is presented in Table 8.

	CHP1	CHP2
Coal	0.32	1.26
Oil	0.00	0.01
Ngas	0.48	0.34
Biomass	2.78	0.09

Table 8. Fuel distribution inputs for CHP plants in EnergyPLAN

Fuel consumption by power plants was found by subtracting consumption of fuels by CHP and DHP plants from total consumption available from energy balance of Estonia (presented in Annex III). The final inputs are presented in Figure 13.

Distribution of fuel (TWh/year)	Coal	Oil	Ngas	Biomass
	Fixed	Fixed	Fixed	Fixed
DHP	0,07	0,254	1,2	0,897
CHP2	0,32	0,003	0,48	2,78
CHP3	1,26	0,006	0,34	0,085
Boiler2	0	0	0	0
Boiler3	0	0	0	0
PP1	32,33	0	1,61	0
PP2	0	0	0	0

Figure 13. Thermal plant fuel distribution input in EnergyPLAN

7. Waste incineration

Consumption of waste for the "Waste incineration" section of EnergyPLAN was taken from Estonian energy balance (Annex III) as amount of municipal waste used for electricity and heat generation. The total consumption of municipal waste in Estonia was 0.5975 TWh. Another input necessary for calculations of this section in EnergyPLAN is efficiency of generators. This data is not publicly available but can be calculated if final generation of heat and electricity from waste is known. These numbers were obtained from "FE032: CAPACITY AND PRODUCTION OF POWER PLANTS by Year, Indicator and Type of power plant" table (Appendix IV). The inputs for heat and electricity production efficiencies were adjusted in the way to give electricity and heat production outputs equal to ones observed in 2014. The final inputs are shown in Figure 14.

	Waste input	DH production		Electricity production	
Unit:	TWh/year	Efficiency	TWh/year	Efficiency	TWh/year
Group 1:	0,5975	0,4	0,24	0,16	0,10
Group 2:	0	0,8	0,00	0	0,00
Group 3:	0	0,8	0,00	0	0,00
Total:	0,60		0,24		0,10

Figure 14. Inputs for the "Waste" section in EnergyPLAN

8. CO2 emissions factors

Estonian energy system is characterized by extremely high consumption of oil shale which represents almost all solid fuels consumption. In EnergyPLAN there are no separate inputs for different solid fuels and they are all grouped in "Coal" category. Emission factor for oil shale was taken from the manual created as a part of the "Cement CO_2 and Energy Protocol" and is equal to 107 tCO_2/TJ [74]. This number was used as input for solid fuels in EnergyPLAN. Emission factor for waste was taken from the same source mentioned above [74].

The oil category in EnergyPLAN represents a variety of different fuels. The input was calculated as a weighted average emission factor of all oil products consumed in Estonia in 2014. Emission factors for these products were obtained from the report "Energy in Ireland 1990 – 2007" created by Sustainable Energy Authority of Ireland (SEAI) [75]. The resulting table is shown below:

Fuel	Consumption in Estonia in 2014, TWh	Emission factor, tCO2/TJ
Heavy fuel oil	0.00	76
Shale oil (heavy fraction)	0.01	76
Shale oil (light fraction)	0.12	71.4
Light fuel oil**	0.05	71.4
Diesel oil	7.26	73.3
Motor gasoline	2.95	70
Aviation gasoline	0.48	71.4
Weighted average emission factor		**72.30**

Table 9. Emission factors for oil products in Estonia in 2014

Emission factors for natural gas and LPG were taken from the same document by SEAI [75]. Resulting inputs for the "CO_2" section are shown in Figure 15.

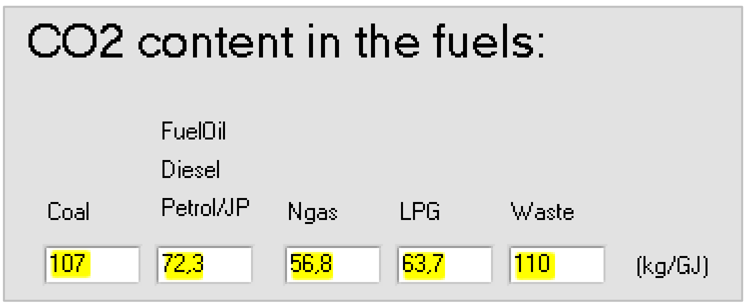


Figure 15. Inputs for the "CO_2" section in EnergyPLAN

9. Costs

All costs in EnergyPLAN are divided in five categories each of which will be described in a dedicated section below.

9.1. General

The “General” tab in EnergyPLAN consists just of two parameters – CO_2 price and interest rate. For this analysis interest rate was assumed to be 5%. CO_2 price was calculated as an average price of EU Emission Allowances during 2014 taken from [75] and is equal to 6 EUR/t CO_2.

9.2. Investment and Fixed OM

In this section investment costs, lifecycle in years and fixed operation and maintenance costs for each available technology should be entered. This data is very specific and obtaining these numbers for a particular country is a topic for a separate study. For the purposes of this thesis all necessary numbers were taken from existent EnergyPLAN models for other countries. The main source for the input was a model of Finland [60]. In the case if some particular number was not available, the model of the UK for the year 2010 was used [76].

The final inputs can be found in Appendix V. Numbers obtained from [60] are highlighted in yellow, where [76] was used as a source, blue colour was used.

9.3. Fuel

Prices of oil shale and biomass were provided by Lauri Ulm and the rest were obtained from the table “FE08: AVERAGE COST OF FUELS AND ENERGY CONSUMED BY ENTERPRISES by Type of fuel/energy and Year” of Statistics Estonia [69] (Table 10).

Coal, euros/ton	64.69
Oil shale, euros/ton	15.06
Sod peat, euros/ton	40.27
Peat-briquette, euros/ton	98.34
Firewood, euros/m^3 sol vol	26.74
Wood chips, euros/m^3	11.58
Wood waste, euros/m^3	11.39
Natural gas, euros/1000 m^3	373.15
Heavy fuel oil, euros/ton	453.92
Shale oil, euros/ton	439.44
Light fuel oil, euros/ton	686.97

Diesel, euros/ton	1 039.09
Motor gasoline, euros/ton	1 290.04
Electricity, euros/MWh	83.18
Heat, euros/MWh	60.12

Table 10. Average prices of fuels in Estonia in 2014, EUR [69]

For the “FuelOil” input of EnergyPLAN the average price for light and heavy fuel oil was taken. For a conversion of prices in EUR/GJ calorific values provided by Statistics Estonia were used [77] (Appendix VI). For each fuel the average calorific value was taken. Fuel handling costs were taken from the model of Irish energy system [78]. The final inputs are shown in the Figure below.

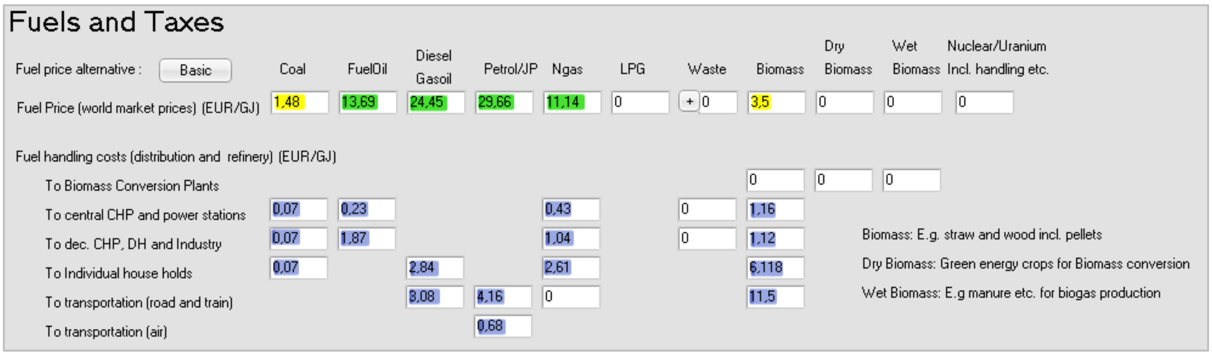


Figure 16. Inputs for the “Fuels and Taxes” section in EnergyPLAN

In order to separate numbers from different sources, different highlighting colours were used:

- Yellow – Data provided by Eesti Energia
- Green – Statistics Estonia
- Blue – Irish energy model

9.4. Variable OM

Variable costs were taken from [76].

9.5. External Electricity Market

This section is used to describe the external market for the modeled system. As it was mentioned before, this thesis is investigating the interaction between Estonian and Latvian energy systems and all other interconnections are described as fixed.

Electricity prices distribution in Latvia was obtained from Nord Pool [71] and is shown in the figure below. The distribution was edited in the same way as other ones.

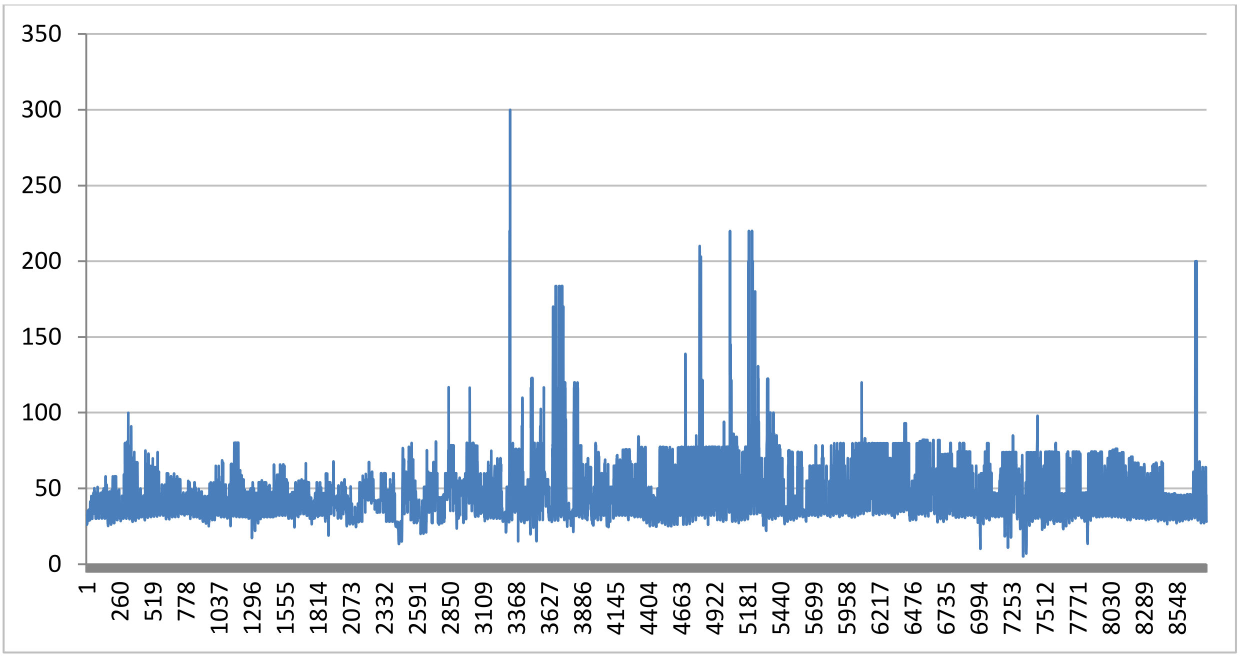


Figure 17. Electricity price distribution for Latvia in 2014

It's also necessary to input interconnection lines capacity. In EnergyPLAN this field is described as a maximum import/export capacity between two countries. Figure 18 shows how it was changing during 2014.

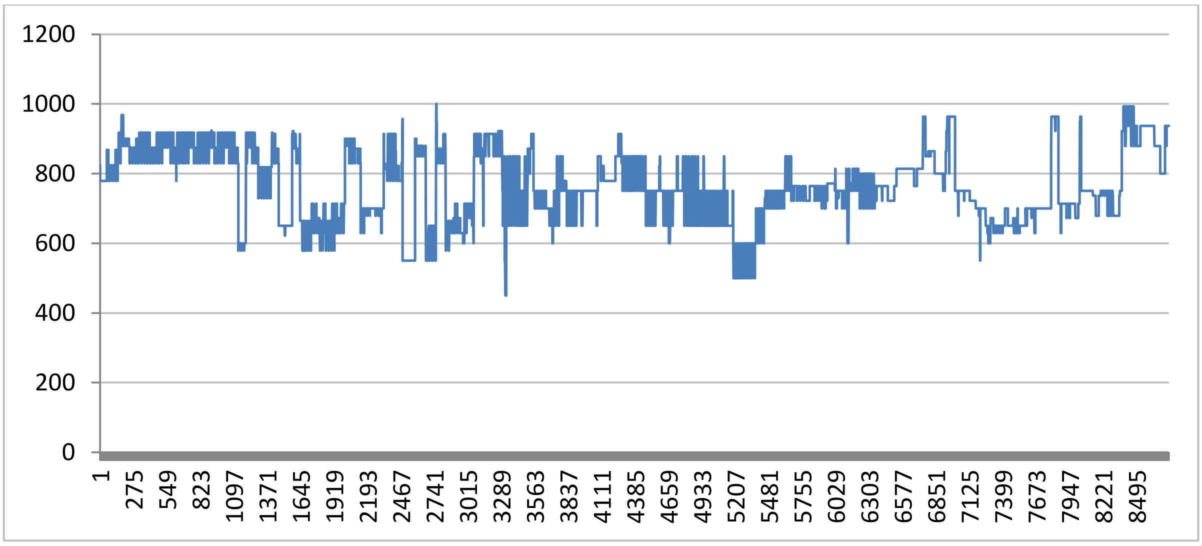


Figure 18. Available interconnection capacity between Estonia and Latvia during 2014

As the final input the capacity equal to 990 MW was taken.

TJ

	Coal	Coke*	Oil shale	Milled peat	Sod peat	Peat briquette	Wood*	Firewood	Wood chips and waste	Wood chips	Wood waste	Briquette and pellets	Briquette	Pellets	Natural gas	Liquefied gas
In stocks at the beginning of the year	1 086	31	33 184	822	547	2	704	191	513	455	58	1 285	6	1 279	1	73
Production of primary energy	0	0	188 956	1 691	1 107	0	32 229	13 271	18 958	11 659	7 299	13 278	333	12 945	0	0
Imports	2 220	6	0	0	0	0	153	54	99	0	99	1 113	69	1 043	17 808	738
Resources of primary energy	3 306	37	222 140	2 513	1 654	2	33 086	13 516	19 570	12 114	7 456	15 676	408	15 267	17 809	811
Exports	0	731	0	0	0	800	1 431	1 412	19	0	19	13 358	85	13 274	0	261
Marine bunkering	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
In stocks at the end of the year	1 204	5	36 864	495	1 449	1	792	247	545	480	65	1 620	10	1 610	0	95
Supply of primary energy	2 102	-699	185 276	2 018	205	-799	30 863	11 857	19 006	11 634	7 372	698	313	383	17 809	455
Consumption for conversion to other forms of energy	131	0	175 942	2 007	205	24	15 220	326	14 894	11 456	3 438	226	17	208	12 366	32
..consumption for electricity generation	60	0	117 820	211	0	0	3 673	22	3 651	3 424	227	0	0	0	343	0
..consumption for heat generation	71	0	3 665	782	205	24	11 547	304	11 243	8 032	3 211	226	17	208	12 023	32
..consumption for conversion to other forms of fuels	0	0	54 457	1 014	0	0	0	0	0	0	0	0	0	0	0	0
Production of converted energy	0	699	0	0	0	992	0	0	0	0	0	0	0	0	0	0
Own use by energy sector	0	0	0	10	0	0	208	19	189	169	20	0	0	0	718	1
Losses	0	0	0	0	0	0	8	7	1	0	1	0	0	0	2	1
Consumption for non-energy purposes	0	0	7 882	0	0	0	0	0	0	0	0	0	0	0	0	0
Final consumption calculated	1 971	0	1 452	1	0	169	15 427	11 505	3 922	9	3 913	472	296	175	4 723	421
Final consumption observed	1 971	0	1 454	0	0	170	15 425	11 503	3 922	10	3 912	472	296	175	4 722	421
..final consumption in industry	1 771	0	1 454	0	0	1	150	24	126	10	116	2	2	0	1 480	166
....final consumption in iron and steel industry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
....final consumption in chemical industry	0	0	0	0	0	0	2	2	0	0	0	0	0	0	147	95
....final consumption in production of non-ferrous metals	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
....final consumption in production of other non-metallic mineral products	1 748	0	1 454	0	0	0	2	2	0	0	0	0	0	0	555	1
....final consumption in production of transport equipment	0	0	0	0	0	1	3	3	0	0	0	0	0	0	29	10
....final consumption in machinery	0	0	0	0	0	0	9	8	1	1	0	0	0	0	134	13
....final consumption in mining and quarrying	0	0	0	0	0	0	0	0	0	0	0	0	0	0	202	0
....final consumption in food processing, beverages and tobacco	1	0	0	0	0	0	6	1	5	3	2	1	1	0	55	8
....final consumption in pulp, paper and printing industry	0	0	0	0	0	0	2	2	0	0	0	0	0	0	52	2
....final consumption in production of wood and wood products	0	0	0	0	0	0	121	3	118	4	114	0	0	0	135	9
....final consumption in construction	3	0	0	0	0	0	1	1	0	0	0	0	0	0	146	5
....final consumption in textile, leather and clothing industry	2	0	0	0	0	0	2	2	0	0	0	0	0	0	15	0
....final consumption in other industries	0	0	0	0	0	0	2	0	2	2	0	1	1	0	10	21
..final consumption in agriculture and fishing	0	0	0	0	0	0	117	16	101	0	101	1	0	1	52	16
..final consumption in transport	0	0	0	0	0	0	0	0	0	0	0	0	0	0	64	10
....final consumption in railway transport	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
....final consumption in land transport	0	0	0	0	0	0	0	0	0	0	0	0	0	0	64	10
......final consumption in urban and suburban passenger land transport	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
....final consumption in waterway transport	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
....final consumption in air transport	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
..final consumption in commercial and public services	1	0	0	0	0	3	63	63	0	0	0	11	6	5	991	47
..final consumption in households	199	0	0	0	0	166	15 095	11 400	3 695	0	3 695	458	288	169	2 135	182
Statistical difference	0	0	-2	1	0	-1	2	2	0	-1	1	0	0	0	1	0

	Heavy fuel oil	Shale oil (heavy fraction)	Shale oil (light fraction)	Light fuel oil and diesel**	Light fuel oil**	Diesel oil	Motor gasoline	Aviation gasoline	Shale oil gas**	Biogas**	Other biomass**	Municipal waste	Other fuels**	Total fuels	Electricity**	Heat	Total energy
In stocks at the beginning of the year	203	863	140	5 046	56	4 990	2 205	127	0	0	19	43	..	46 381	0	0	46 381
Production of primary energy	0	0	0	0	0	0	0	0	0	403	1 473	2 851	..	241 988	2 271	0	244 259
Imports	24 170	0	0	29 244	2 331	26 913	19 075	2 277	0	0	0	0	..	96 803	13 428	0	110 231
Resources of primary energy	24 373	863	140	34 290	2 387	31 903	21 280	2 404	0	403	1 492	2 894	..	385 172	15 699	0	400 871
Exports	12 716	23 648	0	364	0	364	8 551	570	0	0	0	0	..	62 431	23 342	0	85 773
Marine bunkering	11 279	0	0	2 116	2 116	0	0	0	0	0	0	0	..	13 395	0	0	13 395
In stocks at the end of the year	366	1 780	94	4 674	81	4 593	2 115	116	0	0	6	36	..	51 712	0	0	51 712
Supply of primary energy	12	-24 565	46	27 136	190	26 946	10 614	1 718	0	403	1 486	2 858	..	257 634	-7 643	0	249 991
Consumption for conversion to other forms of energy	9	1 535	785	165	1	164	0	0	7 082	269	1 422	2 151	..	219 570	32	0	219 602
..consumption for electricity generation	0	444	0	7	1	6	0	0	3 206	133	108	980	..	126 985	0	0	126 985
..consumption for heat generation	9	1 091	785	158	0	158	0	0	3 876	136	1 314	1 171	..	37 114	32	0	37 146
..consumption for conversion to other forms of fuels	0	0	0	0	0	0	0	0	0	0	0	0	..	55 471	0	0	55 471
Production of converted energy	0	26 256	1 170	0	0	0	0	0	7 201	0	0	0	..	36 318	42 535	32 086	110 939
Own use by energy sector	1	104	0	640	0	640	1	0	119	6	0	0	..	1 808	6 967	2 237	11 012
Losses	0	1	0	2	0	2	2	0	0	0	0	0	..	16	3 031	3 234	6 281
Consumption for non-energy purposes	0	0	0	0	0	0	0	0	0	0	0	0	..	7 882	0	0	7 882
Final consumption calculated	2	51	431	26 329	189	26 140	10 611	1 718	0	128	64	707	..	64 676	24 862	26 615	116 153
Final consumption observed	1	51	431	26 327	188	26 139	10 611	1 717	0	128	61	707	..	64 668	24 861	26 613	116 142
..final consumption in industry	1	28	256	1 357	0	1 357	57	0	0	62	0	707	..	7 492	7 621	7 314	22 427
....final consumption in iron and steel industry	0	0	0	0	0	0	0	0	0	0	0	0	..	0	3	2	5
....final consumption in chemical industry	0	0	0	18	0	18	0	0	0	0	0	0	..	262	542	501	1 305
....final consumption in production of non-ferrous metals	0	0	0	2	0	2	0	0	0	0	0	0	..	21	19	0	40
....final consumption in production of other non-metallic mineral products	0	0	0	43	0	43	0	0	0	0	0	707	..	4 510	751	171	5 432
....final consumption in production of transport equipment	0	0	0	21	0	21	1	0	0	0	0	0	..	65	221	143	429
....final consumption in machinery	0	0	0	11	0	11	0	0	0	0	0	0	..	167	893	499	1 559
....final consumption in mining and quarrying	0	0	0	221	0	221	1	0	0	0	0	0	..	424	66	4	494
....final consumption in food processing, beverages and tobacco	0	1	1	11	0	11	0	0	0	0	0	0	..	84	1 144	1 240	2 468
....final consumption in pulp, paper and printing industry	0	0	0	9	0	9	0	0	0	62	0	0	..	127	1 321	1 466	2 914
....final consumption in production of wood and wood products	0	0	0	124	0	124	1	0	0	0	0	0	..	390	1 315	2 606	4 311
....final consumption in construction	0	27	255	888	0	888	54	0	0	0	0	0	..	1 379	281	137	1 797
....final consumption in textile, leather and clothing industry	0	0	0	2	0	2	0	0	0	0	0	0	..	21	414	184	619
....final consumption in other industries	1	0	0	7	0	7	0	0	0	0	0	0	..	42	651	361	1 054
..final consumption in agriculture and fishing	0	18	174	3 942	0	3 942	7	0	0	66	0	0	..	4 393	738	394	5 525
..final consumption in transport	0	0	0	17 413	19	17 394	2 555	1 717	0	0	0	0	..	21 759	180	94	22 033
....final consumption in railway transport	0	0	0	837	2	835	0	0	0	0	0	0	..	837	25	15	877
....final consumption in land transport	0	0	0	16 163	0	16 163	2 555	0	0	0	0	0	..	18 792	141	77	19 010
......final consumption in urban and suburban passenger land transport	..	..	..	..	..	..	..	..	..	..	..	..	..	..	65	..	76
....final consumption in waterway transport	0	0	0	413	17	396	0	0	0	0	0	0	..	413	13	1	427
....final consumption in air transport	0	0	0	0	0	0	0	1 717	0	0	0	0	..	1 717	1	1	1 719
..final consumption in commercial and public services	0	5	1	485	0	485	29	0	0	0	61	0	..	1 697	10 063	6 319	18 079
..final consumption in households	0	0	0	3 130	169	2 961	7 963	0	0	0	0	0	..	29 327	6 259	12 492	48 078
Statistical difference	1	0	0	2	1	1	0	1	0	0	3	0	..	8	1	2	11

TWh

	Coal	Coke*	Oil shale	Milled peat	Sod peat	Peat briquette	Wood*	Firewood	Wood chips and waste	Wood chips	Wood waste	Briquette and pellets	Briquette	Pellets	Natural gas	Liquefied gas
In stocks at the beginning of the year	0,30	0,01	9,22	0,23	0,15	0,00	0,20	0,05	0,14	0,13	0,02	0,36	0,00	0,36	0,00	0,02
Production of primary energy	0,00	0,00	52,49	0,47	0,31	0,00	8,95	3,69	5,27	3,24	2,03	3,69	0,09	3,60	0,00	0,00
Imports	0,62	0,00	0,00	0,00	0,00	0,00	0,04	0,02	0,03	0,00	0,03	0,31	0,02	0,29	4,95	0,21
Resources of primary energy	0,92	0,01	61,71	0,70	0,46	0,00	9,19	3,75	5,44	3,37	2,07	4,35	0,11	4,24	4,95	0,23
Exports	0,00	0,20	0,00	0,00	0,00	0,22	0,40	0,39	0,01	0,00	0,01	3,71	0,02	3,69	0,00	0,07
Marine bunkering	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
In stocks at the end of the year	0,33	0,00	10,24	0,14	0,40	0,00	0,22	0,07	0,15	0,13	0,02	0,45	0,00	0,45	0,00	0,03
Supply of primary energy	0,58	-0,19	51,47	0,56	0,06	-0,22	8,57	3,29	5,28	3,23	2,05	0,19	0,09	0,11	4,95	0,13
Consumption for conversion to other forms of energy	0,04	0,00	48,87	0,56	0,06	0,01	4,23	0,09	4,14	3,18	0,96	0,06	0,00	0,06	3,44	0,01
..consumption for electricity generation	0,02	0,00	32,73	0,06	0,00	0,00	1,02	0,01	1,01	0,95	0,06	0,00	0,00	0,00	0,10	0,00
..consumption for heat generation	0,02	0,00	1,02	0,22	0,06	0,01	3,21	0,08	3,12	2,23	0,89	0,06	0,00	0,06	3,34	0,01
..consumption for conversion to other forms of fuels	0,00	0,00	15,13	0,28	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Production of converted energy	0,00	0,19	0,00	0,00	0,00	0,28	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Own use by energy sector	0,00	0,00	0,00	0,00	0,00	0,00	0,06	0,01	0,05	0,05	0,01	0,00	0,00	0,00	0,20	0,00
Losses	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Consumption for non-energy purposes	0,00	0,00	2,19	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Final consumption calculated	0,55	0,00	0,40	0,00	0,00	0,05	4,29	3,20	1,09	0,00	1,09	0,13	0,08	0,05	1,31	0,12
Final consumption observed	0,55	0,00	0,40	0,00	0,00	0,05	4,28	3,20	1,09	0,00	1,09	0,13	0,08	0,05	1,31	0,12
..final consumption in industry	0,49	0,00	0,40	0,00	0,00	0,00	0,04	0,01	0,04	0,00	0,03	0,00	0,00	0,00	0,41	0,05
....final consumption in iron and steel industry	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
....final consumption in chemical industry	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,04	0,03
....final consumption in production of non-ferrous metals	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
....final consumption in production of other non-metallic mineral products	0,49	0,00	0,40	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,15	0,00
....final consumption in production of transport equipment	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,00
....final consumption in machinery	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,04	0,00
....final consumption in mining and quarrying	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,06	0,00
....final consumption in food processing, beverages and tobacco	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,02	0,00
....final consumption in pulp, paper and printing industry	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,00
....final consumption in production of wood and wood products	0,00	0,00	0,00	0,00	0,00	0,00	0,03	0,00	0,03	0,00	0,03	0,00	0,00	0,00	0,04	0,00
....final consumption in construction	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,04	0,00
....final consumption in textile, leather and clothing industry	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
....final consumption in other industries	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,01
..final consumption in agriculture and fishing	0,00	0,00	0,00	0,00	0,00	0,00	0,03	0,00	0,03	0,00	0,03	0,00	0,00	0,00	0,01	0,00
..final consumption in transport	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,02	0,00
....final consumption in railway transport	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
....final consumption in land transport	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,02	0,00
......final consumption in urban and suburban passenger land transport	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
....final consumption in waterway transport	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
....final consumption in air transport	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
..final consumption in commercial and public services	0,00	0,00	0,00	0,00	0,00	0,00	0,02	0,02	0,00	0,00	0,00	0,00	0,00	0,00	0,28	0,01
..final consumption in households	0,06	0,00	0,00	0,00	0,00	0,05	4,19	3,17	1,03	0,00	1,03	0,13	0,08	0,05	0,59	0,05
Statistical difference	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

	Heavy fuel oil	Shale oil (heavy fraction)	Shale oil (light fraction)	Light fuel oil and diesel**	Light fuel oil**	Diesel oil	Motor gasoline	Aviation gasoline	Shale oil gas**	Biogas**	Other biomass**	Municipal waste	Other fuels**	Total fuels	Electricity**	Heat	Total energy
In stocks at the beginning of the year	0,06	0,24	0,04	1,40	0,02	1,39	0,61	0,04	0,00	0,00	0,01	0,01	..	12,88	0,00	0,00	12,88
Production of primary energy	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,11	0,41	0,79	..	67,22	0,63	0,00	67,85
Imports	6,71	0,00	0,00	8,12	0,65	7,48	5,30	0,63	0,00	0,00	0,00	0,00	..	26,89	3,73	0,00	30,62
Resources of primary energy	6,77	0,24	0,04	9,53	0,66	8,86	5,91	0,67	0,00	0,11	0,41	0,80	..	106,99	4,36	0,00	111,35
Exports	3,53	6,57	0,00	0,10	0,00	0,10	2,38	0,16	0,00	0,00	0,00	0,00	..	17,34	6,48	0,00	23,83
Marine bunkering	3,13	0,00	0,00	0,59	0,59	0,00	0,00	0,00	0,00	0,00	0,00	0,00	..	3,72	0,00	0,00	3,72
In stocks at the end of the year	0,10	0,49	0,03	1,30	0,02	1,28	0,59	0,03	0,00	0,00	0,00	0,01	..	14,36	0,00	0,00	14,36
Supply of primary energy	0,00	-6,82	0,01	7,54	0,05	7,49	2,95	0,48	0,00	0,11	0,41	0,79	..	71,57	-2,12	0,00	69,44
Consumption for conversion to other forms of energy	0,00	0,43	0,22	0,05	0,00	0,05	0,00	0,00	1,97	0,07	0,40	0,60	..	60,99	0,01	0,00	61,00
..consumption for electricity generation	0,00	0,12	0,00	0,00	0,00	0,00	0,00	0,00	0,89	0,04	0,03	0,27	..	35,27	0,00	0,00	35,27
..consumption for heat generation	0,00	0,30	0,22	0,04	0,00	0,04	0,00	0,00	1,08	0,04	0,37	0,33	..	10,31	0,01	0,00	10,32
..consumption for conversion to other forms of fuels	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	..	15,41	0,00	0,00	15,41
Production of converted energy	0,00	7,29	0,33	0,00	0,00	0,00	0,00	0,00	2,00	0,00	0,00	0,00	..	10,09	11,82	8,91	30,82
Own use by energy sector	0,00	0,03	0,00	0,18	0,00	0,18	0,00	0,00	0,03	0,00	0,00	0,00	..	0,50	1,94	0,62	3,06
Losses	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	..	0,00	0,84	0,90	1,74
Consumption for non-energy purposes	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	..	2,19	0,00	0,00	2,19
Final consumption calculated	0,00	0,01	0,12	7,31	0,05	7,26	2,95	0,48	0,00	0,04	0,02	0,20	..	17,97	6,91	7,39	32,26
Final consumption observed	0,00	0,01	0,12	7,31	0,05	7,26	2,95	0,48	0,00	0,04	0,02	0,20	..	17,96	6,91	7,39	32,26
..final consumption in industry	0,00	0,01	0,07	0,38	0,00	0,38	0,02	0,00	0,00	0,02	0,00	0,20	..	2,08	2,12	2,03	6,23
....final consumption in iron and steel industry	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	..	0,00	0,00	0,00	0,00
....final consumption in chemical industry	0,00	0,00	0,00	0,01	0,00	0,01	0,00	0,00	0,00	0,00	0,00	0,00	..	0,07	0,15	0,14	0,36
....final consumption in production of non-ferrous metals	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	..	0,01	0,01	0,00	0,01
....final consumption in production of other non-metallic mineral products	0,00	0,00	0,00	0,01	0,00	0,01	0,00	0,00	0,00	0,00	0,00	0,20	..	1,25	0,21	0,05	1,51
....final consumption in production of transport equipment	0,00	0,00	0,00	0,01	0,00	0,01	0,00	0,00	0,00	0,00	0,00	0,00	..	0,02	0,06	0,04	0,12
....final consumption in machinery	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	..	0,05	0,25	0,14	0,43
....final consumption in mining and quarrying	0,00	0,00	0,00	0,06	0,00	0,06	0,00	0,00	0,00	0,00	0,00	0,00	..	0,12	0,02	0,00	0,14
....final consumption in food processing, beverages and tobacco	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	..	0,02	0,32	0,34	0,69
....final consumption in pulp, paper and printing industry	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,02	0,00	0,00	..	0,04	0,37	0,41	0,81
....final consumption in production of wood and wood products	0,00	0,00	0,00	0,03	0,00	0,03	0,00	0,00	0,00	0,00	0,00	0,00	..	0,11	0,37	0,72	1,20
....final consumption in construction	0,00	0,01	0,07	0,25	0,00	0,25	0,02	0,00	0,00	0,00	0,00	0,00	..	0,38	0,08	0,04	0,50
....final consumption in textile, leather and clothing industry	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	..	0,01	0,12	0,05	0,17
....final consumption in other industries	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	..	0,01	0,18	0,10	0,29
..final consumption in agriculture and fishing	0,00	0,01	0,05	1,10	0,00	1,10	0,00	0,00	0,00	0,02	0,00	0,00	..	1,22	0,21	0,11	1,53
..final consumption in transport	0,00	0,00	0,00	4,84	0,01	4,83	0,71	0,48	0,00	0,00	0,00	0,00	..	6,04	0,05	0,03	6,12
....final consumption in railway transport	0,00	0,00	0,00	0,23	0,00	0,23	0,00	0,00	0,00	0,00	0,00	0,00	..	0,23	0,01	0,00	0,24
....final consumption in land transport	0,00	0,00	0,00	4,49	0,00	4,49	0,71	0,00	0,00	0,00	0,00	0,00	..	5,22	0,04	0,02	5,28
......final consumption in urban and suburban passenger land transport	..	..	..	..	..	..	..	..	..	..	..	..	..	..	0,02	..	0,02
....final consumption in waterway transport	0,00	0,00	0,00	0,11	0,00	0,11	0,00	0,00	0,00	0,00	0,00	0,00	..	0,11	0,00	0,00	0,12
....final consumption in air transport	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,48	0,00	0,00	0,00	0,00	..	0,48	0,00	0,00	0,48
..final consumption in commercial and public services	0,00	0,00	0,00	0,13	0,00	0,13	0,01	0,00	0,00	0,00	0,02	0,00	..	0,47	2,80	1,76	5,02
..final consumption in households	0,00	0,00	0,00	0,87	0,05	0,82	2,21	0,00	0,00	0,00	0,00	0,00	..	8,15	1,74	3,47	13,36
Statistical difference	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	..	0,00	0,00	0,00	0,00

APPENDIX IV: CAPACITY AND PRODUCTION OF POWER PLANTS by Year, Indicator and Type of power plant

FE032: CAPACITY AND PRODUCTION OF POWER PLANTS by Year, Indicator and Type of power plant

	All power plants	Public power plants	Autoproducers power plants
2014			
Installed electrical capacity of thermal power plants, MW	2 798	2 777	21
Available electrical capacity of thermal power plants, MW	2 411	2 394	17
Installed thermal capacity of thermal power plants, MW	2 258	2 121	137
Available thermal capacity of thermal power plants, MW	1 847	1 725	122
Installed capacity of hydroplants, MW	5.0	5.0	0.0
Available capacity of hydroplants, MW	5.0	5.0	0.0
Installed capacity of windplants, MW	334.0	334.0	0.0
Available capacity of windplants, MW	334.0	334.0	0.0
Electricity production, GWh	12 430	12 373	57
Electricity production from coal, GWh	6	6	0
Electricity production from oil shale, GWh	10 246	10 246	0
Electricity production from peat, GWh	53	53	0
Electricity production from wood, GWh	687	687	0
Electricity production from heavy fuel oil, GWh	0	0	0
Electricity production from shale oil, GWh	43	43	0
Electricity production from natural gas, GWh	64	49	15
Electricity production from biogas, GWh	29	27	2
Electricity production from municipal waste, GWh	112	112	0
Electricity production from other renewable sources, GWh	24	0	24
Electricity production from shale oil gas, GWh	534	534	0
Electricity production from hydro energy, GWh	27	26	1
Electricity production from wind energy, GWh	604	590	14
Heat production, GWh	4 077	3 714	363
Heat production from coal, GWh	3	3	0
Heat production from oil shale, GWh	768	768	0
Heat production from peat, GWh	111	111	0
Heat production from wood, GWh	1 495	1 495	0
Heat production from heavy fuel oil, GWh	1	0	1
Heat production from shale oil, GWh	5	5	0
Heat production from natural gas, GWh	502	430	72
Heat production from biogas, GWh	21	17	4
Heat production from municipal waste, GWh	248	248	0
Heat production from other renewable sources, GWh	286	0	286
Heat production from shale oil gas, GWh	637	637	0

Footnote:
1999-2008 data of electricity and heat produced from renewable sources include energy produced from wood, biogas and black liquor.
Since 2009 data of electricity and heat produced from wood are shown separately.
Since 2013 data of electricity and heat produced from biogas are shown separately.
The data on coal, biogas and municipal waste are added on 05.09.2014.
Due to rounding, the values of the aggregate data may differ from the sum.

Indicator
Electricity production from other renewable sources, GWh
Other renewable sources are black liquor, biogas and animal waste.

Indicator
Heat production from other renewable sources, GWh
Other renewable sources are black liquor, biogas and animal waste.

APPENDIX V: Inputs for the "Investment and fixed OM costs" section

Prod. type	Investment		Period	O. and M.	Total Inv. Costs	Annual Costs (MEUR/year)	
	Unit	MEUR pr. Unit	Years	% of Inv.	MEUR	Investment	Fixed Opr. and M.
Small CHP units	223 MW-e	0,9	20	5	201	16	10
Large CHP units	194 MW-e	1,3	35	3,5	252	15	9
Heat Storage CHP	0 GWh	0	0	0	0	0	0
Waste CHP	0,60 TWh/year	215,6	20	7,37	129	10	9
Absorp. HP (Waste)	0 MW-th	0	0	0	0	0	0
Heat Pump gr. 2	0 MW-e	0,6	30	1	0	0	0
Heat Pump gr. 3	0 MW-e	7	15	1	0	0	0
DHP Boiler group 1	758 MW-th	0,13	40	0,5	99	6	0
Boilers gr. 2 and 3	0 MW-th	0,13	40	0,5	0	0	0
Electr Boiler Gr 2+3	0 MW-e	0	0	0	0	0	0
Large Power Plants	1751 MW-e	1,3	35	4	2276	139	91
Nuclear	0 MW-e	0	0	0	0	0	0
Interconnection	990 MW	0	0	0	0	0	0
Pump	0 MW-e	0	0	0	0	0	0
Turbine	0 MW-e	0	0	0	0	0	0
Pump Storage	0 GWh	0	0	0	0	0	0
Indust. CHP Electr.	0,06 TWh/year	68,3	25	7,32	4	0	0
Indust. CHP Heat	0,36 TWh/year	68,3	25	7,32	25	2	2
	Unit	MEUR pr. Unit	Years	% of Inv.	MEUR	Investment	Fixed Opr. and M.
Wind	334 MW-e	1,45	25	2,7	484	34	13
Wind offshore	0 MW-e	1,95	30	3	0	0	0
Photo Voltaic	0 MW-e	1,3	30	2,09	0	0	0
Wave power	0 MW-e	0	0	0	0	0	0
Tidal Power	0 MW	0	0	0	0	0	0
CSP Solar Power	0 MW	0	0	0	0	0	0
River of hydro	5 MW-e	1,5	50	0,5	8	0	0
Hydro Power	0 MW-e	1,5	50	0,5	0	0	0
Hydro Storage	0 GWh	0	0	0	0	0	0
Hydro Pump	0 MW-e	0,6	50	1,5	0	0	0
Geothermal Electr.	0 MW-e	0	0	0	0	0	0
Geothermal Heat	0 TWh/year	0	0	0	0	0	0
Solar thermal	0 TWh/year	0	0	0	0	0	0
Heat Storage Solar	0 GWh	0	0	0	0	0	0
Indust. Excess Heat	0 TWh/year	0	0	0	0	0	0

Fuel	**Calorific value (GJ per unit)**
Coal, m. t. (metric tons)	25.0–28.0
Coke, m. t.	29.0–30.0
Oil shale, m. t.	8.0–11.5
Milled peat, m. t.	7.0–10.0
Sod peat, m. t.	8.0–12.0
Peat briquette, m. t.	15.0–18.0
Firewood, m^3 sol. vol.	7.0–8.0
Wood waste, m^3 sol. vol.	6.0–7.0
Natural gas, thousand m^3	33.0–34.0
Liquefied gas, m. t.	45.0–46.0
Heavy fuel oil, m. t.	40.0–41.0
Shale oil, m. t.	39.0–40.0
Light fuel oil, m. t.	42.0–43.0
Diesel, m. t.	42.0–43.0
Motor gasoline, m. t.	43.0–44.0
Aviation gasoline, m. t.	43.0–44.0
Electricity, MWh	3.6
Heat, MWh	3.6

APPENDIX VII. Sankey diagram of Estonian energy system [14]