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Energy Transition Impact Assessment Methodology for Fossil Fuel Based Energy Systems

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Declaration:
I hereby declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been submitted for a doctoral or equivalent academic degree.

Mihkel Härm

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Fossiilsetel kütustel põhinevate energiamajanduste ümberkorraldamise mõjude hindamise metoodika

MIHKEL HÄRM

TALTECH KIRJASTUS

Contents

List of Publications

This doctoral thesis is based on the following publications, which are referred to using Roman numerals I-III:

I **Härm, M**.; Hamburg, A. (2020). Implications of the Possible Exit from Oil Shale for Estonian Electricity Sector. Oil Shale, Vol 37 (3). Accepted paper.

II Kisel, E.; Ots, M.; Hamburg, A.; Leppiman, A.; **Härm, M.** (2016). Concept for Energy Security Matrix. Energy Policy, 95, 1−9.10.1016/j.enpol.2016.04.034.

III Reino, A.; **Härm, M.**; Hamburg, A. (2017). The impact of building renovation with heat pumps to competitiveness of district heating. *Conference Proceedings*: Riga Technical University, RTUCON.2017.8124791.

In the Appendix, copies of these publications are included.

Author’s Contribution to the Publications

Contributions to the papers in this thesis are:

I Mihkel Härm was the main author and was the main person responsible for data gathering and analysis. He had a key role in writing the article.

II Mihkel Härm took part in writing the paper, contributing insights into the development of the article’s core hypotheses and methodology. He provided expert assessment, was partly responsible for the literature review, and took part in the editorial work.

III Mihkel Härm was one of the lead writers. He had a major role in data collection and in composing the literature review. He had a relevant role in writing and editing the paper.

Introduction

This thesis examines the effects of transitions from fossil fuel based energy systems to carbon neutral economies. The aim is to develop a methodology to assess the impacts of such transitions. The analysis is largely based on studying the effects that stopping oil shale use for energy purposes by 2030 would have for the Estonian energy sector.

This topic is relevant as more and more countries are starting to reform their energy sectors, it is especially important for Estonia because while oil shale has been the backbone of the Estonian energy sector for more than a century, it is sure to change in the light of new European climate regulations. Currently there are still more than 1 billion tonnes of economic reserves and more than 4 billion tonnes of total oil shale reserves unused in Estonia, meaning the transition will have considerable opportunity costs [1]. As similar dilemmas are faced by other countries, developing a methodology is highly topical.

The simplest way to achieve an energy transition is to simply ban the use of certain fuels; in Estonia's case it would mean banning the use of oil shale. The question, however, is what would the ideal pace and effects of different scenarios be. Answering this is complicated, because energy systems are complex and intertwined with all other aspects of life. Additionally, asset lifetimes in the energy sector are more than half a century; a power plant commissioned today will be operational for the next 50 years. Further, today's energy systems are mostly heavily reliant on fossil fuels, meaning all changes will have wide ranging effects. Looking at final energy consumption in Estonia (Figure 1), it can be seen that the largest share is taken up by liquid fuels; these, together with solid fuels, gaseous fuels, and electricity are all mainly fossil. Therefore, a change that is affecting almost 80% of energy consumption will need to be carefully analysed and thought through. This thesis aims to bring some more clarity to the issue for Estonia and help policymakers all over the world take more thought-out decisions by developing a methodology for assessing such transitions.

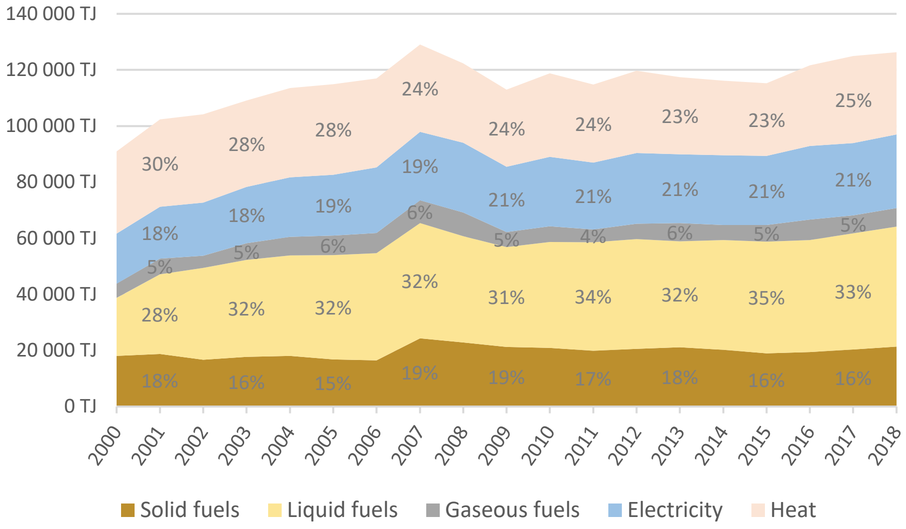


Figure 1. Final energy consumption in Estonia (TJ) [2]

One of the core concepts for analysis carried out in this thesis is the energy trilemma framework developed and popularised by the World Energy Council [3]. This approach is used by the World Energy Council to evaluate and compare energy policies of different countries by looking at the energy policy of countries from three vantage points: 1) energy security, 2) energy equity, and 3) environmental sustainability [3].

There have been some prior works looking at different options for energy transition in Estonia, for example the Estonian Renewable Energy Association popularised a study about the effects of a 100% renewables based energy sector in Estonia [4] and some analyses were carried out regarding different energy transition scenarios while updating the Estonian National Development Plan of the Energy Sector until 2030 [5] and additionally for the General Principles of Climate Policy until 2050 [6]. These national energy policy documents foresaw greenhouse gas reductions of -70% by 2030 and -80% by 2050 compared to 1990 [5], [6]. Still, none of these beforementioned documents gave a complete picture of the implications of an exit from oil shale.

Further, there has not been one study looking holistically at the effects that this kind of transition would have on the Estonian energy trilemma. Socio-economic analyses have been carried out by Ernst & Young [7] and Praxis [8], [9] some energy security related works by World Energy Council Estonia [10], and some environmentally focused works by the Estonian Fund for Nature together with Tallinn University of Technology [11], and also by World Energy Council Estonia [12]. The main drawback of these existing analyses is the fact that they usually focus on just one aspect of the energy transition and do not therefore give the complete picture.

Tools employed in making this thesis can be very broadly categorised into two categories: 1) literature review and 2) trend-based analysis. Literature review is used to examine and analyse the current state of knowledge on the topic. The review itself can be divided into subcategories, as firstly there is a focus on scenario based analysis and its applicability to the energy sector; secondly there is a brief focus on energy transitions, and thirdly this thesis looks at tools and metrics used for analysing the three categories of the energy trilemma. Accompanying the theoretical discussion is a trend-based analysis looking at the current state of the Estonian energy sector and trying to extrapolate possible future developments, supported by calculations of the different effects.

Based upon the analysis, a methodology for assessing energy transitions is composed and tested on Estonia. Using this methodology some recommendations for optimal energy policy for Estonia are given. These can be used as input for updating Estonian long-term energy policy documents and for developing new policy measures. However, it has to be noted, that this thesis is in no way a political document saying what must be done. The real value of this thesis is that the approach developed can be used by policymakers elsewhere.

This thesis will have been successful if it first sparks conversations about different long-term energy policy scenarios, and if thanks to this, thesis scenario-based thinking becomes more widespread. Finally, it would be a welcome development if discussions regarding long-term energy policy would more often use the energy trilemma as a tool of choice when evaluating the different possible futures and political actions.

1 Energy Transition as Part of Long-Term Energy Policy

1.1 Energy Transitions in Energy Policy Research

The main objective of the country's energy policy is to guarantee a secure, affordable, and sustainable energy supply for its inhabitants – also known as the energy trilemma [3]. The prioritisation of these three aspects, however, varies in time. Due to global climate concerns most countries are turning their focus more and more towards the environmental aspects of energy policy.

The changing focus of energy policy can be seen from the growing number of energy transition initiatives undertaken across the globe. One of the most talked about energy transitions is the *Energiewende*, which Germany already started back in 2011 [13]. The word has since become synonymous with energy transition, although *energiewende* itself does not have a specific translation to English [14]. Today, almost 10 years later, when one looks at publications dealing with the change of countries from a traditional energy policy paradigm to post-fossil or carbon-neutral paradigms, one can find an overwhelmingly large number of papers to read. A quick search on ScienceDirect gives almost 19 000 results for "energy transition"; the same query from Google Scholar gives 129 000 results [15], [16]. Conducting the same search for publications before 2000, the result from Google Scholar is only 14 000. Looking at the literature in more detail, it becomes apparent that there is a strong European influence, meaning a lot of focus on the deregulation of energy markets, climate policy, and energy security from the viewpoint of energy supplies [17].

It is clear that analysing energy transitions and their effects is something that has been performed countless times before. Although, it should be noted that the analyses mostly focus on the desired results, and the actual, or most probable results of transitions are overlooked. However, one of the most important conclusions to be taken from these previous studies is the multi-dimensionality of energy transitions. Multi-dimensionality here means that usually more than one of the three prior mentioned aspects of energy policy is looked at. These same dimensions have been used by international organisations when they evaluate the energy policy of countries; for example, the World Energy Council [3] and World Economic Forum [18] both use energy security, energy affordability, and environmental sustainability as the basis for their energy policy assessments.

So, energy transitions and their impacts have been important topics on the radars of both policymakers and energy policy experts for many decades. This is easy to understand, as energy security and affordability are issues that each country needs to deal with day-to-day and the sustainability of environment and energy supplies is relevant for the long-term prosperity of every nation. History can provide abundant examples of cases when nations have mismanaged either one or many aspects of the energy trilemma. The most famous being Nauru [19]. Although there the question was not so much related to energy, a parallel can be drawn. Too much importance was put on economic aspects and therefore other dimensions suffered. Another thought exercise can be carried out as well; one can argue that the results would have been the same if mining had been stopped for environmental reasons and not because the supplies ran out.

Energy transitions have been studied and the modus operandi is usually scenario analysis together with calculations of outcomes for each of the envisioned scenarios.

A big caveat here is that all these scenarios are based on assumptions, and the quality of these assumptions plays a crucial role in the quality of the results.

As scenario analysis is so important in analysing the implications of energy transitions, it makes sense to look at the literature on scenario analysis and its use in an energy policy context.

1.2 Looking into the Future – Scenario Analysis

People have sought ways to look into the future from the beginning of time; the most famous example is probably the Oracle of Delphi, and it is hard to imagine that this wish will ever go away. Today this wish has been formulated into a branch of social sciences called “future studies”, “futurology”, “futuristics” or “foresight” [20]. Although some see this as a pseudoscience, others have argued that future research has the potential to lead to better policies [21].

Nowadays, it is common practice to use scenarios to plan and prepare for the future. Scenarios have become an irreplaceable tool for policymakers and for executives in the business world, especially after the 9/11 attacks [22]. In the UK for example, over a third of companies have said they use scenario planning [23]. Therefore, it sometimes becomes too easy to forget that this has not always been the case. Paul Schoemaker, one of the founders of the modern scenario planning process back in the 1980s, argued that the use of scenario analysis has become ever more important because the business environment has become more uncertain and complex, and also because the pace of change has increased [24], [25]. Others have pointed out that the use of scenarios has become more popular because using scenarios helps organisations be more flexible and hence better cope with the various situations that might arise [26]. Further, it has been pointed out that in addition to the growing complexity of the external environment one needs to factor in challenges arising from more complicated human communication and the human factor as a whole [27].

Previously, there has already been many mentions of “scenarios” and “scenario analysis”; these are terms that on the one hand are understood by many, as they are part of the vocabulary used daily at work, during academic discussions, and even in different media outlets. On the other hand, precisely defining these terms is more complicated. Looking the word “scenario” up in the dictionary, one can see at least two possible definitions: “*a screenplay*” or “*a sequence of events*” [28]. For the purposes of this thesis, the latter definition is clearly more suitable, but it is helpful to give some more examples of more concrete definitions. One possible definition comes again from Paul Schoemaker who defines scenarios as follows: “*focused descriptions of fundamentally different futures presented in a coherent script-like or narrative fashion*” [25]. Schoemaker adds that scenarios should not be viewed as predictions and that the outcomes described in scenarios need to be viewed as boundaries of what could be possible [25]. In his later work Schoemaker adds that the focus of scenarios is on “*bounding the uncertainty range of the future”* [29]. Others agree that that scenarios should be treated as possible futures and not predictions [30]–[33].

Another possible description comes from Herman Kahn, one of the founding fathers of scenario planning together with Schoemaker. Kahn has written that scenarios are “*a set of hypothetical events set in the future constructed to clarify a possible chain of causal events as well as their decision points*” [34]. It is also pointed out that scenarios could be viewed as alternative futures shaped by different combinations of policies [35].

Contemporary authors add that one function of scenarios is to "*reveal the 'unknown unknowns'*" [36].

It needs to be understood that there is no single and universal "scenario process"; nevertheless, several different approaches have been established as the norm in the last 50 years [37]. The most well known, are approaches developed by RAND Corporation in the 1950s and by Shell in the 1970s and 1980s. Spaniol and Rowland summarise the development of scenario planning in three stages: from the 1960s to 1980s a period of hypothetical sequence planning as part of the Cold War, then from the 1980s to mid-1990s the period of scenarios as corporate tools, and finally since the 2000s a period widespread use together with methodological chaos [38]. Shell is still considered to be one of the leading experts on scenarios. Shell uses the following steps in the scenario analysis process: 1) selecting the issues, 2) analysing the areas of concern, 3) organising the scenario around a logical concept, and 4) focusing the scenario [39].

In addition to common traits of the process, there are some widely used ways of how scenarios are set up. The main scenarios can be described as follows: 1) business as usual, 2) disaster, 3) authoritarian control, 4) hyper-expansion, and 5) humane ecological [40].

The usefulness of scenarios and scenario analysis was briefly mentioned at the beginning of this chapter; to paraphrase Schoemaker [24] and Bentham [36], one could say that the main benefit of scenario analysis is to define the boundaries of what could happen and, while doing this, reveal the unknown unknowns. Schoemaker adds that scenarios also help people to think more clearly about the future and they stimulate thinking by challenging the status quo; using scenarios also reduces the risk of falling prey to overconfidence bias [24], [25].

The benefits of scenarios are well described by Pierre Wack, who published two articles in Harvard Business Review back in the 1980s. Wack points out that the scenario process, if carried out correctly, 1) helps people understand the importance of historical events and their impact on the future, 2) makes people look at the environment surrounding their business, and 3) scenarios help managers to look at their business with a fresh perspective [32], [33]. The latter is confirmed by more contemporary authors who point out that scenarios improve decision-making by illuminating the issues at hand, and by pointing out potential pitfalls that may face organisations in the future [41]. Meissner and Wulf further showed that the scenario process reduces framing bias and thus increases the overall quality of the decision process [42].

All in all, it can be said with certainty that scenario planning helps organisations improve the quality of their strategic planning, make better decisions, and steer clear of many cognitive biases. The same applies for countries and governments making long-term policy decisions.

2 Methodology of Research

The research method was described in the introductory part of this thesis as using the literature review and trend-analysis. To categorise it more scientifically, the research method used in this thesis can be described and classified as the systematic collection and analysis of data, which has also been called "*grounded theory*" [43].

Grounded theory is a method where one first creates a theoretical account of the general features of the topic, while keeping in mind the empirical observations and the data one finds [43]. Grounded theory as a method has many advantages, namely the fact that using this method generates more than enough evidence to prove or disprove the theory, while also keeping track and systematically analysing the data [44]. Grounded theory relies heavily on data analysis, but it needs to be noted that analysis needs to be systematic and carried out in a thought-out way [45].

Looking further into the method of research, it is useful to describe the process in more detail. Having employed the grounded theory methodology and having used the literature review as the main apparatus of research, there was also a systematic process for carrying out the literature review.

The process started with compiling a list of keywords that seemed to be the most relevant for the case and then using these keywords to look for relevant scientific articles from databases such as ScienceDirect, Emerald, JSTOR, Google Scholar and Scopus.

As the topics of scenario analysis, energy policy, energy trilemma, energy security, climate policy, and energy transition are quite popular, the need to narrow down the list arises, as it was clearly understood that having an exhaustive overview of the literature was neither feasible nor needed. Instead the aim was to analyse materials that would be representative of the field, e.g. articles from the best-known authors and the top-tier journals and magazines. To do this the following criteria were used: relevance to the topic, age of the material, geography. To sum up the criteria, the following rule can be formulated: the suitable article was directly related to the topic, was usually not more than 10 years old, and was published in a top peer-reviewed journal with the topic of the article being about Europe or the US. This was not always the case of course, as some of the ground-breaking articles are already more than half a century old, but more often than not, this beforementioned rule could, and was, followed.

Identifying the problem was the easy part; the hard part, however, was formulating the specific research questions. The issue with this was the broad domain of both the scenario analysis and energy transitions. Petticrew and Roberts have analysed this topic and suggest that the process should start with justifying the need for the research [46]. This again was rather simple to accomplish, as the author had more than ample proof from first-hand experience. Nevertheless, knowing the problem is not the same as being able to articulate the specific problem, let alone the specific questions one needs to ask to solve the problem. It has been said that clearly worded questions are the key to guide the whole process of literature review, as clear questions both underscore the type of information one needs and guide one in finding the relevant literature and driving forward the analysis [47].

The following trend-based scenario analysis was carried out in a normative way, meaning that two separate futures were envisioned; one where all use of oil shale for energy purposes is stopped by 2030 and another where there is no such strict deadline. The analysis for the implications of ending the use of oil shale started from a specific goal and assumptions was made on the basis that these goals could be achieved. The technical limitations were analysed to make sure that both of these scenarios could, at least technically, be achieved. Quantitative data was sourced from the Estonian Statistics Authority, annual reports from companies active in the oil shale sector, yearbooks composed by the Oil Shale Competence Centre, and from Estonian long-term policy documents. The two scenarios were then modelled and effects on energy security, energy equity, and environmental sustainability were analysed.

The analysis is replicable elsewhere as long as the required data is available. The first step is composing alternative scenarios; these might differ in terms of timeline or in the level of decarbonisation that is required. Once the scenarios are composed, quantitative models should be created; these are used for calculating emissions, employment figures, governmental income and other numerical values. At the same time a qualitative assessment needs to be carried out regarding criteria where sufficient data is not available. The most important aspect to remember is that in order to get a complete picture, all three core dimensions need to be looked at. In other words, energy security, energy equity, and environmental sustainability, need to be assessed. The specific indicators to focus on are examined in Chapters 5-7.

Finally, it must be noted that all research carried out for this dissertation was performed in an ethical manner. All the articles and other information was obtained lawfully, and the authors of the original work have always been credited. All information presented in this thesis has been reported accurately and according to the best knowledge of the author.

3 Challenges of Existing Assessments and Their Methodologies

3.1 General Observations on Existing Methodologies

As previously mentioned, there are several overviews and assessments of energy transitions. In general, these assessments are normative, i.e. a desired future is described and then ways for achieving the proposed outcome are analysed. An alternative way of looking at things is explorative analysis, i.e. looking at the tools available and exploring where the use of these tools might lead. Generalising, both are part of scenario analysis, one of the most widely used tools in energy policy assessment.

Estonian policymakers used scenario based analysis in preparing the Estonian Long-Term Energy Policy Development Plan [5]. This plan brings together all fields of energy: electricity, heating, fuels, transportation and housing. It is also the foundation of Estonian long-term renewable energy policy. The authors of this plan have pointed out that the goal of energetics is to serve both the other fields of the economy and the Estonian population by providing the cheapest possible energy that takes environmental and energy security considerations into account [5]. This is basically the Energy Trilemma promoted by the World Energy Council.

3.2 Challenges of Existing Methodologies

Here we will look at the main problems and shortcomings of the most widely used methodologies for analysing energy transitions. The main challenges mostly comprise 1) insufficiently thorough analysis, 2) too high-level view, resulting from overly general data, and 3) reliance on historic data.

Insufficiently thorough analysis can be seen in cases where the goal of analyses has been to promote some political or business interest. In these cases, authors cherry pick indicators and aspects to consider when giving recommendations and making conclusions. Usually, this kind of analysis is correct in what is presented; it is that which is not presented that is the source of problems.

Too high-level view or generalising is in itself not a problem; on the contrary, it can be extremely useful when policymakers need to take decisions on a regional or even global scale. The problems arise when these same findings are used to make decisions on a local scale, or even on national scale in a small country such as Estonia. For example, the goal of cutting European carbon emissions by 80% by 2050 compared to 2005 might be a great goal, but finding the optimal path for achieving this goal requires local analysis and planning. Merely using average reduction targets for all countries achieves sub-optimal results. To find the best solutions, alternatives need to be compared on a much more detailed level. To do this, country, and sometimes even more specific data, is needed.

Finally, there is a reliance on historical data for making predictions about the future. It is not to say that one should not use past experience in preparing for the future, after all, there really isn’t an alternative. The problem is that some studies use data from many years ago, meaning that this data no longer truthfully represents the situations that policymakers try to improve. Not to mention that all energy related issues have much to do with current climate, infrastructure and market conditions, meaning all of these must be considered when comparing alternatives or giving recommendations to policymakers.

There are of course more ways in which analyses can misrepresent the actual situation, but these are the main ones. To overcome these restrictions, one must first make sure to use the most recent data available. Secondly one needs to look beyond general indicators, such as only the primary energy demand; it is necessary to look at electricity, heat and transportation separately. This may of course bring up the question of data availability, but an effort should be made to have data about these three categories. Thirdly, one should always make sure that data is not cherry picked, but instead all relevant years and necessary data points are included.

3.3 Novel Approach to Energy Transition Assessment

This thesis looks at energy subsectors such as electricity, heating and transport, and examines socio-economic impacts as well as environmental ones. The analysis is specific to the energy sector because oil shale is an issue of the energy sector. This can be clearly seen in Figure 2; more than 99% of oil shale used in Estonia is being used by the energy sector. Finally, it must be remembered that the goal is to show the implications that the choice of ending the use of oil shale would have; the goal is not to give judgements on what policies the Estonian policymakers should choose.

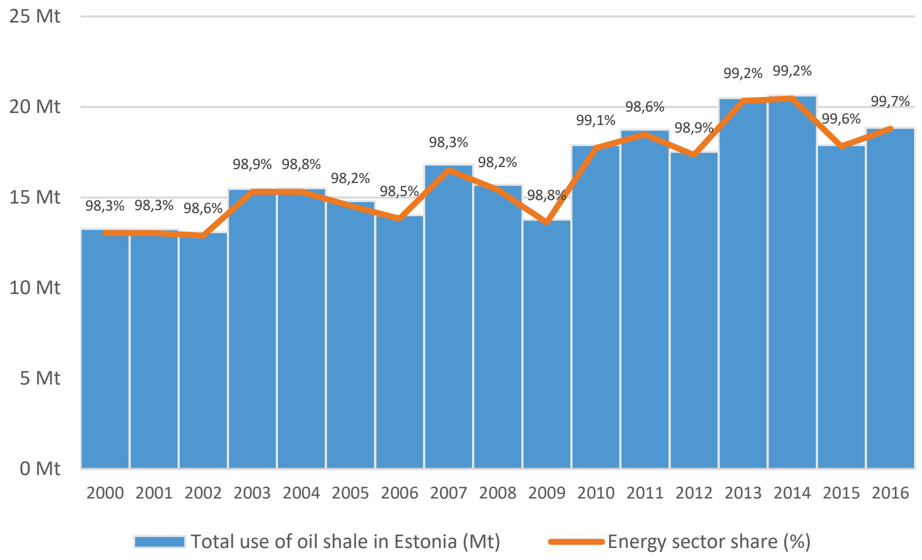


Figure 2. Consumption of oil shale in Estonia [2]

4 Developing Energy Transition Assessment Methodology

The current chapter gives an overview of how the analysis was carried out. It should be noted that the analysis in this thesis was constrained by what data was available. Still, the objective was to give as good an assessment as possible using the available resources.

The development of energy transition assessment methodology is carried out using the example of Estonia. Estonia is a country that is heavily reliant on fossil fuels, particularly on oil shale, which is the cornerstone of the Estonian energy sector. Oil shale's importance in the Estonian primary energy supply can be seen in Figure 3.

The most current data from 2018 puts the share of oil shale in the primary energy supply at 72%; this has risen quite a lot compared to the beginning of this century, with the reason being an increase in shale oil production.

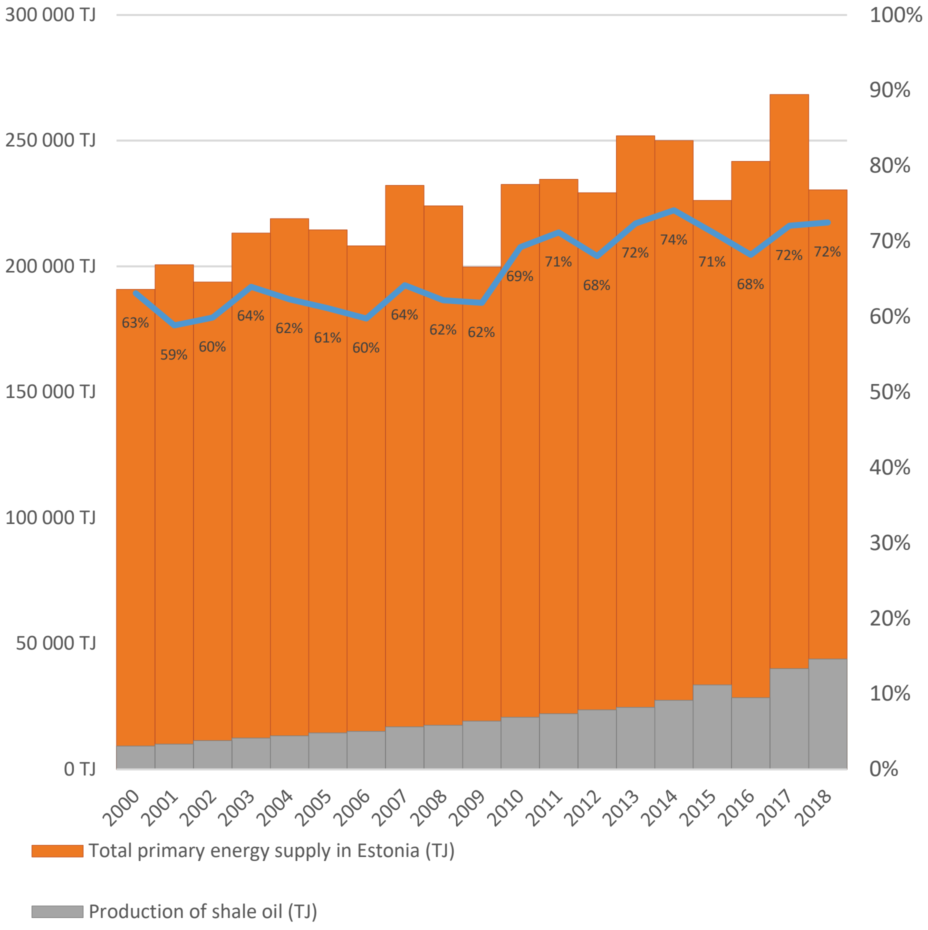


Figure 3. Share of oil shale in Estonian primary energy supply [2]

The methodology for assessment follows energy trilemma logic, and the same logic is used in structuring the chapters. There are separate chapters for energy security, energy affordability and environmental sustainability. The analysis part is preceded by a description of assumptions and two scenarios that were developed: "Oil Shale Exit" (OSX) and an alternative called “Gradual Transition” (GT). Oil Shale Exit means the complete end of oil shale use for energy purposes in Estonia by 2030. As currently most other uses of oil shale are related to by-products of using oil shale in the energy sector, it can be said that OSX would mean an almost complete end of oil shale use in Estonia by 2030. The alternative scenario (GT) was used as a benchmark for evaluating the implications that OSX would have on the Estonian energy sector.

The core of OSX is shutting down the oil shale industry. As there are thousands of people employed in the industry and billions of euros invested, this shut down cannot happen in one day, nor even in one year. Both scenarios for OSX and for GT will need to entail planned closures of the existing production assets. As a reference, there is currently 2055 MW of installed capacity in power plants using oil shale in Estonia [I]; in addition, there are production facilities for producing over 1 million tonnes of shale oil annually [I].

4.1 General Assumptions Used in Both Scenarios

Here, the main assumptions used for composing the scenarios are described. First, the following analysis assumes that neither European nor Estonian climate policies make the use of oil shale impossible before 2050.

Secondly, it is assumed that the long-term average oil price will be above 60 USD/bbl., as this is the limit for shale oil profitability [48]. This assumption is definitely inaccurate, but the long-term price range of 60-70 USD/bbl. seems to be the consensus of many analysts [49]–[51]. To back up this most probably inaccurate forecast, one can bear in mind that the most prominent forecast in the world, IEA’s World Energy Outlook, has been highly inaccurate in its projections, being on average 17% wrong when predicting one year into the future [52].

Thirdly, it is assumed that the mining limit for oil shale in Estonia will remain at today’s level of 20 million tonnes of rock mined annually. Although this might not be the optimal level, it is an agreement accepted by a wide majority, and most probably this limit will not affect either scenario.

Fourthly, it is assumed that the development of renewable energy will be the same regardless of OSX, meaning both GT and OSX will make the same new investments in renewable energy. The assumption is made that OSX will not entail some extra subsidy for building up capacity and that the markets work the same as in GT. The only new capacities built are new boiler houses for supplying heat for places that currently get heat from oil shale-fired CHP plants, but this effect is minimal and is not studied in detail.

Fifthly, an assumption is made that in the next 20 years, carbon capture and storage (CCS) technologies will not become competitive, at least for the oil shale industry. It has been said that CCS projects have historically had little success because the industry has not been able to engage a wider stakeholder base, governments have not been willing to cover the high investment costs, and the CO_2 market has not given a strong enough signal for supporting the development of CCS technology [53]. Karimi found that CCS has not progressed, because of “*institutional inertia and poor temporal fit*” [54]. Others have said that CCS “*increases total system cost significantly*” [55], with the CO_2 avoidance cost for coal-fired powerplants being in the range of 24-110 USD/t_{CO2} [56].

Sixthly, an assumption that is perhaps the most questionable, is made regarding the profitability of oil shale-based power production. It is assumed that power prices rise in accordance with increases in CO_2 prices and therefore oil shale-based electricity produced in efficient power plants will not be priced out of the market. This analysis is supported by many forecasts. For example, the 2019 report on European CO_2 policies says analysts predict the long-term CO_2 price to be in the range of 15-40 EUR/t_{CO2} [57]. Others predict that the CO_2 price will reach 50 EUR/t by 2030 [58]. Bloomberg New Energy Finance predicted that the power price in Germany will rise from today's level of 35-40 EUR/MWh to 55 EUR/MWh by 2035 (in real terms) [59]. Statista forecasts a significant price increase for the United Kingdom [60] and a similar outlook can be predicted for the Nordics; this is backed up by analysis from Dansk Energi [61]. The same analysis says that coal plants can still earn money, because there will be enough hours with low renewable generation [61]. The power price increase post 2025 in the Nordics is also predicted by SP Global [62], as well as by the Nordic transmission system operators [63].

Finally, some more assumptions are made to get a better overview of these two scenarios. In Table 1 there are the main technical characteristics of oil shale-fired power plants. It has to be mentioned that for the purposes of simplification, the power plants have been grouped into four categories: 1) Auvere power plant, 2) power plants with circulating fluidised bed boilers (CFB PP), 3) power plants with pulverised combustion boilers (PC PP), and 4) other smaller power plants in Estonia using oil shale (other). PC PP refers to power plants with flue gas cleaning systems, as the other older units will not be used according to the scenarios constructed in this thesis. Other refers to power plants such as VKG Põhja SEJ, which use oil shale gas, but also to electricity produced as a by-product in shale oil plants. Data is from [64]–[67] and [I].

Table 1. Technical characteristics of oil shale-fired power plants

	Auvere PP	**CFB PP**	**PC PP**	**Other**
Capacity (MW) [64]	300	215	180	40
Efficiency (%) [64], [65]	40	36	35	35
Fuel use (t/MWh)	1.25	1.15	1.55	1.2
CO_2 emissions (t/MWh) [66]	0.95	0.99	1.30	1.0
SO_2 emissions (kg/MWh) [66]	0.001	0.045	1.45	1.0
NO_x emissions (kg/MWh) [66]	0.355	0.375	0.55	0.90
Waste – ash and waste rock (t/MWh) [67]	1.35	1.35	1.35	1.35
Capacity factor (%) ***Assumed by the author***	45%	35%	25%	50%
Last year of operation (OSX)	2030	2030	2023	2030
Last year of operation (GT)	2050	2040	2023	2040

Similar grouping and simplification is performed for shale oil plants; the technical characteristics for these plants can be seen in Table 2. Here the grouping is as follows: 1) Enefit140 plants, 2) Enefit280 plants, 3) Petroter plants, and 4) other shale oil production plants. Other shale oil plants include Kiviter plants operated by Viru Keemia Grupp AS, as well as GSK and TSK plants operated by Kiviõli Keemiatööstuse OÜ [65] and [I].

Early closures of PC PP plants are due to their high costs compared to the modern Auvere plant and the renovated CFB units. With shale oil plants, the early closures are not a cost issue, but rather an educated guess regarding the upcoming changes in environmental regulations.

Table 2. Technical characteristics of shale oil plants (author's calculations)

	Enefit140	**Enefit280**	**Petroter**	**Other**
Annual production (Mt)	0.12	0,20	0.08	0.50
Annual oil shale use (Mt)	0.90	1.45	0.90	2.30
CO_2 emissions (t/t)	1.90	1.90	1.80	1.90
SO_2 emissions (kg/t)	0.95	0.75	6.10	15.50
NO_x emissions (kg/t)	1.55	0.85	0.40	0.35
Last year of operation (OSX)	2024	2030	2030	2024
Last year of operation (GT)	2024	2050	2050	2024

5 Energy Security

Energy security is a dimension of energy policy that is easy to understand, at least on a general level. The problems arise when one starts exploring the issue at a more detailed level. Many authors have examined the issue of energy security [68]–[85]. Looking at these works, it becomes clear that there is no silver bullet solution or one best indicator for measuring energy security. The author of this thesis, together with fellow researchers at Tallinn University of Technology, examined the issue in [II] and came up with the Energy Security Matrix seen in Table 3.

Energy Security Matrix is a theoretical concept for structuring and evaluating the energy security of countries. The matrix looks at the operational, technical, economic, and political vulnerability of electricity, heat and transport fuels. These categories refer to different time scales, operational and technical aspects examine the short-to-medium term, while economic and political aspects look at longer term issues. Short term here refers to time-scales form seconds up to a year, meaning issues related to existing infrastructure, while long-term issues are more related to planning and preparations for the future.

Table 3. Energy Security Matrix [II]

	Electricity Sector	**Heat Sector**	**Transport Sector**
Operational Resilience to Internal disturbances (flexibility)	• Share of unreliable capacity compared to minimum load (with and without interconnections) • Share of reliable capacity (incl. capacity available during peak via interconnections) compared to peak load		
Operational flexibility to external disturbances (flexibility)	• Resilience to acts of terror • Resilience to cyber-attacks • Resilience to natural disasters • Resilience to climate change		
Technical Resilience (capacity)	• Reserve margin (also in N-1 and N-1-1 cases) • Weighted average age of reliable power capacities and networks • Average return on reliable power production and network investments	• Stocks of fuels for heating compared to monthly peak consumption • Weighted average age of district heating capacities and networks • Average return on district heat production and network investments	
Technical Vulnerability (energy)	• Diversity of potential electricity supplies (Herfindahl Index) • Potential supply compared in annual consumption	• Diversity of potential heat supplies (Herfindahl Index) • Share of potential heat/cooling supply compared to annual consumption	• Diversity of energy for transport supplies (Herfindahl Index) • Potential of supply in the case of supply disruptions compared to annual consumption
Economic Dependence	• Merchandise value of power exports or imports compared to GDP	• Merchandise value of fuels imported for heating/cooling supplies compared to GDP	• Merchandise value of fuels imported for energy for transport compared to GDP • Merchandise value of exported energy for transport compared to GDP
Political Affectability	• Level of political stability in a given country • Level of political stability in supplying countries • Interest level from other countries to influence the policy of sectors • Openness of the country to external influence • Level of corruption		

5.1 Operational Resilience

This aspect is relevant in the electricity sector as other sectors are less time critical. District heating as a system has high inertia, and both heating and transport are generally distributed systems where operational resilience comes from the distributed nature of these systems. The main indicators for operational resilience towards internal disturbances are 1) share of unreliable capacity towards minimum load and 2) share of reliable capacity compared to peak load. It must be noted that in both cases the impact of interconnections is relevant, as also highlighted before.

These indicators look at two of the most critical situations for power system operators, cases of minimum load and peak load. Periods of minimal load are complicated because too much intermittent capacity might mean there is overproduction, and this might lead to system failure and, in the worst case scenarios, even to black-outs. Periods of peak consumption on the other hand put stress on the energy system from the opposite direction and if there is not enough reliable production capacity then brown-outs are inevitable. Interconnections are a good remedy for both cases.

Estonian transmission system operator Elering forecasts that there are enough interconnections to facilitate both planned additions of intermittent generating capacity and consumption peaks [86]. This is true, even for when there is no oil shale-fired power generation in the system [87].

Looking at the indicators in more detail, the importance of interconnections becomes even more apparent. Figure 4 shows two days from 2018, where electricity consumption reached a peak of more than 1500 MW. Electricity from wind and solar covered less than 10% of this. Therefore, it is clear that without new investments and without interconnections OSX is not feasible, at least from the viewpoint of electricity security of supply. So, without interconnections, gradual transition provides better operational resilience as there is a larger share of reliable capacity available during periods of peak consumption.

Operational resiliency during periods of minimum load is not related to OSX, as OSX does not entail extra investments for unreliable power production, i.e. wind and solar.

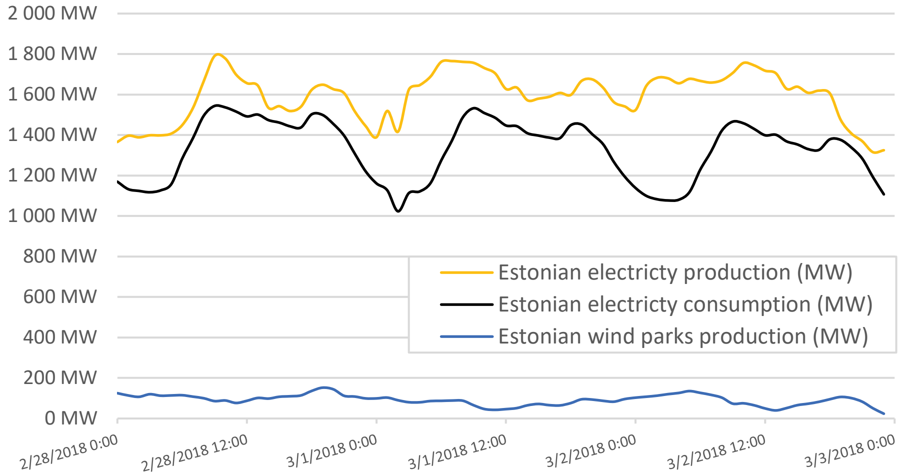
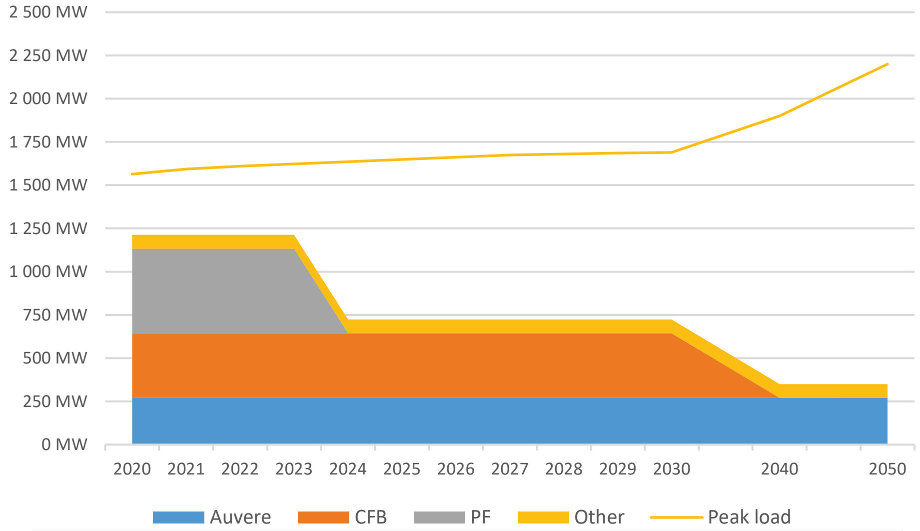


Figure 4. Electricity production in Estonia during the period of peak demand in 2018 [88]

Summing up, one can see that the question of operational resiliency to internal disturbances boils down to the mix of generating assets in the Estonian system and the availability of interconnections. OSX itself does not have negative implications for operational resiliency as additions of solar and wind parks are not part of OSX. OSX, however, has negative implications for energy security during periods of peak demand; in GT almost 700 MW of dispatchable generating capacity from oil shale is available in the Estonian energy system in 2030 and this is definitely a positive sign. Not to mention that Auvere PP and power production related to shale oil manufacturing will be operational up to 2050. Still, as long as there are enough interconnections, energy security is sufficient in both scenarios.



GT&OSX are the same up to 2030, then capacity drops to zero in OSX.

Figure 5. Available capacity and Estonian peak consumption in Gradual Transition (MW)

Another part of operational resiliency is the resilience to external disturbances. Unlike resilience to internal disturbance, resilience to external disturbances is relevant to all energy sectors. Here, the timescales are already longer, and these disturbances can have adverse impacts to the whole energy system.

Indicators used (resilience to acts of terror, cyber-attacks, natural disasters, and climate change) are more qualitative than quantitative in their nature and usually entail carrying out holistic in-depth analysis. Here, a very basic thought exercise is carried out to assess the impacts that OSX would have on the operational resilience of the Estonian energy system compared to GT.

The first aspect of resilience to external disturbances examines acts of terror. As OSX means less reliance on large centralised power stations, it could be said that OSX in fact increases operational resilience as there are less high value targets for terrorists to attack. The same holds true for cyber-attacks.

From the point of view of natural disasters and climate change, both scenarios are the same. Natural disasters and effects of climate change are more hurtful for GT, as there, the production of electricity is more dependent on the weather conditions and the smaller assets are typically more vulnerable to heavy winds and floods. Large power stations have been built bearing the worst weather conditions possible in mind.

5.2 Technical Resilience (Capacity)

Technical resilience assesses the capability of energy systems for dealing with changes in demand as problems with capacity usually emerge during periods of high demand. For Estonia it would be during the coldest days of winter when demand is highest for heating, electricity and even transport fuels.

The main tool for dealing with potential supply risks is storage; it is easier for the transport sector where liquid fuels are easily storable, but less so for electricity and heating sectors. Still, innovation and technological advancements have made storing both heat and electricity a lot easier and cheaper.

As oil shale or liquid fuels produced from oil shale are not used for transport purposes in Estonia, neither OSX nor GT will have any impact on the technical resilience of this sector. The same is true for the heating sector, although OSX would mean some district heating networks will switch from oil shale to biomass; there will not be any problems with supplying the heat that is needed or gathering the necessary biomass. Assuming, of course, that the boiler houses are built with sufficient capacity.

The electricity sector is once again the sector where OSX would have an actual impact. The reasoning follows the same logic as in the case of operational resilience and once again the solution is in having enough cross-border transmission capacity together with enough generating capacity for supplying the whole region.

5.3 Technical Vulnerability (Energy)

Technical vulnerability here is reliance on a small number of suppliers, who then might have power over supply sources or supply routes. In this analysis the technical vulnerability is considered from the viewpoint of one supplier’s impact. This is done for all three aspects of energy security.

Once again, neither OSX nor GT would have any impact on the technical vulnerability of the heating and transport sectors of Estonia; there simply is no energy supplied from the oil shale sector to these sectors. The energy currently supplied for heating purposes from oil shale-fired power plants will be replaced by biomass, but the situation with suppliers would remain the same. Both before and after the transition, district heating would be a part of regulated business and although there is only one supplier, the risk is minimal because of strong oversight and regulation by the Estonian Competition Authority.

The electricity sector is slightly different, as oil shale-fired electricity could currently be used to meet the whole Estonian demand. Figure 6 shows Estonian electricity production and consumption from 2000 to 2016, and for all this time Estonia has been a net electricity exporter; most of this electricity has been supplied by one company. One might assume that this poses a huge risk for the technical vulnerability of the Estonian power sector, but there are many factors suggesting otherwise. First, this supplier is a state-owned company that hopefully should act both in its selfish interest to maximise profits, but due to influence from its owner; its secondary objective should focus on the wider interests of Estonia. Should the latter not be true, then there are also no problems. As stated many times before, Estonia is so well interconnected with its neighbours that at any time all necessary electricity could be imported from other countries. So, although there seems to be a large influence of one player, this is not true.

Finally, analysing the impact of OSX and GT on the technical vulnerability of the Estonian energy system, it becomes clear that there is no real impact. At a superficial level, OSX might seem to improve the situation, as the influence of one major supplier is reduced. From Figure 7 the same can be seen for GT. However, as this player did not have any large influence over the market, there is nothing to improve.

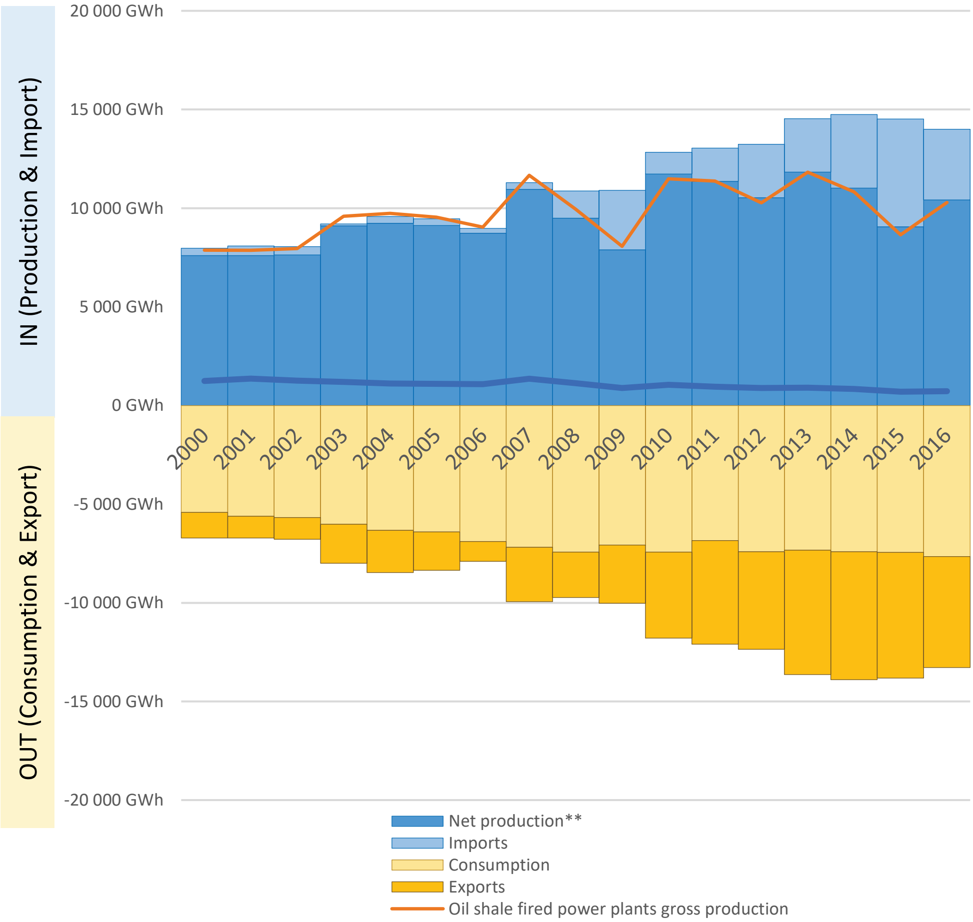
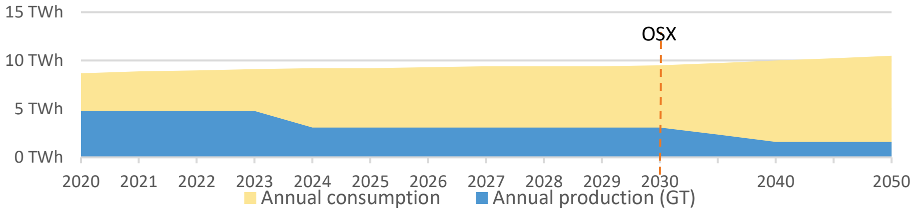


Figure 6. Electricity production and consumption in Estonia (GWh) [2]



GT & OSX are the same up to 2030, then both production and consumption drop to zero in OSX.

Figure 7. Electricity consumption and production from oil shale in Gradual Transition

5.4 Economic Dependence

Economic dependence is related to the overall wellbeing of countries, meaning that even if there are no actual problems with energy supplies, then being overly reliant on energy imports can influence the budgets of countries and have a strain on their economy. This is also true for exporting countries; for them, the negative effects appear when for one reason or another, energy prices fall and then they suddenly have large budget deficits.

Here, the impact of oil shale on Estonian GDP and the overall export-import balance is looked at. The reasoning behind this is, that if the country is reliant on the import of some sources of energy, but is exporting other sources, and is therefore more or less balance, then the impact of economic dependence has been minimised.

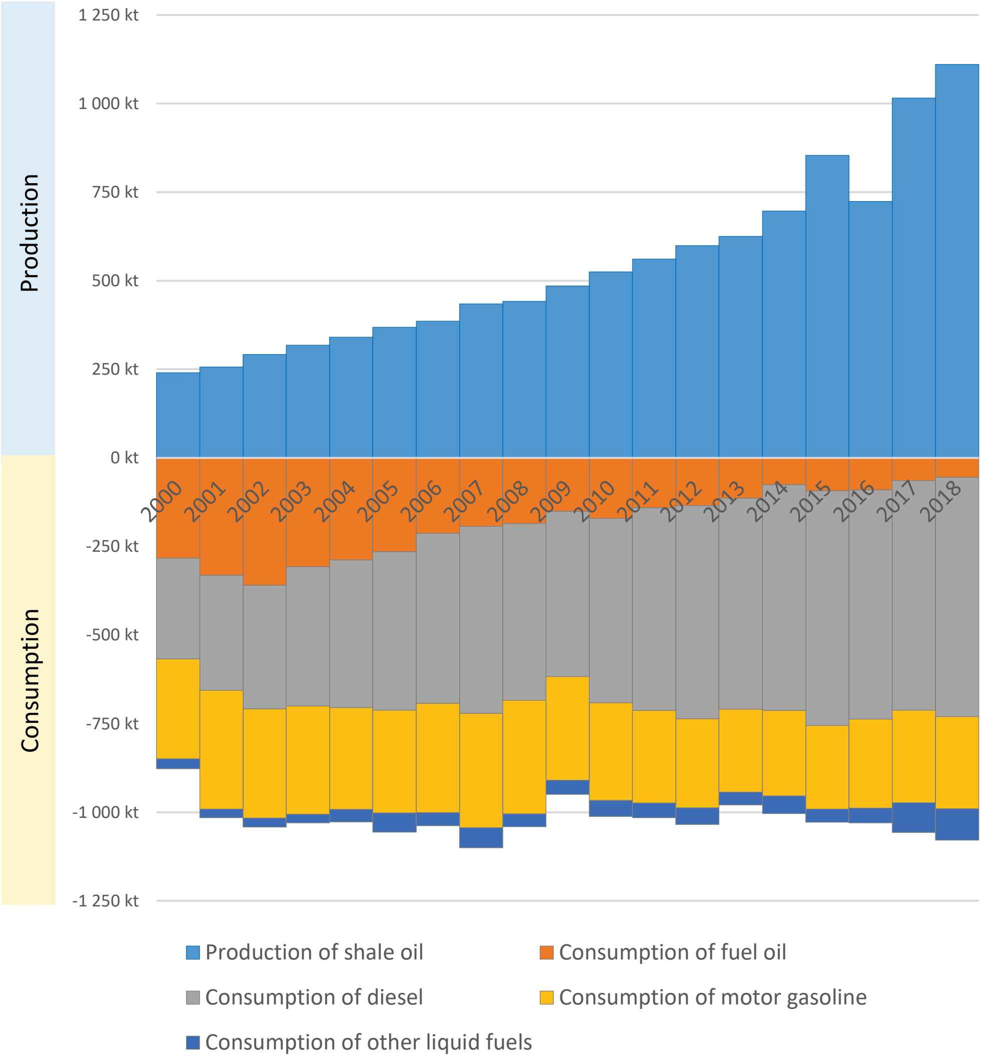
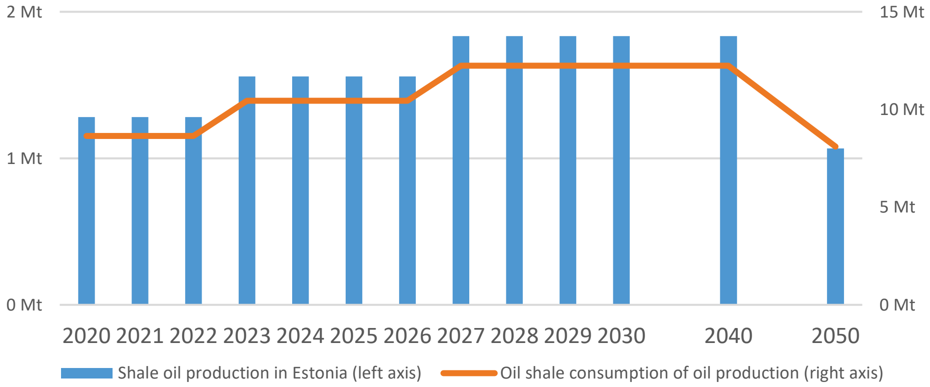


Figure 8. Production and gross inland consumption of liquid fuels (kt) [2]

Figure 8 shows the consumption and production of liquid fuels in Estonia from 2000 to 2018. Looking at the figure, it can be seen that the production of liquid fuels has grown almost 5 times. Secondly, the consumption and production of liquid fuels are almost in equilibrium, with a small surplus on the production side. Thirdly, the portfolio of consumption is totally different from the portfolio on the production side, meaning Estonia is exporting and importing a lot of liquid fuels at the same time.

To sum up the analysis of economic dependence, it can be said that there is some dependence, as Estonia is exporting more electricity (Figure 6) and liquid fuels (Figure 8). What is positive is that the dependence is minor, and it is on revenues from export.

Now, looking at what would happen in the case of OSX compared to GT, it is clear that the situation would worsen. OSX would mean a more rapid closure of oil shale-fired power generation, making Estonia dependent on power imports. GT would also entail some reduction of oil shale-fired power generation, but this would be less, over a longer period (Figure 7). The main difference, however, is in the economic dependence of liquid fuels (Figure 9). In the case of GT, Estonia would remain the net exporter of liquid fuels, and a refinery would most probably be built in Estonia, making the fuels have a higher quality and price. In the case of OSX there is no liquid fuel production in Estonia, making Estonia 100% dependent on liquid fuel import, both in volume and monetary terms.



GT & OSX are the same up to 2030, then both production and consumption drop to zero in OSX.

Figure 9. Shale oil production and oil shale use in Gradual Transition (Mt)

5.5 Political Affectability

Political affectability means the vulnerability of countries to political and geopolitical externalities. Usually countries are rather stable in this regard, but for some countries this aspect of energy security is one of the most important ones. These are countries that are on the radar of interest for other nations or countries, where due to internal politics the political stability is low or lacking.

Here, the only impact of OSX is related to the political stability of the region of Ida-Virumaa, the region of Estonia where most of the oil shale industry is located. OSX would mean that for short periods, unemployment reaches up to 20% [9]. So a high unemployment rate might cause civil unrest and therefore must be taken with the utmost care. More emphasis is placed on this issue and the concept of “just transition” in the following chapters.

5.6 Summary of the Implications of OSX on Estonian Security of Supply

Summing up the previous discussion, it can be said that OSX will have a somewhat negative effect on the Estonian security of supply. Still, it must also be noted that the effects will not be as drastic as one might assume. In fact, most of these issues can be neutralised with rather small investments, assuming Estonia will have enough interconnections.

The impacts on each category of the energy security matrix are shown in Table 4. Indicators where OSX would have a positive impact compared to GT are shown in green, where the impact would be negative is shown in red, and where there is no impact, the indicator is shown in black.

Table 4. Implications of OSX compared to GT on the Estonian energy security matrix

	Electricity Sector	**Heat Sector**	**Transport Sector**
Operational Resilience to Internal disturbances (flexibility)	↔ Share of unreliable capacity compared to minimum load (with and without interconnections) ↓ Share of reliable capacity (incl. capacity available during peak via interconnections) compared to peak load		
Operational flexibility to external disturbances (flexibility)	↑ Resilience to acts of terror ↔ Resilience to cyber-attacks ↔ Resilience to natural disasters ↔ Resilience to climate change		
Technical Resilience (capacity)	↓ Reserve margin (also in N-1 and N-1-1 cases) ↑ Weighted average age of reliable power capacities and networks ↔ Average return on reliable power production and network investments	↔ Stocks of fuels for heating compared to monthly peak consumption ↔ Weighted average age of district heating capacities and networks ↔ Average return on district heat production and network investments	
Technical Vulnerability (energy)	↔ Diversity of potential electricity supplies (Herfindahl Index) ↓ Potential supply compared in annual consumption	↔ Diversity of potential heat supplies (Herfindahl Index) ↔ Share of potential heat/cooling supply compared to annual consumption	↔ Diversity of energy for transport supplies (Herfindahl Index) ↔ Potential of supply in the case of supply disruptions compared to annual consumption
Economic Dependence	↓ Merchandise value of power exports or imports compared to GDP	↔ Merchandise value of fuels imported for heating/cooling supplies compared to GDP	↔ Merchandise value of fuels imported for energy for transport compared to GDP ↓ Merchandise value of exported energy for transport compared to GDP
Political Affectability	↓ Level of political stability in the given country ↔ Level of political stability in supplying countries ↔ Interest level from other countries to influence the sectors' policy ↔ Openness of the country to external influence ↔ Level of corruption		

6 Energy Affordability and Economic Impact

The second dimension of the energy trilemma is energy affordability; here affordability is examined together with the wider socio-economic impact OSX would have compared to GT. In the analysis, issues brought forward in the author's previous work related to the impacts of OSX [I], are also looked at. The main indicators are revenues for the state, employment, average wages, and the impact on GDP.

6.1 Impact on GDP and Revenues for the State

The oil shale industry is not only important for energy security reasons, but also an important source of income for the Estonian state. The author has examined the issue in one of his publications [I]; here the discussion is built on these previous findings.

According to studies, the oil shale sector comprises about 4-5% of Estonian GDP [7]. This in itself is not good or bad, GDP is just a calculated number that in many cases will not tell one anything about the actual impact on people's lives. Of more importance than the sector's contribution to GDP, is the actual contribution to the state's budget and the salaries paid to employees.

Looking at Figure 10, it can be seen that in the last 5 years the Estonian state treasury has received more than 100 million euros annually from the oil shale industry. This is more than 15% of the total revenues of the industry. Some proponents of OSX might say that the actual impact of the oil shale industry is negative, because the externalities are not taken into account. This might be true, but unfortunately, the issue of externalities has not been sufficiently analysed to make any conclusive conclusions. The Estonian government ordered analysis on the subject, but the results have been debunked by Estonian leading scientists [89]. Further, already in 2014, experts from Tallinn University of Technology showed that analysis of the external costs of the oil shale sector is flawed [90].

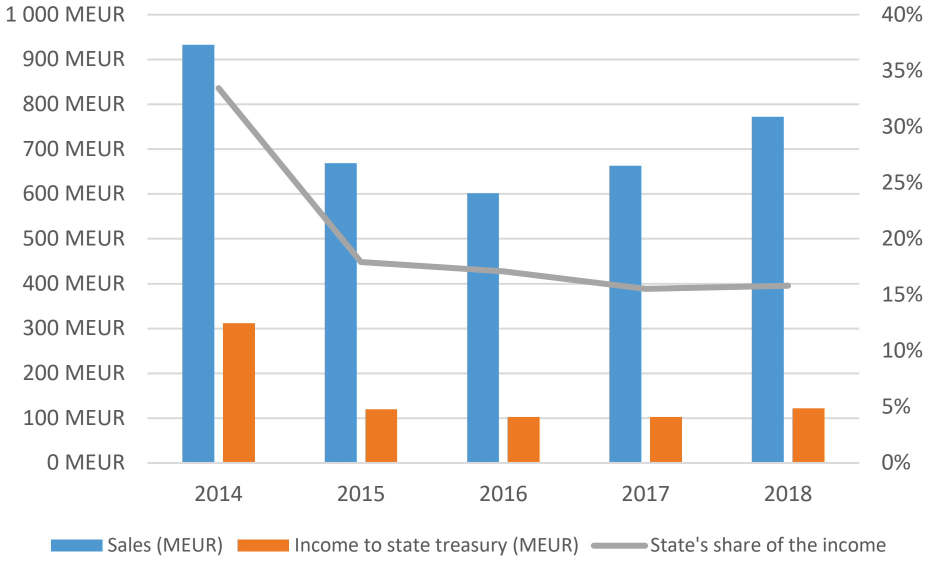
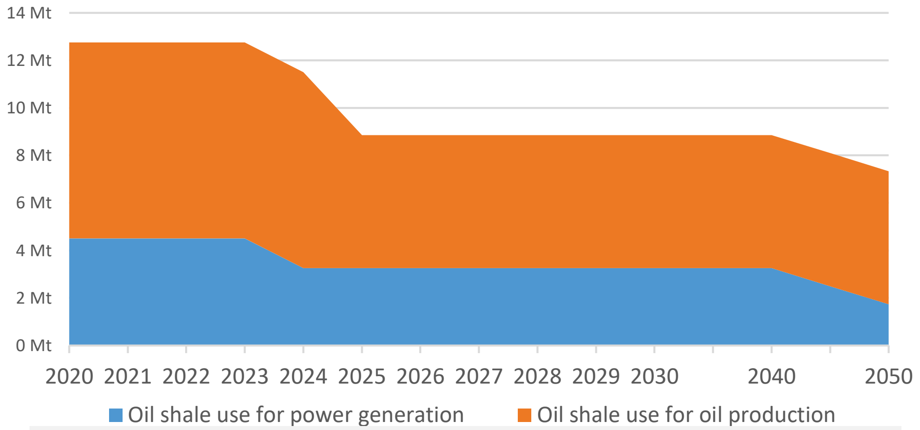


Figure 10. Oil shale industry's impact on the state's income [48]

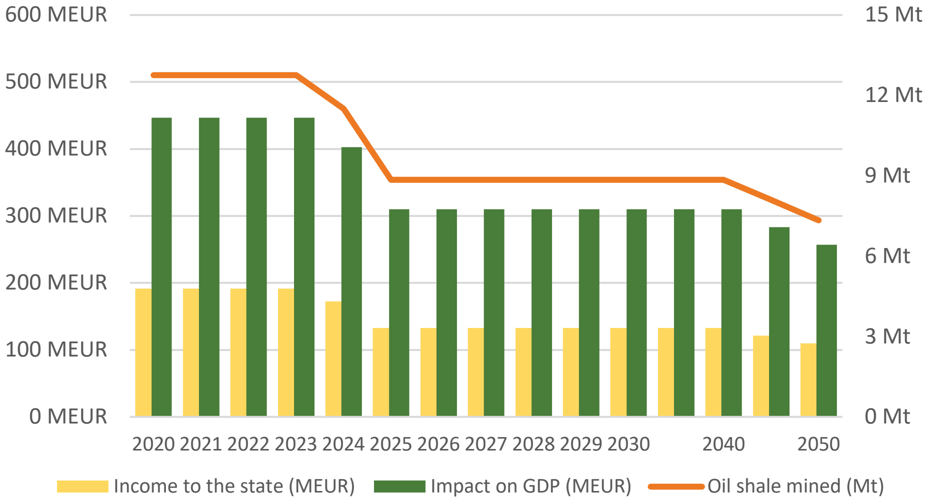
Going forward, one wants to understand what the total loss of the government would be resulting from OSX by 2030 and 2050. These calculations use the assumptions made previously about the existing assets and the prices of CO_2, electricity and oil. The results can be seen in Figure 12.



GT & OSX are the same up to 2030, then both power generation and shale oil production drop to zero in OSX.

Figure 11. Oil shale use for power and oil production in Gradual Transition (Mt)

Having made clear that the Estonian state would lose hundreds of millions of euros should OSX be realised, one must also bear in mind that this is only the state's direct income from the sector; additionally, it has to be noted that an even larger income to the state comes from the sale of CO_2 quotas. The fact that Estonia has CO_2 quotas to sell is largely due to the existence of the oil shale industry, if there was no oil shale usage in the past, then Estonia would not have any quotas to sell. To make sure Estonia also has quotas to sell in the next period, it would be wise to have a functioning oil shale sector, at least until the next allocation has been agreed.



GT & OSX are the same up to 2030, then both production and consumption drop to zero in OSX.

Figure 12. Economic impact of Gradual Transition

6.2 Impact on employment

The oil shale industry is one of the biggest employers in the region it is situated in; together with secondary and tertiary employment the impact is more than 13 000 jobs [7]–[9]. As this number is quite subjective, the number of direct employees is used in the following analysis, although some have even indicated the number of affected people might be as high as 17 400 [8].

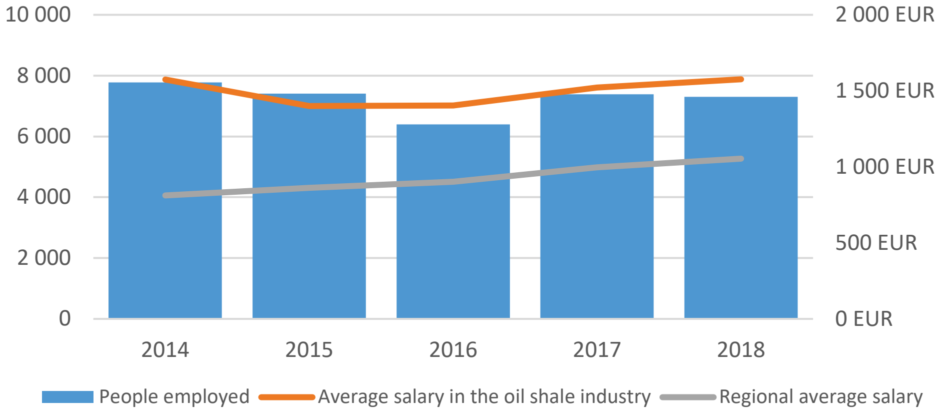
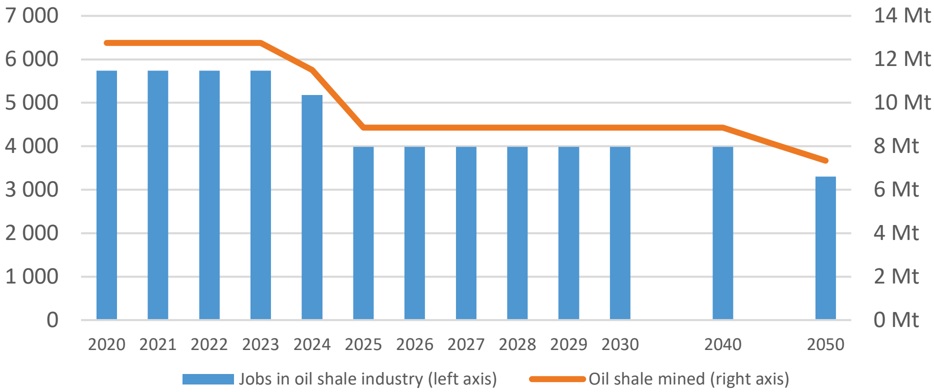


Figure 13. Socio-economic impact of the oil shale industry

The number of people directly employed by the industry can be seen in Figure 13; the number has been around 7000 people in recent years. With OSX the number would drop to zero; with GT there will also be a decline, but the transition will be smoother. The number of people employed in the GT scenario can be seen in Figure 14.

One must also consider the average salaries in the industry compared to the regional averages seen in Figure 13. The average salary in the oil shale industry is almost 1.5 times the regional average [I]. It is clear that closing down an industry and laying off 7000 people who on average earn 1.5 times the local average salary, will have a negative effect on the socio-economic situation of this region. Some reports show that for short periods the unemployment in the region might reach 20% [8].



GT & OSX are the same up to 2030, then both production and consumption drop to zero in OSX.

Figure 14. Gradual Transition's impact on jobs in the oil shale industry

6.3 Other Socio-Economic Impacts

One of the aspects that was not covered before is OSX's impact on the incomes of local municipalities. For some municipalities in the region of the oil shale industry (e.g. Illuka, Mäetaguse), income from environmental taxes is more than half of their budget [8]. Such a windfall from one industry means these municipalities have had up to 3.5 times higher expenses per inhabitant compared to other municipalities in the region [8].

Environmental taxes are not the only income for municipalities from the oil shale industry; one also has to account for the share of income tax that goes to local governments. Looking at the income tax, the city of Narva would lose more than 30% of this revenue, while the cities of Sonda and Kiviõli would lose approximately 20% [8].

One additional aspect is the "justness" of transition. Just transition is a rather new concept in energy policy and energy transition analysis. It was first coined as a term that would join together the switch of carbon neutral energy production technologies and assurance of jobs; nowadays, this term has a wider meaning of simultaneously achieving climate, energy, environmental, and social goals [91]. The final aspect of just transformation is related to embedded emission or "exporting" or "offshoring" emissions [92]. This is something policymakers need to bear in mind, because if the only effect of OSX would be increased imports of carbon-intensive products and electricity, then the whole goal of OSX would have been missed.

Such "just transition" might actually be a viable alternative as the current European Commission is preparing a Just Transition Fund with a budget of 30 to 50 billion euros [93]. This money could be used for generating new business opportunities, retraining, and generally diversifying the economic activities of regions away from fossil fuels [93]. Right now, however, the creation and details of this fund are still being discussed.

6.4 Summary of the Implications of OSX on Estonian Energy Equity

It was clear from the start that OSX would have negative implications for the equity aspect of the Estonian energy trilemma. Modelling the two scenarios showed the effect in more detail.

First, when looking at the extra amount of oil shale that would be mined in the Gradual Transition scenario, one sees more than 250 million tonnes of oil shale is mined in GT compared to OSX. These 250 million tonnes translate to 4 billion euros of lost income for the Estonian government, assuming that Estonia will not lose any CO_2 quotas once the oil shale sector has been shut down. Should this happen, then the negative effect on the Estonian state budget would be even higher. Early exit from oil shale would also mean a higher trade deficit as 40 TWh of electricity will not be generated and 30 million tonnes of shale oil will not be produced. Finally, all of this also means a loss of jobs; approx. 4000 jobs will be lost if OSX is accomplished in 2030.

From the energy equity point of view GT is highly preferred to OSX. GT means higher income for the state, a better balance of trade, and higher employment. It needs to be noted that the model did not take into account the potential investment into a shale oil refinery; should this come to life, then the positive impact of GT on employment and state revenues will be even higher.

7 Environmental Sustainability

The consensus seems to be that environmental sustainability is mostly related to CO_2 emissions; the same indicator is used as the main signpost in this analysis as well. However, CO_2 emissions are not used as the only indicator to examine the impacts OSX would have on the sustainability of the Estonian energy policy. In addition, other emissions such as emissions of NO_x, SO_2, and waste generation are looked at as well.

The aim of environmental sustainability assessment is to give policymakers a better overview of what the benefits of OSX could be and if there could be some unforeseen drawbacks. There is no doubt that the assessment will not be complete and that there will be some important aspects not covered. Still, an as complete picture as possible is given, considering the limitations of the available data and other resources.

One of the aspects not covered here is the fact that less dispatchable capacity in the power system results in a need for major energy storage, overcapacity in renewables and transmissions, or the acceptance of lower quality in service [94]. The first two options would mean a higher environmental footprint of the energy sector and the third option would entail a whole rethinking how our society functions.

7.1 Air Emissions from the Oil Shale sector

The first impact of OSX on the environmental sustainability of the Estonian energy sector is, no doubt, the positive effect on CO_2 emissions from the industry. As seen from Figure 16, greenhouse gas emissions quite closely follow oil shale usage in Estonia. It is also easily understandable because roughly speaking the CO_2-intensity of oil shale electricity is 1 tonne_{CO2}/MWh. The exact figure is slightly different and has been declining. The fact that greenhouse gas emissions have declined more than oil shale usage is due to more shale oil production and less emissions of other greenhouse gases that are not related to the oil shale industry.

Looking ahead, it can be seen that both OSX and GT will have a positive impact on CO_2 and other air emissions in Estonia. This is perfectly logical, as in both scenarios oil shale usage will decline, and even more so for power production. So, the question remains that if both scenarios are good, is one better, and OSX does indeed come out ahead. The effects of GT can be seen in Figure 17, whereas in OSX the emissions would already drop to zero after 2030.

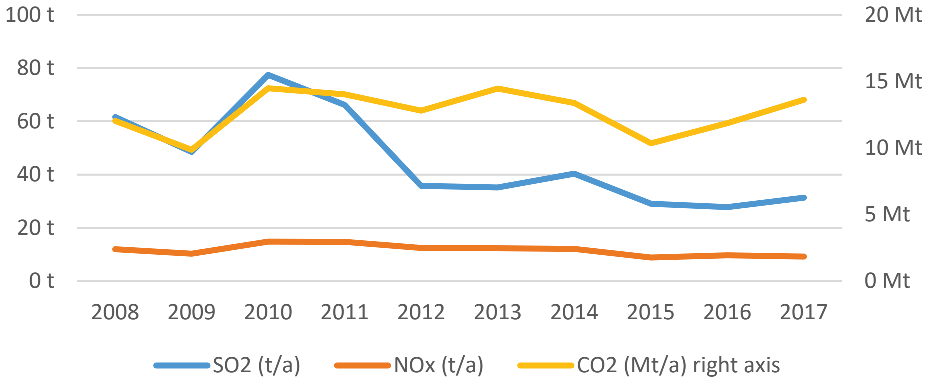


Figure 15. Emissions to air from the oil shale sector [2]

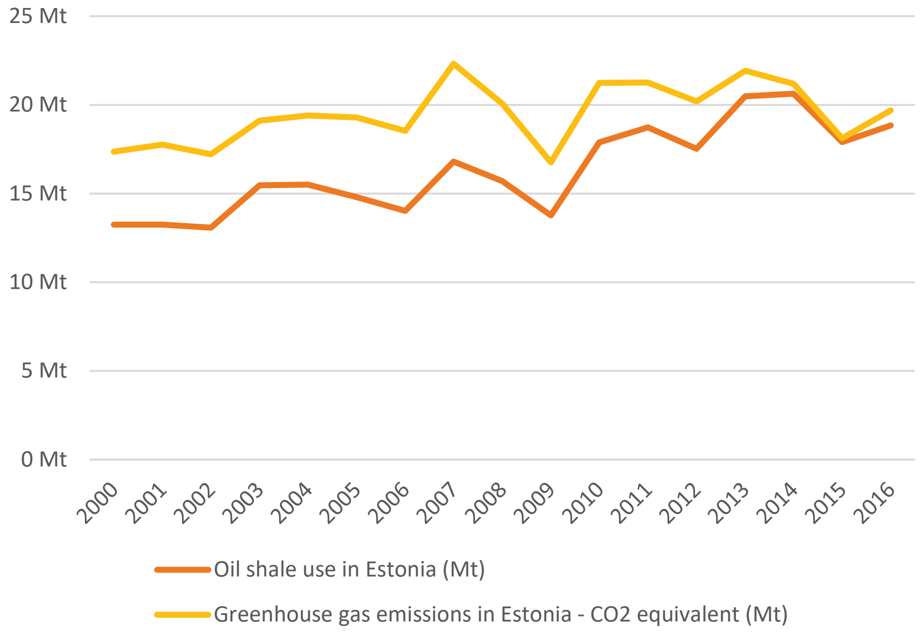
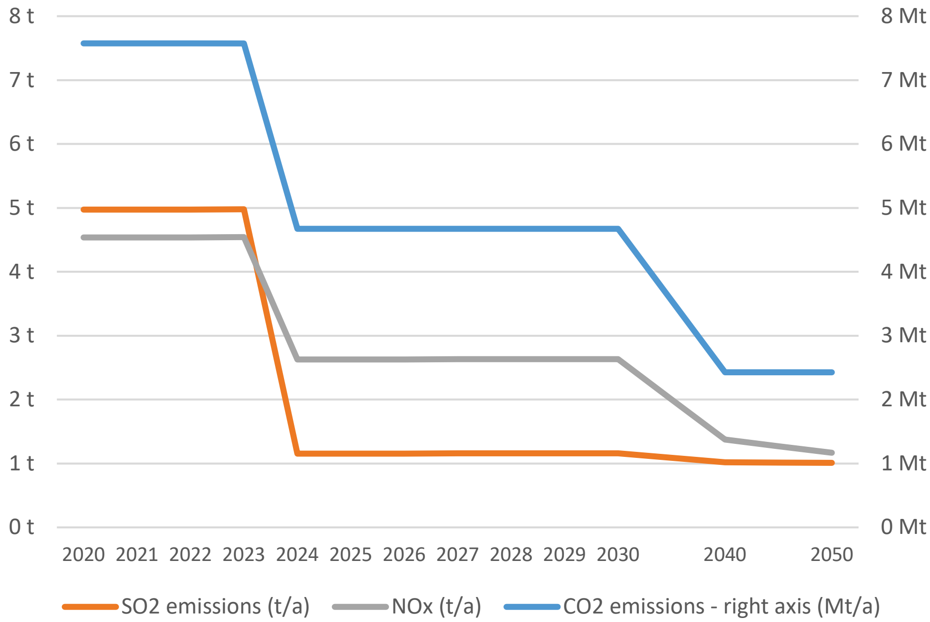


Figure 16. Greenhouse gas emissions and oil shale use in Estonia [2]



GT & OSX are the same up to 2030, then all emissions drop to zero in OSX.

Figure 17. Air emissions from the oil shale sector in Gradual Transition

7.2 Water Usage and Waste Creation

The oil shale industry is considered to be environmentally unsustainable due to large water usage and waste creation. This, however, is only a half-truth. It is true that the industry has a large footprint both with regards to water and waste, but the water usage is actually only pumping water from one place to another and “waste” is gravel and other materials that could easily be used for other purposes. There is also the aspect of semi-coke, but this is not examined in this thesis.

Water use in the oil shale industry is a two-fold issue: first, there is water pumped out of mines, and secondly, there is cooling water used by powerplants. Water pumping is directly related to the area of active mines, and a large share of water pumped out of mines is actually rain water that would have ended up in rivers either way [12]. Similarly for power plants, as a rule, the number for water usage (withdrawal) in thermal power plants is large (25 000 – 225 000 L/MWh), but the actual consumption is usually magnitudes lower (50 – 2300 L/MWh) [95].

Although water pumping out of mines may be problematic, there are two issues that one needs to bear in mind. First, in the case of OSX one would either have to continue pumping water out of the already opened mines or accept that the oil shale resource in these mines becomes unusable, even for future generations. Secondly, stopping the pumping of water might mean some areas become flooded; as long as the industry is operating this will not happen [11]. Therefore, OSX will also need to include a plan for dealing with the residual impacts.

Speaking of oil shale mining and water usage, Puura and Orru point out that water pumped from mines might have positive impact on preventing the eutrophication of lakes [89]. Again, one important aspect to consider.

The main waste associated with the oil shale industry is actually waste rock which is a by-product of mining and enrichment. Then there is oil shale ash that is a product of thermal treatment of oil shale and is actually low-grade cement [12]. By volume, the amount of waste seems large, but actually this waste rock could all be used in infrastructure projects such as road building, or even for RailBaltic. Therefore, stopping oil shale mining would mean there will be a need to open quarries in Northern and Western Estonia to supply gravel for RailBaltic [96].

7.3 Summary of the Implications of OSX on Estonian Environmental Sustainability

While it was clear from the beginning that GT will have a greater positive effect in the energy equity dimension, it was equally clear that OSX will have more positive effects on environmental sustainability.

Looking at the result from modelling the two scenarios, it becomes apparent that 8 million tonnes less CO2 will be emitted from the oil shale industry in OSX compared to GT. The same is true for SO_2 and NO_x, where the figures are 32 tonnes and 50 tonnes respectively.

Additionally, more than 110 million tonnes of waste will not be produced in OSX compared to GT. As half of this waste is actually gravel, this of course means new quarries need to be opened and, in this regard, GT is actually preferred to OSX. In conclusion it can be said that OSX is preferred to GT when it comes to environmental sustainability.

8 Updating Estonian Energy Policy

The Paris agreement says that the part of countries in the agreement should aim for emission reductions in an amount that would limit global warming to below 2 °C above pre-industrial levels [97]. At the same time, lights must be kept on and economies competitive. This means that an updated energy policy is needed; a policy that would be suitable for transitory times.

This updated energy policy must be compatible with the wider European climate and energy policy. The caveat being, that European climate and energy policy is centred around the themes of renewables, carbon emissions, and energy security [94]. It could even be said that "*for the union, renewable energy is not only a means to combat climate change, but is an end in itself*" [94]. Harjanne and Korhonen explain that this claim is supported by the fact that policies supporting renewables overlap and could be seen as potentially hindering the effectiveness of the EU Emissions Trading System [94].

The energy sector has been in a transitional phase for more than a decade already; some might even say that the transitional periods are now the norm rather than an exception when it comes to the energy sector [98]. The most recent transitions have been brought about due to changes in the regulatory environment and successful innovations in the renewable energy sector [99]. Both of these trends, together with findings from analysis of the impacts that the oil shale sector has on Estonian energy policy, provide valuable insights in reshaping Estonian energy policy.

The biggest changes in the regulatory environment already took place in the 1980s and 1990s, when the energy sector saw the first wave of deregulation and privatisation. In more recent times, Estonia together with its Baltic neighbours opened electricity markets, first partly in 2007 and then fully in 2013 [100]. This meant big monopolies had to learn how to compete in an open marketplace. These changes all mostly happened in the electricity sector; transport on the other hand has always been an open market, and the heating sector is still a part of the regulated business when one talks about district heating, and has always been a part of open markets in other areas of the heating and cooling industry. The author analysed the impacts of innovation in regulation and technical solutions on the heating market and fossil-based electricity in [III].

Additional change in renewable support schemes mean that the number of zero-marginal-cost producers in the marketplace is growing, thus, driving down market prices in hours when there is a lot of wind or sun, and creating price peaks in hours of low renewable electricity production. This implies that oil shale-based power generation in its current form is not sustainable, ramp-up and ramp-down times of current units are too long, meaning the generators either have to be ready to work during hours of a too low price to be ready for periods of higher prices, or that they have to seasonally choose periods of a higher price. Alternatively, these powerplants could look at other ways of making their production more flexible; for example, using heat storage [101].

Innovation in renewables has largely been driven by feed-in tariffs, and as a result this innovation and the emergence of new technologies have brought about the biggest change in the energy sector [102]. Solar and wind today are almost cost-competitive with other power generation technologies; this means that the world finally has cost-effective solutions for facing climate change. Climate change is also the operative word when one talks about the future of the oil shale industry. There is no alternative to adhering to European and Estonian long-term climate goals, and while 2050 is far in the future, carbon neutrality is coming.

Innovation is not restricted to large-scale power production; cost-effective alternatives are available in other sectors as well. Electric cars are slowly but surely replacing internal combustion engines in private vehicles and thereby reducing the need for motor fuels. This has an effect on the demand for oil, and thereby the price of shale oil on global markets. Still, the proposed effects will not be happening too soon, and it is still the European climate policy that is the driving force behind changes in the oil shale sector.

The growing number of electric vehicles has another impact on energy systems that is highly relevant for the oil shale sector. Namely, today oil shale power plants are needed for energy security reasons, providing power during periods of no wind or sun, and even being back up for cases when there might be interruptions with some of the cables to our neighbouring countries. When there are enough electric vehicles in the system, their batteries can be used for the same purposes.

Finally, there are discussions about building a fourth-generation nuclear power plant in Estonia. This is, no doubt, a good idea. Unfortunately, there are no fourth-generation nuclear power plants available. Once the technological progress reaches a state where these kinds of small modular reactors are available and competitive with other technologies, then of course nuclear would also be an option for Estonia. Today, however, nuclear power plants cannot be considered a viable alternative for designing the Estonian energy sector.

Considering all of this together, it becomes evident that energy transition is once again occurring. This transition is taking us to a world where the oil shale industry can only function if carbon capture and storage technologies become cost-effective, and even then, the actual need for oil shale is questionable. Still, this is in 30 years’ time; 30 years might not be a long time for the energy sector, where lifetimes of assets can be 50-100 years, but 30 years is an extremely long time for making day-to-day policy decisions. Assuming that Estonia and the European Union will stick to the goal of reaching carbon neutrality by 2050, one can suggest making a good transition plan and managing the transition smartly. A good transition plan must entail both a plan for investments, as investment made in 2020 might still be in use in 2050, but also a plan for divestments.

The transition plan also has to account for making the most of already existing assets and having a plan in place for retraining current employees and redesigning the curricula of trade schools and universities to make sure that the system is giving people professions that are needed and valuable.

9 Conclusions

Transformation of energy sectors is ongoing all around the world, with the EU showing the way. Estonia is no exception, as the author of this thesis has spent the last 10 years working with a multitude of issues related to oil shale and the Estonian energy sector as a whole. This thesis tried to identify the most important aspects that one should assess when developing scenarios for the energy transition of countries. The assessment methodology was then tested on one specific transition – the future of the Estonian oil shale sector.

The methodology developed in this thesis was largely based on the energy trilemma framework used by the World Energy Council, with additional indicators proposed for energy security, and a more simplified approach suggested for energy equity and environmental sustainability. Methodology developed and tested in this thesis uses the energy security matrix for evaluating the impact of transitions on the overall energy security of countries. This is a novel approach developed by the author and his fellow researchers at TalTech. Energy equity is mainly assessed using the impact on the income, GDP, employment, and balance of trade of countries. Environmental impact is evaluated using metrics for emissions of greenhouse gases, waste generation, and the effect on water supply.

Having developed the methodology, this thesis tested it by looked at two alternative scenarios for the Estonian energy sector, Oil Shale Exit (OSX), which would mean shutting down the Estonian oil shale industry by 2030, and Gradual Transition (GT), which would give the sector breathing room until 2050, or perhaps even longer.

It was seen that closing down the oil shale industry has more to do with the economic and political stability of the region and income for both local municipalities and Estonian government than it has to do with either energy security or environmental aspects. The analysis confirmed that OSX would have some negative implications on Estonian energy security, but as long as Estonia has good relations with its neighbours and functioning infrastructure for importing energy, the lights will be kept on, houses warm, and car engines running. Similar results were seen for the environmental aspects of this transition. While OSX would have quicker and larger drops in emissions to the air and faster reduction of waste generation, the effect would not be so dramatic. The reason mainly being the closure of the oldest oil shale-fired power plants.

Going forward, it is the responsibility of the Estonian government to ensure a just and thought out transition from today's energy paradigm to one with much less emphasis on oil shale. While doing this, many boundary conditions have to be met, the harmful effects on the energy system have to be minimised, and the prosperity of the oil shale region and the country as a whole need to be kept in mind. To do this, a long-term strategy needs to be prepared. This strategy should use the energy trilemma framework as its basis; this ensures that all important aspects of energy policy are examined.

This thesis has shown that long-term climate goals, the country's energy security, and the economic wellbeing of its inhabitants can coexist. The best way to achieve this is by not taking radical steps in any direction. While Gradual Transition performs worse on the environmental axis compared to OSX, it is better for the country as a whole in the energy security and energy equity dimensions. Still, although OSX would bring quicker results from the environmental aspect, it will not matter so much in the longer run. Neither scenario is stepping over the strict environmental rules and regulations in place, and in neither case are international obligations broken.

It has been shown that Gradual Transition is the preferred route, and in this scenario, there is some investment in new production facilities. However, these investments are into shale oil production and shale oil upgrading. Both of these have a lower environmental footprint compared to the direct combustion of oil shale for power generation, and shale oil upgrading considerably increases the income from producing and selling shale oil.

In conclusion it can be said that energy transition in Estonia is happening; the pace and the target however are to be set by policymakers. One recommendation from this thesis would be to think with long-term targets and energy trilemma dimensions in mind. And if policymakers were to want just one recommendation, then it would be that Gradual Transition is preferred to OSX. Still, the decision regarding the future of Estonian long-term energy policy is up to Estonian policymakers.

Analysing the potential transition of the Estonian energy system confirmed that the methodology developed works and gives clear input for policymakers upon which to base their decisions regarding long-term energy policy. The methodology, however, is not complete and still needs further work; the author plans to devote his time to refining the methodology, testing it on other countries, and developing an easy-to-use tool for policymakers to use.

Table 5. Oil Shale Exit and Gradual Transition comparison

Category	Oil Shale Exit (OSX) compared to GT	Gradual Transition (GT) compared to OSX
Energy Security	Higher resilience to acts of terror due to less centralised power production.	+700 MW reliable capacity in 2030.
Energy Equity		+4 billion euros of income to the Estonian government from 2030 to 2050. + 40 TWh electricity produced from 2030 to 2050. + 30 million tonnes of shale oil produced from 2030 to 2050. + 4000 jobs saved in 2030.
Environmental Sustainability	-8 million tonnes of CO_2 emitted from 2030 to 2050. -32 tonnes of SO_2 emitted from 2030 to 2050. -50 tonnes of NO_x emitted from 2030 to 2050.	

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Abstract

Energy Transition Impact Assessment Methodology for Fossil Fuel Based Energy Systems

The main research task undertaken in this thesis was to develop a methodology for assessing the effects of energy transitions from fossil fuel based energy economies to carbon neutrality. The methodology was later used to examine the implications of Estonia’s potential exit from oil shale by 2030 and to compare these effects to an alternative scenario. The developed methodology was based on the energy trilemma prism, meaning the transition’s effects on energy security, socioeconomics, and environment were looked at.

The work was undertaken because more and more countries are looking at transitioning their economies from traditional energy systems to carbon neutral energy economies. This is being done due to growing climate concerns. The same is true in Estonia where more emphasis in society is being placed on long-term energy policy. On the one hand Estonia needs to adhere to European climate targets, while on the other, there are still more than 1 billion tonnes of economic oil shale reserves available in Estonia; this means here is a perfect candidate for testing the developed methodology.

It can be said that the thesis is novel in its premise, as such methodologies have not been developed, and such analyses have not been performed that would examine this kind of major transition of the Estonian energy sector. Although this analysis was carried out for oil shale and therefore is specific to Estonia, the methodology and tools can be applied elsewhere. Considering how topical the issue of carbon-neutrality is all over the world, it can be said that this thesis has wider implications as well.

The thesis looks at the role of oil shale in the Estonian energy sector during the last decades and forecasts its role for the coming years as well. Two scenarios are envisioned, one foreseeing the end of oil shale use by 2030 (OSX) and the other assuming the newest power plants and shale oil production plants carrying on until at least 2050 (GT). Both scenarios are analysed from the viewpoints of the energy trilemma.

Category	Oil Shale Exit (OSX) compared to GT	Gradual Transition (GT) compared to OSX
Energy Security	Higher resilience to acts of terror due to less centralised power production.	+700 MW reliable capacity in 2030.
Energy Equity		+4 billion euros of income to Estonian government from 2030 to 2050. + 40 TWh electricity produced from 2030 to 2050. + 30 million tonnes of shale oil produced from 2030 to 2050. + 4000 jobs saved in 2030.
Environmental Sustainability	-8 million tonnes of CO_2 emitted from 2030 to 2050. -32 tonnes of SO_2 emitted from 2030 to 2050. -50 tonnes of NO_x emitted from 2030 to 2050.	

OSX does have some negative implications for the energy security of Estonia, but the impacts were rather minor. Larger negative effects are seen on socioeconomic indicators; there, OSX means higher unemployment and significantly decreased revenues for the government. In the environmental category OSX has more positive impacts than GT, but it must be noted that GT also brings about many positive environmental changes.

In conclusion it was found that GT would be the more advisable scenario for Estonian long-term energy policy than OSX. However, the issue needs more thorough analysis, which the author plans to undertake in his post-doctoral studies.

Lühikokkuvõte

Fossiilsetel kütustel põhinevate energiamajandusete ümberkorraldamise mõjude hindamise metoodika

Doktoritöö peamine uurimisküsimus oli töötada välja metoodika energiamajanduse ümberkorraldamise mõjude hindamiseks. Välja töötatud metoodikat testiti, hinnates põlevkivist loobumise potentsiaalseid mõjusid Eesti energiasektorile. Välja töötatud metoodika hindab mõjusid lähtudes energeetika trilemmast, teisisõnu analüüsitakse potentsiaalse muutuse mõju energiajulgeolekule, sotsiaalmajandusele ja keskkonnale. Töö peamine olulisus ja päevakajalisus tuleneb viimastel aastatel hoogu kogunud kliimadiskussioonist. Nii Eestis kui paljudes teistes riikides peavad poliitikud lähiaastatel otsustama, milline on riikide pikaajaline energia- ja kliimapoliitika, kuid see otsus eeldab teema põhjalikku analüüsi, mille läbiviimiseks on oluline õige metoodika.

On selge, et Eesti peab täitma kõik Euroopa Liidu energia- ja kliimapoliitika eesmärgid, aga kas ja mis ulatuses tasuks võtta siseriiklikus energiapoliitikas ambitsioonikaimaid eesmärke, on hoopis raskem küsimus. Teema muudab veelgi keerukamaks asjaolu, et Eestis on jätkuvalt üle 1 miljardi tonni majanduslikult kasutatavat põlevkiviressurssi.

Töö ja kasutatud lähenemine on uudsed, seda nii väljatöötatud metoodika kui läbi viidud analüüsi osas. Kuigi analüüsiti Eestit, siis omab töö laiemat olulisust, sest sarnane poliitikadebatt ootab ees paljusid fossiilkütuseid kasutavaid riike ning siin töös kasutatud metoodika ja meetodid on sellisel juhul kasutatavad ka neis riikides.

Kategooria	OSX võrrelduna GT-ga	GT võrrelduna OSX-ga
Energiajulgeolek	Hajutatud tootmise suuremast osakaalust tingitud kõrgem vastupanuvõime terrorismile	+700 MW juhitavat võimsust aastal 2030
Majanduslik mõju		+ 4 miljardit eurot tulusid riigile aastatel 2030 kuni 2050. + 40 TWh elektritoodangut Eestis aastatel 2030 kuni 2050. + 30 miljonit tonni põlevkiviõli toodangut aastatel 2030 kuni 2050. + 4000 töökohta säilib aastal 2030.
Keskkonnamõju	-8 miljonit tonni CO_2 emissioone aastatel 2030 kuni 2050. -32 tonni SO_2 emissioone aastatel 2030 kuni 2050. -50 tonni NO_x emissioone aastatel 2030 kuni 2050.	

Dissertatsioonis vaadeldi põlevkivikasutust Eestis viimase kümnendi jooksul ja selle põhjal koostati kaks võimalikku tulevikku vaatavat põlevkivi kasutamise stsenaariumi. Esimene nägi ette põlevkivist loobumist 2030 aastal (OSX), teises (GT) eeldati, et Auvere elektrijaam ja põlevkiviõli tehased töötavad vähemalt 2050. aastani. Mõlemat stsenaariumi analüüsiti kasutades töös väljatöötatud metoodikat.

Analüüsi tulemusena selgus, et OSX omab teatavat negatiivset mõju Eesti energiajulgeolekule, kuid seni kuni Eesti välisühendused toimivad, ei ole mõju kuigi suur. Olulisem mõju on OSX stsenaariumi rakendumisel Eesti sotsiaalmajandusele, eriti regionaalsele tööhõivele ja riigi tuludele. Keskkonnamõjud on suuremad GT stsenaariumil, kuid tänasega võrreldes on ka GT stsenaarium oluline edasiminek.

Kokkuvõttes võib töö tulemusid analüüsides öelda, et GT eelistatum stsenaarium, kuid teema vajab edasist analüüsi. Autor plaanib oma järeldoktorantuuris teemaga aktiivselt tegeleda.

Appendix

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Editor's Page

Implications of the possible exit from oil shale for Estonian electricity sector

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1. Introduction

Estonia recently celebrated the 100th anniversary of its oil shale industry. This event gave the industry an opportunity to present achievements made in both the technology and economics of oil shale mining and end use. While the companies presented remarkable success stories about the reduction of air emissions and gains in the overall efficiency of both power and oil production, there were others who voiced concerns about the sustainability of the sector. This was at the end of 2016, today, more than three years later, these concerns are expressed even louder.

During the last 100 years approx. 1 billion tonnes of oil shale has been used, theoretically, there is still more than 4 billion tonnes of oil shale left, but out of this only around 1 billion tonnes can be classified as active reserves [1]. Taking today's yearly regulatory limit for oil shale mining (20 million tonnes) [2] as a basis for calculating the theoretical lifetime of oil shale industry, we see there are enough active reserves for at least 50 years, combined with the passive reserves oil shale will suffice for at least two centuries. For many this is too long a time and they are advocating for a quicker exit from oil shale.

The successful exit from oil shale would mean that by 2030 there would be no oil shale use by the energy sector in Estonia. In other words, no production of electricity, heat, or oil from oil shale. No new investments, no jobs, and no more environmental impact post 2030. It is clear that this kind of radical transformation would have major consequences in at least three dimensions:

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1) socioeconomic, 2) environmental, and 3) energy security. It is the job of politicians to weigh all these effects and pick the best course to set our sights on. However, it is the job of the scientific community to provide adequate information on which policymakers could act.

The job of both policymakers and researchers is complicated due to the fact that energy policy is a multi-dimensional issue, and hence, the regulations governing it come from many different fields. First there is the General Principles of Climate Policy until 2050 [3] approved by the Estonian parliament on 5 April 2017. Then there are national development plans for oil shale [4], long-term energy policy [1] and climate change adoption [5]. These are Estonian national policy documents. In addition, there are international agreements like the Paris Climate Agreement or the European roadmap for greenhouse gas emissions reduction.

The mentioned policy documents are no doubt impactful and need to be considered, but the most important one, and the one used as a reference for business-as-usual, is the Estonian National Development Plan of the Energy Sector until 2030 (ENMAK). ENMAK outlines the following future for Estonia [1]:

- energy intensity of economy will decline by 66% from the year 2012 to the year 2030
- energy independence will be reached by 2030
- share of imported electricity will remain at 0% until 2030
- energy market will remain open, non-subsidized, and market-based
- there will be enough electricity production assets in Estonia to fulfil the N-1-1 criterion
- renewable electricity production will cover at least 50% of inland electricity consumption
- share of renewable energy in heating will be at least 80%

In the following analysis these axioms are taken as something Estonia must accomplish and are hence not up for debate.

When examining the future, it is always useful to first see where one is coming from. Looking back on the historical use of oil shale in Estonia, it can be seen that the use of oil shale has steadily grown since 2005, except for the two low-oil-price periods: first in 2009 and then again in 2015 (Fig. 1) . It should be noted that in this paper, oil shale use figures refer to tonnes of oil shale used, not tonnes of oil shale mined.

It is clear that all radical transformations disturb the *status quo*, the question is how much.

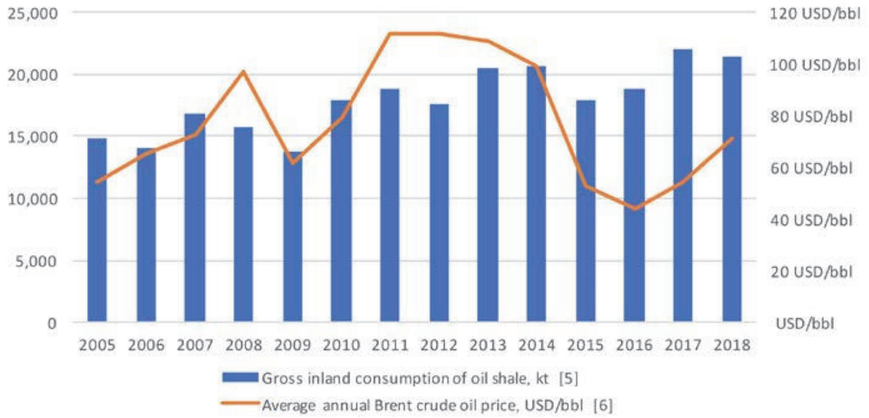

Fig. 1. Oil shale use in Estonia [6, 7].

2. Socioeconomics

The first category to look at is socioeconomics. The socioeconomic effects include the impact on employment, governmental revenues, and the overall economy of Estonia. Historical analysis shows that oil shale industry has generated a lot of income for both the government and the economy. Eesti Energia, the biggest company using oil shale in Estonia, pointed out in their last annual statement that in 2018 the company generated almost 900 million euros of economic value, out of this 130 million euros was paid as taxes to the state and 115 million was paid out to employees [8]. The same holds true for other companies working in the sector. This of course includes other businesses of Eesti Energia as well, like the grid services or the renewables business. Still, the majority of Eesti Energia's income was generated from the oil shale business, in 2018 the share of electricity and liquid fuels was more than 60% of the company's total sales revenue, this equates to more than half a billion euros [8].

Companies operating in the sector have jointly published yearbooks of Estonian oil shale industry. Covering all the most important aspects of the industry, these yearbooks represent the best publicly available source of information about the sector and give a unique insight into the industry-related socioeconomic impact since 2014 when the first yearbook was issued.

Concerning the impact on economy and state treasury, the data published in the yearbooks reveal that prior to 2015 the companies had annual sales revenues from oil shale-related business in the amount of more than 900 million euros, of which more than 30% was paid to the state [9]. As the oil price fell, so did the sales revenues and, as a result, also the profits and income to the state treasury. Despite the low oil price, oil shale industry still generated

Fig. 2. Economic impact of oil shale industry [9].

more than 600 million euros of annual sales revenues, out of this each year more than 15% was paid to the state. For comparison, the total Estonian state budget in 2014 was 8 billion euros, which means that the oil shale industry's contribution to the state budget was almost 4%. By 2017 the state budget had grown to 9.48 billion euros, indicating that the oil shale industry's contribution had fallen to 1%.

Additionally, the industry generates the spillover effect on the economy by creating jobs servicing the companies and the people working in the industry. The issue was analysed in more depth four years ago by Ernst & Young. Then the analysis showed that the oil shale industry generated approx. 4% of Estonian GDP and employed about 2% of Estonian workforce [10]. Even more important for Estonia is the fact that oil shale industry is largely a regional phenomenon. Most of the people employed are working in the northeastern part of Estonia and while the average salary in the oil shale industry exceeded

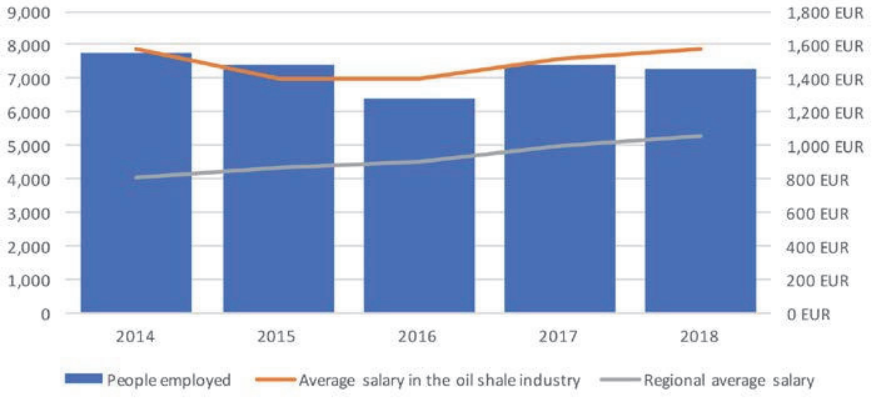

Fig. 3. Socioeconomic impact of oil shale industry [9, 11].

the national average by 20%, it exceeded this region's average by more than 50%.

Speaking of oil shale industry, one of the most commonly overlooked aspects is allocation of CO_2 quotas. If there were no oil shale industry, the Estonian government would have almost no income from the sale of free CO_2 quotas allocated to Estonia by the European Commission. This is due to the fact that the country-by-country quotas depend on the actual CO_2 emissions in each country in 2005 [12]. We do not know what the allocation of quotas in the next period 2021–2030 will be, but we do know that with no oil shale industry operating in Estonia, the allocated quota will be lower.

These are just some of the positive aspects of the oil shale industry, others include income from the export of electricity, oil, and know-how. It is very important that domestic oil shale energy supply guarantees stability both in terms of market price and energy security for large energy-intensive consumers. It is exactly this stability that has made several big industrial players bring their production next to the oil shale-fired power plants.

As regards the export of know-how, then Estonian scientists and engineers have participated in the development of new technologies available for oil and power production from oil shale. A good example of know-how export is the 2.1 billion USD power plant project in Jordan, the world's largest single investment into oil shale-based energy and the biggest foreign direct investment in Jordan. The state-of-the-art circulating fluidized bed boilers used in the project are developed with the help of scientists from Tallinn University of Technology. The same scientists have helped to develop and refine shale oil pyrolysis technologies like Enefit280 which is considered to be the most efficient and environmentally friendliest technology for producing shale oil.

The authors interviewed senior project managers from Eesti Energia to have information about the achievements made in developing the technology for producing shale oil. The following aspects were brought out as most important. First, Eesti Energia confirmed their Enefit280 plant has exceeded the design parameters and is currently working with 10% higher efficiency than planned (12.3% planned oil yield vs 13.6% actual oil yield, oil yield here refers to tonnes of oil produced from one ton of oil shale). Secondly, it was pointed out that the plant has high availability, which is currently around 90%. These two factors combined resulted in record production numbers. For example, the 90-day production volume in 2019 exceeded 66 thousand tonnes of shale oil. Eesti Energia also confirmed there is a lot of interest from countries with oil shale resources in acquiring the technology for shale oil production purposes.

3. Environment

Stopping the use of oil shale is, at least for proponents of the idea, mainly an environmental issue. And while it is true that the oil shale industry has relatively high CO_2 emissions, it is also true that the industry is adhering to all environmental rules and regulations. However, Estonia is part of the European Union and therefore needs to fulfil the targets commonly agreed by the member states.

The environmental aspects of Estonian energy sector are covered also in ENMAK [1]. ENMAK mandates Estonia to meet all European targets related to climate policy and sets some national targets as well. For example, according to ENMAK, Estonia will need to reduce the CO_2 emissions from energy sector by 70% by 2030 (compared to 1990), the share of renewable energy in the final energy consumption must be higher than 50%, and the share of renewables in electricity consumption must be more than 50%.

In 2016 the total oil shale use across all sectors was 18.84 Mt [6], which contributed 67.5% of national primary energy supply. In 2016 the total emissions of greenhouse gases (GHGs) were 16.9 Mt CO_2 eq and without land use, land-use change and forestry or the change in CO_2 emissions resulting from human effects on land use (LULUCF) were 19.6 Mt CO_2 eq [13]. A major contributor to GHG emissions was energy sector, which accounted for 17.5 Mt (89.1% of total emissions), followed by agriculture with 1.3 Mt (6.8%), industrial processes with 0.5 Mt (2.5%) and waste with 0.3 kt (1.6%). Within energy sector the main contributors to GHG emissions were energy industries with 13.8 Mt (70.3% of national total) and transport sector with 2.4 Mt (12.1%). Oil shale was not used in transport sector.

Going even deeper into energy industries, oil shale is mainly used for public electricity and heat production where oil shale related GHG emissions in 2016 were 11.3 Mt, accounting for 90.6% of the sectoral emissions. GHG emissions from the manufacture of solid fuels and other energy industry, including shale oil production, were 1.3 Mt and accounted for 100% of the sectoral emissions. Oil shale contribution to emissions in other sectors was just over 0.1 Mt. Altogether, the use of oil shale resulted in 12.8 Mt of CO_2 eq. So, we could say that oil shale was responsible for 64.9% of total GHG emissions in Estonia or 72.9% of energy related emissions in 2016.

We can lower the CO_2 content of power production by using oil shale more efficiently, in the combined production of oil and power as is already applied in Enefit280 process. This process first extracts oil from the shale and power is then produced from the residues of oil production. Estonia has taken the aim for 2030 to emit less than 10.5 Mt of CO_2 eq from energy sector. This means that GHG emissions in energy sector need to be lowered by 7 Mt of CO_2 eq (i.e. by 40%) compared to 2016. That can be achieved by further replacing the direct firing of oil shale for power production with the co-production of oil and electricity, and by replacing oil shale with biomass.

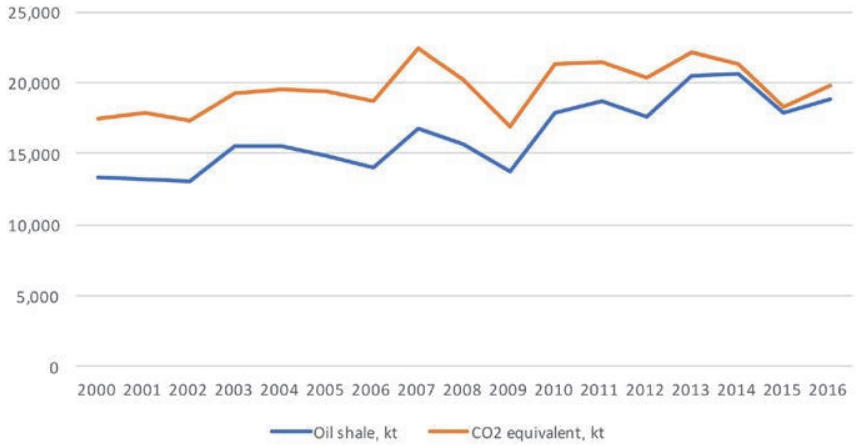

Fig. 4. Greenhouse gas emissions and oil shale use in Estonia, kt [6, 14].

Another important factor is the amount of renewables in the system and their share in the end consumption of electricity. Electricity consumption (with losses) was 8.4 TWh in 2016. Renewable electricity (RE) generation was 1400 GWh and the share of renewable energy was 15.1%. This mainly came from biomass and renewable waste from cogeneration of heat and power (CHP) 681 GWh and wind 589 GWh. Forecast for the electricity consumption in 2030 is 10 TWh. As ENMAK targets to achieve the share of renewable energy of 30%, then renewables must contribute 3 TWh. This means that the generation of RE must more than double. Most of the renewables today are unfortunately intermittent and need supporting assets for balancing the energy system during times when there is no wind or sun. Today the power plants using oil shale are effectively used for this purpose. Should these plants be shut down, the need for new balancing assets will arise.

4. Energy security

The final aspect to look at is energy security. In Estonia the majority of electricity is produced in oil shale-based power plants. The total available production capacity from oil shale is approx. 2000 MW of electricity [15]. Most of the capacity was put into operation in 1959 and 1973, while the newest unit, Auvere Elektrijaam, started production in 2015.

Now we see that the power generation from oil shale is decreasing, unfortunately this means that the total available generating capacity in Estonia is declining as well. This puts Estonia in a rather tricky situation

Table 1. Oil shale-fired power plants in Estonia [15]

Power plant	Installed net capacity, MW
Eesti Elektrijaam	1355*
Balti Elektrijaam	322*
Auvere Elektrijaam	274
Enefit	10
Põhja SEJ	78
Sillamäe SEJ	16
Total	2055

* In total, ten energy blocks and four units are equipped with $DeSO_x$ SDA devices and two units are equipped with fluidized bed boilers, altogether 1058 MW. Four blocks out of ten with a capacity of 619 MW have limited allowed production hours – 17,500 hours during 2016–2023.

when it comes to energy security. One view is that as Estonia is part of the Nordic power market, then all the necessary electricity can be bought from the market. However, this viewpoint does not take into account the fact that most of Estonia's neighbouring countries are in electricity deficit themselves (Table 2). During 2016–2018 the Baltic states' (Estonia, Latvia, Lithuania) electricity market total production volume was 58.8 TWh, while market consumption was 77.2 TWh. On average Baltic states were in deficit with 713 MW. It is clear that removing oil shale-fired power plants from the market would put the whole region in a worse position when it comes to energy security.

Table 2. Electricity balance of Estonia's neighbouring countries in 2017, TWh

	Finland	Sweden	Denmark	Latvia	Lithuania	Poland
Production	63.3	158.5	28.0	7.3	2.5	152.1
Consumption	83.4	138.1	32.4	7.2	10.4	168.1

5. Conclusions

Energy policy is a multi-dimensional issue and needs to be examined as such. This paper scanned different aspects of a potential transformation of Estonian long-term energy policy and found many arguments that support re-examination of which path to take. This article confirms that the issue needs a more in-depth analysis and the authors plan to take the three categories into focus in their upcoming research.

In the environmental dimension the authors found that stopping the use of oil shale would reduce CO_2 emissions, but further work is needed on other environmental concerns. From socioeconomic analysis it is clear that the state would lose an important source of revenue and the region would suffer from loss of jobs, but again the exact degree of impact needs to be examined in more detail. The same is true for energy security. It was found that stopping the use of oil shale would have a negative impact on the region as a whole because most of Estonia's neighbours are in deficit. From the research it became clear that Estonia needs a domestic energy industry which would be capable of providing flexible energy production that is competitive on the regional market – exactly what the oil shale sector is offering.

All in all, it can be said that the transformation of Estonian energy industry is already ongoing, now only the pace needs to be set. For best results, the issue needs more thorough research. Today the proponents of oil shale exit are mainly environmental groups and green lobby organizations looking for bigger subsidies for their industry. For the former it is almost a religious issue, the latter on the other hand are merely doing their job and are trying to keep the bread on the table, letting their employers feel happy.

Everyone is entitled to their own opinion, but when it comes to issues with impacts as high as oil shale exit could potentially have, then one cannot rely only on religious beliefs or concerns voiced by lobby groups. These kinds of decisions need to be based on thorough research and all the facts need to be on the table. Later, after all the facts have been considered, Estonian long-term energy policy will still need to be a political decision. It is the job of the scientific community to make sure that policymakers have had the chance to see all the facts and that they understand the consequences of both decisions. This applies not only to Estonia and Estonian policymakers, but also to all countries going through an energy transition. Energy transitions need to be analysed thoroughly, minimally from the three aspects covered in this article, but most probably on an even wider scale. Oil shale might be Estonia-specific, but the discussion is not, and this is where the scientific community must be the one to carry out similar analyses to give policymakers right tools for choosing the right path.

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Concept for Energy Security Matrix

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HIGHLIGHTS

- Energy security should be analysed in technical, economic and political terms;
- Energy Security Matrix provides a framework for energy security analyses;
- Applicability of Matrix is limited due to the lack of statistical data and sensitivity of output.

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ABSTRACT

The following paper presents a discussion of short- and long-term energy security assessment methods and indicators. The aim of the current paper is to describe diversity of approaches to energy security, to structure energy security indicators used by different institutions and papers, and to discuss several indicators that also play important role in the design of energy policy of a state. Based on this analysis the paper presents a novel Energy Security Matrix that structures relevant energy security indicators from the aspects of Technical Resilience and Vulnerability, Economic Dependence and Political Affectability for electricity, heat and transport fuel sectors. Earlier publications by different authors have presented energy security assessment methodologies that use publicly available indicators from different databases. Current paper challenges viability of some of these indicators and introduces new indicators that would deliver stronger energy security policy assessments. Energy Security Matrix and its indicators are based on experiences that the authors have gathered as high-level energy policymakers in Estonia, where all different aspects of energy security can be observed.

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1. Introduction

Assessment of the quality of energy policy has been the topic for a number of recent studies. The most prominent general assessment of energy policies has been issued by the World Energy Council (WEC) in association with Oliver Wyman [1], another recent energy policy assessment has been issued by the World Economic Forum (WEF) in association with Accenture [2]. Both of these assessments regard energy security as one of the main dimensions of energy policy. Table 1 provides the dimensions and indicators used in these two reports to assess energy security.

Also International Energy Agency has described the approach to assess the short-term energy security of the country [3] with its MOSES model. IEA has also analysed in detail oil and gas supply security in its member states [4] and has described a general framework to assess governance and electricity market arrangements, power system security and adequacy by looking at external and domestic risks and resilience of the power system. However, as IEA admits, their frameworks “cannot be used to compare the overall energy security of different countries, although specific sources and fuels can be compared”. European Commission has used Energy Import Dependence as the main numerical indicator for energy security in its communication on energy security [5].

However, if energy policymakers would try to use these sets of indicators in their national strategic planning activities in order to improve their country's situation, they would find that these indicators would depend on several unpredictable factors. Even worse: some of these indicators may even incentivise policy makers to take national decisions, which would have negative

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Table 1
Main characteristics of the energy security policy assessment methodologies by WEC and WEF.

WEC energy sustainability index	WEF energy triangle
1. Diversity of electricity generation (Shannon index)	1. Diversity of total primary energy supply (Herfindahl index)
2. Ratio of total energy production to consumption	2. Electrification ratio (%)
3. Distribution losses as percentage of Generation	3. Quality of electricity supply (Survey)
4. 5-year compound aggregated growth rate of the ratio of TPEC (Total primary energy consumption) to GDP	4. Percentage of population using solid fuels for cooking (%)
5. Days of oil and oil product stocks	5. Import dependence (%)
5a. Exporters: fuel exports merchandise value as a percentage of GDP	6. Diversification of Import counterparts
5b. Importers: net fuel imports as a percentage of GDP	

regional or global impact. For example, in order to calculate Energy Import Dependence, official statistics uses for some energy resources primary or secondary energy (coal, crude oil and oil products, biomass), but for some resources tertiary energy (as electricity from nuclear, wind and solar). This misleading statistics delivers that final energy produced from primary energies always has a bigger weight in these calculations: for example electricity originating from biomass (counted in statistics as used primary energy of biomass) has much higher weight than electricity produced from wind (counted as tertiary energy of electricity produced) due to the technological losses of transformation. Therefore Energy Import Dependence delivers very misleading signals to the policy makers that try to decrease the dependence of a country.

The aim of the current paper is to discuss the approach to energy security indicators and to provide some additional viable indicators that should be considered by the policymakers for higher quality of energy strategies. Following observations are based on long-term experience of the authors as energy policymakers in Estonia. Nevertheless, current paper does not intend yet to provide an exhaustive methodology for full assessment of energy security of a country, but discusses the components for such methodology.

However, it is understood that the main problem is associated with the availability of data: indicators which are currently collected and available in world-wide energy-related databases are not providing adequate background for energy policymakers. This is another issue for the policymakers to address: in the absence of data, which would provide right incentives, it is extremely difficult to make adequate energy policy decisions.

2. Materials on energy security

In addition to the studies by World Energy Council and World Economic Forum, several national approaches have been also applied to energy security assessments. Most interesting ones have been applied by the USA [6] and Lithuania [7]. There is also a number of scientific assessment methods used to approach the energy security from different angles. Christie [8] has approached energy security from the perspective of the vulnerability of the energy infrastructure, Chester [9] and Ciuta [11] have described the multiplicity of the definitions and indices of the energy security, Rogner [10] and Makovich [12] have approached energy security from the perspective of costs to the society. Hughes [13] has described a generic framework for IEA conceptual approach to short term energy security [3] and Winzer [14] has defined energy security as the continuity of energy supplies relative to demand. All of these references have in turn used a number of earlier studies in this regard.

Nevertheless, if energy policymakers would try to use these different assessment methods for the development of their national energy policies, they would soon find that the application of energy security indicators from these investigations is quite difficult. These reports provide variety of retrospective indicators and overviews about the energy security levels and its changes over the years in history, but it is nearly impossible to provide plausible forecasts of these energy security indicators. And as far as energy security is one of the main pillars of the Energy Trilemma [1], it is a constant struggle for policymakers to find proper indicators, which would help them to prepare stronger energy policies in this respect.

For example, it would be rather difficult to forecast the energy mix of power production in the liberalised energy markets, especially in case when there is a high share of variable hydro power in the power system or strong interconnections to neighbouring countries, which can be used to import or export substantial volumes of power. And it is even more cumbersome to predict the geopolitical or national political changes, which may also influence national energy security.

The definition of energy security is another widely disputed matter in the literature. One of the most comprehensive set of energy security definitions is provided by Winzer [14]. From the variety of definitions one could come to the conclusion that we should distinguish between short- and long-term energy securities. Short-term energy security can be largely assessed by the potential of an energy system to deal with disturbances (in other words by describing the Operational Resilience of the energy sector). In case of long-term energy security (which should aim to describe the investment climate to tackle energy security issues), one could distinguish three layers, which should be part of every energy security policy: Technical Resilience and Vulnerability, Economic Dependency and Political Affectability. So all in all there are four layers to energy security:

1. Short Term Operational Resilience should describe the ability of the current infrastructure of the national energy system to cope with different disturbances of energy supply and demand from seconds to days. The question one should ask here would be “how flexible is the current infrastructure to cope with potential disturbances? ” This layer is usually described by the characteristics of technical infrastructure and its operations (power capacity margin, diversity of power and heat production, oil stocks, SAIDI, etc.). To capture the level of technical resilience the WEC [1] measures in its methodology Ratio of Total Energy Production to Consumption, and Days of Oil and Oil Product Stocks for transport sector. The WEF [2] uses for similar purposes in its assessment indicator on the Quality of Electricity Supply for electricity sector (based on their Survey). IEA [4] looks in terms of electricity in general to the power system operating practices, situational awareness, coordination, communication and other such aspects, which subjectively can describe the power system resilience to shocks.
   However, majority of these indicators show only the result of the operations (subject to market situation, weather impacts, unexpected outages etc.), but they do not describe the capabilities of the infrastructure (capabilities of different production

facilities, network configuration, impact of intermittent producers, interconnections, stocks etc.) and do not take into account implications from other potential threats to energy infrastructure (as cyber threats, water restrictions, terrorism etc.), which would ideally provide much better overview about the responsiveness of the infrastructure to potential threats. Only WEC's oil and oil product stocks indicator (see Table 1) indicate the level of vulnerability of a country to oil supply disruptions, other indicators are a result of the operations of an energy system. IEA analyses the operational practices, but other such international frameworks do not address such kind of short term resilience.

In case of power supplies one could also analyse an additional layer of Operational Resilience (as an example by ENTSO-E [16,17]), which looks separately at the immediate flexibility of power system to deal with potential disturbances. European Commission has recently also used this approach in their special stress-tests on the short term resilience of the EU gas sector [18]. For the energy policy planning purposes it could be taken into account in the analysis of Technical Resilience.

2. Technical Vulnerability should describe the ability of the energy system to cope with operations in long term (up to 10 years). This layer should describe the diversity of energy systems and the ability to cope with expected long-term loads. The question one should try to answer here is “how capable is the system to cope with long term trends? ” Diversity of supplies (both by source and by market players) should enable energy systems to address the issues of the demand changes, potential abuse of market situations and potential impact of the failures of important infrastructures. In parallel one should look at the age of infrastructures and the ability to renew them, potential share of indigenous resources, and also the ability of the infrastructures to incentivise demand side energy efficiency.

   WEC [1] measures in its methodology Diversity of Electricity Generation (based on Shannon Index), Distribution Losses as percentage of Generation, 5-year compound aggregated growth rate of the ratio of TPEC to GDP. For similar purposes WEF [2] uses in its assessment indicators of Diversity of Total Primary Energy Supply (based on Herfindahl Index). MOSES model form the IEA [3,4] looks at the resource adequacy, diversity, flexibility, asset performance and sustained emergency events. European Commission has used also the market share of 3 largest power suppliers [15] as an indicator of the market power, ENTSO-E has also looked from the perspective of long term system adequacy for power sector [16,17]. As one can see, these indicators can provide quite vague retrospective assessment of the levels of energy security of the countries, and are usually more suitable to be used in case of energy importing countries.

3. Economic Dependency describes the magnitude of influence, which energy sector has to the economy of a country. The question one should ask here is “how much is the country's economy dependent from energy sector? ” This layer is usually described with macro-economic indicators (Energy Import Dependence, share of energy exports/imports merchandise volumes in the GDP, share of production from indigenous energies etc.). Depending on countries energy balance, the nature of risks associated with Economic Dependency influences largely also the next layer: energy importing countries are striving to reduce their economic and political dependence, while energy exporting countries are more interested about their income and geopolitical influence. WEC [1] addresses this layer with indicators on the share of fuel exports/imports merchandise value as a percentage of GDP, WEF [2] tries to capture it by measuring Energy Import Dependency.

   Though, it would again be rather difficult to make any energy policy decisions based on these indicators: the merchandise value is dependent on the price of energies, the import volumes are dependent on the market conditions and availability of local resources. However, they provide quite good incentive about the level of current Economic Dependence and can be used also to forecast potential future dependence.

4. The layer of Political Affectability should characterise the openness of the energy policy to the (geo)political influence. This layer should respond to the question “how much can other countries influence the energy policy of the country? ” This layer is usually not measured, though it has a vast impact to the energy sector developments. The openness to political corruption, instability of governments and potential geopolitical interests may have very clear influence to the energy policies and to the investments in the energy sector. This layer can be assessed by the different political stability and corruption indexes, though the forecasting of this layer is always unpredictable. WEC [1] tries to take this layer into account with its contextual performance indicators on Political Stability and Control of Corruption; WEF [2] indicators do not address this layer at all. IEA [4] analyses in electricity market the regulatory and institutional frameworks, applied legislation, rules and standards. In terms of oil and gas markets IEA has also analysed the legislation and preparedness measures in cases of emergencies.

But again, for the forecasting purposes it would be nearly impossible to make any predictions of these indicators in majority of the countries. To assess that, one could look for the trends in political stability of a country and of a geopolitical region, and the openness of a country to a political interference.

Another aspect that could be discussed in terms of energy security is the division of energy sectors. Very often energy sector is divided into electricity, oil and gas sectors, sometimes coal sector is added there. However, one may argue that from the state citizens' basic needs perspective it should be essential to guarantee the supplies of electricity, heat and transport fuels. In this context gas can be one source of these supplies, which can to some extent be replaced. Indeed, gas is often also used for industrial purposes to produce other products, but this may not be considered as the basic need for the citizens' energy supplies.

When considering heat supplies, both local and district heat production shall be considered. In this context another mislead comes out from statistics: usually heat supplies are only measured in terms of district heating (as secondary energy), and local heat supplies are measured as fuel supplies to consumers (in terms of primary energy). For the sake of comparability and the general purpose, the governments should measure more heat energy and not the primary energy put into the process. Current article considers heat consumption both in terms of district and local heat output.

In case of cooling as one form of energy supplies to customers, ideally one should measure the volume of delivered cooling volume. However, it is understood that the measurement of this volume is nearly impossible, so cooling in terms of the current article is considered to be a part of electricity consumption, as it is also appearing in the statistics. It is clear that the countries with hotter climate have therefore higher need for electricity per capita.

Therefore current paper takes an approach that for the basic energy needs of a state we should look for electricity, heat and transport fuels sectors, and to assess them in aforementioned four layers of energy security.

3. Indicators for Technical Energy Security

Technical Energy Security in terms of this article covers the layers of Technical Vulnerability, Technical Resilience and Operational

Resilience of electricity, heat and transport sectors. In practice it means in terms of energy policy the requirement to guarantee accordingly needed energy, capacity and flexibility of an energy system. However, it is clear that not all of these layers have the same importance for different energy sectors. The latter layer (flexibility/ Operational Resilience) makes actually electricity sector very different form the other energy sectors. Even more, in practice one can observe that power supply markets have designed separate markets for all these objectives: balancing markets for flexibility, power markets for energy supplies, and capacity remuneration mechanisms or national power security reserves for capacity delivery.

In following sub-chapters are discussed the most important indicators for Operational Resilience, Technical Resilience and Technical Vulnerability.

3.1. Indicators for Operational Resilience

In terms of Operational Resilience one should look for disturbances that may have an immediate widespread impact to the operations of an energy system. Here we can distinguish between internal and external disturbances – the ones that are originating from energy system operations and the others that are affecting system from outside. The most important internal disturbances are usually changing load and intermittent power production, while the most important external disturbances may occur from acts of terror or cyber-attacks. Power sector may have by far the largest impact due to internal disturbances; therefore it is worthwhile to look for indicators of Operational Resilience only for this sector. In order to assess the Operational Resilience of the power system to internal disturbances one can ask, how manageable power system in difficult situations is.

In this respect, managing minimum and maximum loads are the most difficult situations for system operator. If intermittent producers produce too much energy during minimum load it may lead to overload of the system and to system failures that bring along brown-outs or black-outs. Similarly, if intermittent producers produce too little during peak load, then it may lead to brown-outs or black-outs. In order to measure this flexibility of the power system, we should analyse the operations of the systems in these two extreme cases. These basic aspects of security of supply must form a part of energy security policy.

In order to assess the magnitude of these impacts, we should assess the potential influence of intermittent capacities to the system operations in these two cases. To assess the magnitude of the potential issue during minimum load, the ratio between intermittent capacities to minimum load can be presented as follows:

$$K_{IM,MIN}=\frac{P_{wind}+P_{solar}+P_{IM}-P_{STOR}}{P_{min}}*100\%, \tag{1}$$

where:

$K_{IM,MIN}$ – Ratio of Intermittent Capacity to Minimum Load
P_{wind}- Installed Net Wind Capacity (MW);
P_{solar} – Installed Net Solar Capacity (MW);
P_{IM} – Other Installed Intermittent Capacities (MW);
P_{STOR} – Capacity of Storage Facilities (as for example Pumped Storage) (MW);
P_{min} – Annual Minimum Load (MW).

$K_{IM,MIN}$ would indicate how difficult it would be to maintain the operational balance between the load and production of a power system in case of low load periods, when intermittent capacities can also peak with their production. Often there is also a potential for countries to export excess power or switch off intermittent facilities, but the indicator would indicate the level of difficulty to manage the balance. It goes without saying that if the share of intermittent capacity is high compared to minimum load, the power system is more difficult to manage.

In other extreme case of internal Operational Resilience one can assess the potential to cover maximum load with reliable capacities (i.e. without intermittent capacities) taking into consideration their average availability (usually around 90% of the time), and including also potential capacity available via interconnections during peak. This would indicate the most difficult potential situation to dispatch in high-load periods:

$$K_{REL,PEAK}=\frac{P_{REL}\cdot 0,9+P_{HYDRO}+P_{IMP}}{P_{PEAK}}*100\%, \tag{2}$$

where

$K_{REL,PEAK}$ – Ratio to cover Peak with Reliable Capacities;
P_{REL} – Capacity of Reliable Power Suppliers, i.e. from fossil fuels, nuclear and biomass (MW);
P_{HYDRO} – Available Capacity of Hydro Plants during Peak (MW);
P_{IMP} – Capacity that can be imported (based on TSO assessment);
P_{PEAK} – Forecasted Peak Gross Consumption (Net Consumption and Losses).

Although this indicator provides good assessment of the potential operations, the flows via interconnectors are not always controlled by the national system operator. Therefore the capacity available via interconnectors during peak hours has to be assessed very carefully. However, if the countries work in the same market designs and rules with no bottlenecks (like Nordic and Baltic countries), it is worthwhile to analyse these indicators not only within national borders, but for the whole region.

By combining these two Ratios into one graph (Fig. 1) we can compare different countries power systems Technical Resilience in the most difficult situations for Transmission System Operators (TSOs). Fig. 1 provides such a comparison among the EU states, based on 2012 data from ENTSO-E [16,19].

These indicators represent how flexible is the power system to deal with intermittent supplies. Lower levels of the Ratio of Intermittent capacity to Minimum Load represent higher flexibility of the power system. However, ratio levels over 100% indicate that countries' power system cannot absorb during minimum loads the whole load and the excess volumes have to be absorbed by neighbouring countries, or some intermittent capacities have to be shut down.

The Ratio of potential supplied load compared to Maximum Load represents the ability of the country to cover its maximum load (including the import capabilities). Level below 100% represents severe difficulties in this regard; level over 150% speaks about the strong ability to cover peak loads (but may fall behind in terms of affordability of the power price in terms of Trilemma).

The countries that are represented in the upper left quadrant of Fig. 1 can be considered to have stronger level of Technical Resilience of the power system, as their power system can take care of the most difficult situations of the system operations. These countries that are in the right side quadrants of Fig. 1 rely on their power supply flexibility largely on their neighbours, and that cannot be always highly assessed.

If internal Operational Resilience indicators would be fairly easy to assess, then external ones are much more complex. These assessments for electricity, heat and transport fuels sectors have to be based on thorough analysis of the vulnerability of the system infrastructure to acts of terror and increasingly also to cyber-attacks. Increasing threats to energy systems in this respect can also be associated with climate change or natural disasters. For

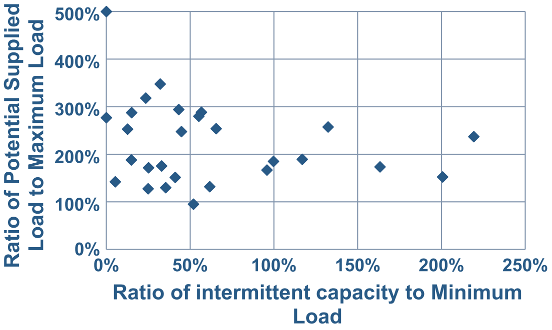

Fig. 1. Share of intermittent capacities to minimum load versus level of reliable capacities compared to maximum load in the EU 28 states in 2012.

example Fukushima nuclear accident was mainly driven from the underestimation of impact of natural disasters that may occur in the relevant region, and had an enormous impact to the energy security situation of Japan.

It is also obvious that the results of such analyses are quite sensitive and would not be usually made public. However, it would be worthwhile if governments would coordinate their methodologies in this respect and use same kind of principles in their national assessments.

3.2. *Indicators for Technical Resilience*

The most widely used indicator for Technical Energy Security in power sector is Power Capacity Reserve Margin that aims to describe the ability of the power system to cover peak load. This margin is often also referred as the main indicator of Power Generation Adequacy. Transmission System Operators often use in their analyses Power Capacity Reserve Margin as the main indicator to assess the security of power supplies:

$$P_{CRM}=\left(\frac{P_{INST}+P_{IMP}-P_{RESTR}-P_{REC}-P_{OUT}-P_{SR}-P_{EXP}}{P_{PEAK}}\right)*100\% \qquad (3)$$

where:

P_{CRM} – Power Capacity Reserve Margin;
P_{INST} – Installed Net Capacity of the system;
P_{IMP} – Capacity that can be imported (based on TSO assessment);
P_{RESTR} – Capacity with Restricted Availability, i.e.:

1) Capacity of Intermittent Power Producers, mainly wind, solar and CHP-s that depend on heat load;
2) Capacities that cannot be used due to environmental restrictions;
3) Preserved capacities (with start-up time more than 168 h);
4) Other net capacities that are permanently not available;

P_{REC} – Capacities under reconstruction or planned maintenance;
P_{OUT} – Capacities in unplanned outage or maintenance;
P_{SR} – System Reserve of TSO (for example Outage Reserve);
P_{EXP} –Capacity booked with binding export agreements;
P_{PEAK} – Forecasted Peak Gross Consumption (Net Consumption and Losses).

This indicator can also be analysed from the N-1 (without largest production capacity) and from the N-1–1 (without largest production capacity and without largest interconnection capacity) perspective, which provides an assessment of the vulnerability of the system to unplanned outages.

P_{CRM} is a good indicator for assessing Technical Resilience of the power sector in a given country or region. Although, it does not take into account potential impact of the network configuration (for example internal bottlenecks) and ignores the potential of intermittent capacities like wind and solar to supply energy also during peaks. One can also observe that different regions in the world apply very different principles for calculating P_{CRM}: often P_{IMP} is not counted, or P_{RESTR} is calculated with very different principles, etc. Therefore often these results are not comparable between countries. In addition, it is often difficult to forecast the availability of capacity via interconnectors during peaks, as it much depends on the market situation in the neighbouring state during these hours.

Similarly can be assessed the Technical Resilience of heat sector for district heating areas, but it is much more complicated to make an overall assessment for heat sector capacities of a whole country: in some district heating areas capacity can be more than enough to cover peak loads, in another it may be scarce. An alternative way for heating sector can be to assess the potential to supply heat from fuel stocks available at production facilities during maximum consumption times: this would provide an assessment how vulnerable are the production facilities to potential disturbances in fuel supplies.

Another aspect of long-term Technical Resilience is the economic viability and the age of power and heat production facilities and networks. If the returns on investments of production facilities or network companies are not high enough to justify investments in these infrastructures, then the long-term security of supplies, especially peak capacity supplies is threatened. In order to assess the economic health of the infrastructures, the average age and returns on investments of infrastructure would incentivise how well are settled the investment requirements for system renewal in a country and would be additional indicators that the policy makers should follow for long term energy security policy.

Often countries look also for the share of potential to supply power and heat from indigenous resources, as it would incentivise the level of the worst case in electricity and heat supplies, when there are no external energy supplies to the country. It may be worthwhile to be analysed, although these indicators largely depend on the reliability of the suppliers of imported fuels and would not deliver comparable results with other countries that may have higher or lower political risks associated with supplies.

3.3. *Indicators for Technical Vulnerability*

If Technical Resilience indicators incentivised how a country is delivering needed electricity and heat capacities for its citizens, then Technical Vulnerability indicators incentivise how the required energy volumes would be guaranteed in long term. Here one should look at the diversity of supplies and how capable are the infrastructures to deliver required energy.

Often here governments look at the diversity of their energy supplies. However, this provides only a result of the market operations and does not provide information of the system capabilities. For example some countries may be reliant mainly on one energy source in everyday operations, but may have also reserve capacities available for the case of supply disruptions. So the diversity of the system is hidden from official statistics. Another example may be the case, when electricity or heat facilities have dual fuel capabilities that allow them to switch from one fuel to another, subject to price or availability. This flexibility provides very valuable diversity for supplies, but cannot be found in official statistics.

Another drawback of this indicator is sometimes high volatility of the outcome: the result of production mix may be largely influenced by the availability of hydro, solar and wind resources and from supplies via interconnections subject to market prices. In principle the potential to supply energy should be based on infrastructure, not on market operations.

An alternative way to assess this potential is to analyse the diversity of potential electricity and heat supplies with Herfindahl Index, subject to average availability of the facilities:

$$HHI_E = {W^{\%}_{Nuclear}}^2 + {W^{\%}_{Coal}}^2 + {W^{\%}_{Gas}}^2 + {W^{\%}_{Oil}}^2 + {W^{\%}_{Mix}}^2 + {W^{\%}_{Biomass}}^2 + {W^{\%}_{Wind}}^2 + {W^{\%}_{Solar}}^2 + {W^{\%}_{hydro}}^2 + {W^{\%}_{Import}}^2, \tag{4}$$

where

$W^{\%} = \frac{P*A*t}{W_{\Sigma}}$ – share of potential production from given energy source;
P – Total Net Capacity of given energy source (MW);
A – Average annual availability of maximum capacity of given facilities (usually 80–90% for nuclear, coal, gas, oil, biomass and mix energies; 15–30% for wind; 15–25% for solar, 20–80% for hydro);
t – annual 8760 h
W_{Σ}-Total potential annual production from all energy production facilities (GWh)

Another indicator to analyse with the same logic would be the ratio of potential energy supplies to the annual consumption that would provide information about the total capabilities of the supply infrastructures:

$$K_{POT} = \frac{W_{Nuclear} + W_{Coal} + W_{Gas} + W_{Oil} + W_{Mix} + W_{Biomass} + W_{Wind} + W_{Solar} + W_{hydro} + W_{Import}}{W_T}, \tag{5}$$

where

$W_{(x)} = P*A*t$- Potential supply from given energy source (GWh);
$W_T = \frac{W_A}{E}$ - Total required energy supply (GWh);
W_A - Annual consumption (GWh);
E – Electrification Rate of the country (%)

Higher values of ratio K_{POT}, indicate also better level of Technical Vulnerability. Formulas 4 and 5 can also be applied to Heat and Transport Fuels sectors with relevant energy sources. In case of transport fuels it would be worthwhile to analyse separately potential supplies from indigenous crude oil production and oil products facilities, and to add there also separately oil stocks.

4. Indicators for Economic Energy Dependence

National security can often be affected by the energy cost or revenue streams of a country. If a country relies too much on the imports of transport fuels, then too high cost of imports influences substantially also economic state of a country. High share of the cost of imported energy in GDP oftentimes reflects also the influence of economic interests to the national energy policy decision making. It can be observed that countries with high dependence on imported energy sources (for example several countries in Eastern and Southern Europe) tend to make more political decisions that take into account the interests of their supplier countries. It also means that they are more open to external influence to their energy policy.

Oppositely one can also observe that countries with very high dependence on energy revenues in their GDP (for example some oil and gas production countries) are largely influenced by the market prices. If a country relies too much on oil export revenues, it would pose a threat to the stability of its economy (GDP might be too much influenced by the changes in global crude oil prices). The higher is the share of revenues of exported energy in the GDP, the more the security policy and political decisions may be reliant on the energy price levels in global or regional markets.

Ideally countries should look for a balance between import and export of energy supplies in monetary terms in order to avoid any external influence to their economic and energy policy. The larger the Economic Dependence of a country on energy import costs or export revenues, the more they may be affected by the economic interests and market fluctuations.

Looking by energy sectors, then Economic Dependence of a national power sector could be assessed by the difference between merchandise value of imports for power supplies (including power imports and imports of fuels for power production) and of exports of power, to be compared with the GDP of a country:

$$EED_{power} = \frac{M_{Import} - M_{Export}}{GDP}, \tag{6}$$

where

EED_{power} – Economic Energy Dependence of power sector (%);
M_{Import} – Merchandise value of imports of power sector (Monetary Unit);
M_{Export} – Merchandise value of exports of power sector (Monetary Unit);
GDP – Gross Domestic Product of a country (Monetary Unit)

This indicator would provide the incentive about the monetary value of the dependence of a country on these revenue streams. In addition one could also look at the diversity of potential revenue streams (to identify the potential of different suppliers to supply the market). Similarly can Economic Dependence be measured for transport fuels.

In the case of heat sector one cannot talk about exports, as usually the sector has a local nature. For the purposes of Economic Dependence level it would be reasonable to measure the merchandise value of imported fuels for heat supplies as a share of GDP, which incentivise the reliance of a country on these costs.

However, these indicators largely depend on the market prices so it may happen that there are quite wide annual variations in results. Even more, for the purposes of policy making, it is difficult to make reliable price forecasts for these indicators. Nevertheless, if the target is to strive towards balance between total merchandise value of energy exports and imports, it would be a self-balancing exercise for policy makers: higher energy import costs oftentimes balance off higher expected export revenues streams.

5. Indicators for Political Affectability of energy sector

As recent decades have proved, energy sector can be used as a tool to influence economic and political decisions of a country. Reliance of a modern society on energy supplies make states more and more vulnerable to energy supply disturbances, and this fact is often abused in acts of war or oftentimes in cases to influence political decisions.

In order to assess the affectability of a country to such interventions, we have to understand the reasons why countries might be in the political turmoil in energy sector: usually it is whether for the reasons of political power (like former Soviet Union states are still under special attention from Russia) or because of their valuable energy resources (like Kuwait in 1990ies, or Central Asian countries through the years).

For majority of the countries this layer has low relevance, as there is low interest of other countries to intervene in their society, economy or political frameworks. In Western European countries such interventions are merely felt, as their political establishment is fairly transparent, markets diversely integrated, and not dependent on only one external supplier country. However, in case of Eastern European countries one can oftentimes note a reliance of energy supplies from Russia and difficulties of processes that try to lessen such dependence. Examples of such cases could be most clearly observed in electricity and gas markets of Ukraine, Bulgaria or Lithuania, where development of alternative supply sources have faced strong and unjustified political opposition.

Nevertheless, this layer is the most difficult one to assess in numerical terms, apart from the openness of a country to external influence which is related to both the Economic Dependence and Technical Vulnerability. In first instance the policymakers should make a subjective assessment of energy sectors in this respect. As regards the Political Affectability one should firstly assess the external political interests to influence country's politics and energy policy or the interest on energy resources from other countries (or vice versa). If some interest can be observed, then we should have a closer look to the potential ways on energy policy manipulations.

In practice one can observe two types of manipulations: manipulation of energy policy decision makers (a number of cases in countries of former Soviet bloc) and manipulation of energy system operations (like with Ukrainian gas supplies by Russia). From these examples it could be observed that there are mainly two aspects that allow such kind of interventions:

a. the precondition for manipulation of political decisions is the openness of decision makers to corruption;
b. The precondition for manipulation of the development of energy system (apart from technical dependence) is the instability of the political settings that make it easier to manipulate the decisions to be made for energy sector development.

From this perspective it can be concluded that corruption and political stability indexes can provide information about potential risks associated with political influence in a country in question. Transparency International measures annually the perceptions towards corruption and the stability of political system that should also be used by countries to assess their energy policy [20]. In the context of corruption it is also worthwhile to assess the level of openness of manipulation of the public opinion, as this may sometimes trigger unwanted developments of energy policy developments in more democratic countries.

Electricity, heat and transport fuels sectors should be assessed separately in these terms in order to better identify the risks associated with abovementioned aspects. In terms of Political Affectability of the Heat Sector one should use the same indicators as for Power Sector (political stability, corruption), but to be assessed separately for the heating fuels supply situation. For policy making purposes countries cannot usually predict these indicators, but can tackle the identified issues with other measures.

6. Energy Security Matrix

To summarise all the above, an Energy Security Matrix could be sketched as follows in Table 2:

This set of indicators could be considered by the energy policymakers in case of each national energy strategy. However, this list is not exhaustive, and should be considered case by case: there are some countries, where some of these indicators have higher relevance than in others.

From the logical sequence of the Matrix one can observe that Operational and Technical Resilience indicators refer to short- to medium term energy security (from seconds up to one year planning), while Technical Vulnerability, Economic Dependence and Political Affectability indicators are addressing more longer term issues of energy security. However, the longevity of long-term energy issues can lead to unwanted developments that can also in short term influence operations of energy system. In practice, operational and technical resilience indicators address potential threats from existing system, while long-term indicators incentivise the needs for energy security investments and/or required regulatory changes in order to encourage improvements in future energy-mix.

Operational Resilience indicators for internal disturbances are relevant only for electricity sector: heat and transport fuel sectors are not so time-critical, their consumption/production balance is more flexible and does not have so much intermittent producers that would pose threat to stable supplies. Listed electricity sector indicators describe the most difficult situations for power system operations and characterise the flexibility of the power system to cope with these situations.

Operational Resilience to external disturbances is relevant for all energy sectors, as it may have a medium term impact to the whole energy system and a country as a whole. Therefore the analysis of the country's energy systems to avoid external disturbances should be part of energy security assessment in all sectors.

Technical resilience indicators incentivise the readiness of the system to cope with extreme demand. This is relevant for electricity and heat sectors, where the energy cannot be stored but has to be produced as much as it is required at the moment. This makes the readiness of the energy system for peak consumption extremely important. However, it has to be noted that with technical advancements in electricity and heat storage systems this set of indicators might need to be revised in coming years.

The key to Technical Vulnerability of energy system lies largely on potential and diversity of different energy supplies and suppliers, both in terms of supply sources and routes. This analysis has to be taken very carefully considering the potential of manipulation of the markets that may influence the economic outcome of energy system operations. Therefore here the analysis has to be country specific in order to find the potential risks of supplies in a more detailed manner.

Economic Dependence of energy sector may have a strong impact to the countries overall economic performance and influence its welfare and stability. However, it could be noted that the lower is the share of costs and revenues of energy sector in the GDP, the lower is the influence that energy can have to the welfare of the country. It can also be noted that high energy costs can be offset with energy exports (that are usually also higher in same cycles) or with energy efficiency measures). So the overall aim of the country should be to have a neutral balance between the energy export revenues and import costs, in order to minimise the impact of the energy sector to political stability.

Lastly, Political Affectability is subject to geopolitical interests, and for majority of the countries does not pose any issue. However, the countries that are under political interest sphere of aggressive countries, this layer of energy security becomes critical in the evaluation. There are number of non-measurable indications that may be found there, but common denominators for those aspects are political stability and corruption. These are the main ways how countries energy policy decisions can be influenced.

Nevertheless, if all these indicators could be gathered by the countries to a common database, it would provide a strong basis for energy security policy assessments and developments.

7. Conclusions and Policy Implications

The assessment of the energy security level of a country is a complex issue. Based on the analysis of the indicators used by

Table 2
Energy Security Matrix.

	Indicators for		
	Electricity Sector	Heat Sector	Transport Sector
Operational Resilience to internal disturbances (flexibility)	– Share of unreliable capacity compared to minimum load (with and without interconnections) (See Formula 1) – Share of reliable capacity (with and without interconnections) compared to Peak Load (See Formula 2)		
Operational Resilience to external disturbances (flexibility)	– Resilience to Acts of Terror – Resilience to Cyber Attacks – Resilience to natural disasters – Resilience to climate change		
Technical Resilience (capacity)	– Reserve Margin (also in N-1 and N-1–1 cases) (See Formula 3) – Weighted Average age of Reliable Power Capacities and networks – Average Return on Reliable Power Production and network Investments	– Stocks of Fuels for Heating compared to Monthly Peak Consumption – Weighted average age of district heating capacities and networks – Average return on district heat production and network investments	
Technical Vulnerability (energy)	– Diversity of Potential Electricity Supplies (Herfindahl Index) (see Formula 4) – Potential Supply compared in annual consumption (subject to Electrification Rate) (see Formula 5)	– Diversity of Potential Heat Supplies (Herfindahl Index) (see Formula 4) – Share of Potential Heat Supply compared to Annual Consumption (see Formula 5)	– Diversity of Energy for Transport Supplies (Herfindahl Index) (See Formula 4) – Potential of Supply (incl. Capacity of Oil Production, Capacity of Oil Products supply facilities, Oil Stocks, etc.) in case of supply disruptions compared to Annual Consumption (see Formula 5)
Economic Dependence	– Merchandise value of power exports or imports compared to GDP	– Merchandise value of fuels imported for heat supplies compared to GDP	– Merchandise value of fuels imported for Energy for Transport compared to GDP – Merchandise Value of exported Energy for Transport compared to GDP
Political Affectability	– Level of Political Stability in given country – Level of Political Stability in supplying countries – Interest level from other countries to influence the sectors' policy – Openness of the country to the external influence – Level of Corruption		

international organisations in their assessments on energy security, we have identified several inadequacies that may lead to wrong political or policy decisions. For the purposes of more adequate development of energy policy it is crucial to use more adequate indicators, which incentivise to decision makers more secure and efficient way of development. From this perspective we have crafted Energy Security Matrix that lists relevant indicators to be explored from short-term perspective (Operational and Technical Resilience) and long-term perspective in three layers (Technical Vulnerability, Economic Dependence and Political Affectability), and is applied to all main energy sectors of a country. However, it applies that long term energy security issues can often lead to short term operational issues, and upside down. Therefore both timeframes are relevant to be analysed and addressed by energy policymakers.

Current misleading indicators, often used by international organisations and policymakers, may lead to inadequate assessments on energy policy, to inadequate investment decisions or to short-sighted energy market designs and regulations. Furthermore, energy statistics gathered today are not representative to describe modern threats to energy systems and are sometimes misused by energy policymakers in their activities. All these inadequacies may lead to energy supply disruptions in shorter or longer term. Indicators listed in Energy Security Matrix would help to avoid such inadequacies.

However, it is well understood that currently there is no sufficient data available in order to fill the full Matrix, but countries should strive to gather this data in order to improve the quality of their energy security policy. Partial analysis can result often in biased or misleading results. Therefore numerical assessment of energy security level of the countries in each of the listed layers and sector should be a topic for further studies subject to availability of relevant data. Even more, as energy security is only part of energy policy trilemma, further studies on the balance between contradicting energy policy objectives would provide even higher value for the policy makers and to the quality of relevant policy decisions and measures. Further studies may also address the ways of weighting of different indicators and sectors, as current approaches of international organisations differ largely in these aspects.

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The Impact of Building Renovation with Heat Pumps to Competitiveness of District Heating

Estonian district heating pricing system needs more flexibility

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Abstract – **The European Union (EU) and the whole world are striving towards less polluting and more efficient energy use and production. For that the EU has set targets for 2020, and has envisioned plans for 2030 and even 2050. In 2015, world leaders have agreed to reduce emission of greenhouse gases in the Paris summit.**

EU sees as one of the measures to fulfil these targets the development of district heating (DH). DH is an economical and environmentally friendly and a very convenient way to supply heat to end consumers. DH is especially popular in Nordic countries where there is high demand for heating due to colder climate, but it has a huge potential also elsewhere in Europe.

Estonia is committed to comply with those targets. The actions of market participants in the energy field have been motivated greatly by subsidies and grants. There are different measures targeting on one hand building energy performance and on the other hand energy delivery and production efficiency and implementation of renewables. This paper analyses how those measures work together and shows shortcomings of the policies and measures developed separately for each target. It becomes clear that to develop successful policy it is necessary to look at the whole system, including the pricing principles, not just its parts alone.

Keywords — district heating; price of heat; apartment buildings; heat recovery; heat pumps; energy efficiency; energy policy; support measures

I. INTRODUCTION

Energy savings and efficiency is one of the priorities of the EU [1]. DH is expected to play a growing role in achieving those targets as it is a technological solution that offers many economic, environmental, and technical benefits, and is extremely convenient for the end consumer. DH has the best potential in high density urban areas, where it can save space in buildings for more valuable use, eliminate air pollution from numerous local boilers and give opportunity for the use of waste heat, municipal waste incineration, renewables, and cogeneration. It is a comfortable and in many cases also the cheapest way to heat or cool buildings.

Most of the DH systems in Estonia have been established along with construction of apartment buildings. There are more than 300 DH systems in Estonia. Major share of the building stock is built during 1960-1990 [2], i.e. it is 30-60 years old. During Soviet time, the development of DH systems and new apartments was focused on quantity rather than on quality, so the energy efficiency was not a concern. Heat was not measured, it was just quantified by living area. Meters for heat started to emerge only in early 90's, causing chaos, because measured consumption was much lower than norms for heat consumption were suggesting. So the price per unit started to grow. Still, even the measured values of heat consumption were high compared to the similar buildings in Finland.

Since then the major developments that have happened in the energy field in Estonia have been triggered by growing energy prices, privatisation of municipal utilities, and political measures to promote renewables. Resulting developments in the building stock and DH sector are described in Sections II and III. Section IV describes DH price regulation system and Section V looks at the competitiveness of DH prices compared to the ones of alternative heating solutions. Section VI describes Estonian energy efficiency policy and the measures for achieving the political targets.

The topic of indoor climate and energy savings in buildings has good coverage in the scientific literature, but the impact of exhaust air heat pumps (EAHP) to building's energy balance is usually based on simulation models [3] or just a follow-up of single specific building [4] rather than analyses of actual data from bigger number of buildings with EAHPs installed. Actual impacts of EAHPs for DH return temperature in Finland is analysed in [5]. Different areas have had some prior coverage, but the actual data based on large number of buildings is not widely analysed yet. Neither has the impact of changes in buildings energy balance to energy systems been analysed. The potential for research in this topic is vast, specially bearing in mind system view and the competitiveness of DH.

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One of the first analyses of larger group of buildings with EAHP-s based on their actual energy consumption data is presented in [6]. This has been carried out according to energy performance model developed by author 1 and under his supervision. The results are described in Section VII.

This paper aims to explore the possible impact of Estonian building sector development to DH sector under the current policy for energy efficiency of dwellings and DH price regulation. Thus DH pricing has been modelled in Section VIII and the challenges have been listed in Section IX. The arguments for the need for change in energy efficiency policy and DH pricing regulation and conclusions are presented in Section X.

II. CURRENT STATE OF THE BUILDING STOCK

Typical non-renovated apartment building from the Soviet era with some renovation (most apartment windows replaced, pipes in the cellar insulated, etc.) during last decades has an heat consumption in the range of 150...200 kWh/m^2/a per year [7]. Some have even higher consumption. Adding electricity for lighting and household use as well as natural gas for cooking, the energy consumption totals at 180...250 kWh/m^2/a or even above. At the same time, average heat consumption of apartment buildings in Finland is about 125 kWh/m^2/a [8, 9], thus being 25…40% lower. Considering that Finnish climate is colder than in Estonia, especially in the North of Finland, it should be clear that Estonian buildings have great potential for energy savings. Huge saving potential is true for the whole EU, where about 2/3 of buildings were built during times when energy efficiency was not the biggest of concerns [1].

In Estonia, energy consumption in dwellings makes up a significant share (about 33%) of final energy consumption [10], therefore renovating those reduces national energy use significantly. So, the trend for heat demand is in downward direction, which is a challenge to DH operators.

III. CURRENT STATE OF DH SECTOR

Just less than two decades ago most of DH production was relying on imported fossil fuels and relative network losses were hardly below 25%. After privatisation of municipally owned DH systems during 1995-2004, new operators invested significantly in the efficiency of DH networks. Customer substations were renovated and meters installed. DH average relative loss in all bigger systems is now far below 20%. Moreover, during the last 10 years local biofuel combined heat and power plants (CHP) have been installed in all the biggest cites. Also first district cooling system in Estonia was started in 2016. However, the systems still need to be developed specially in small towns.

Now the government is supporting the development to improve efficiency and introduce renewables.

IV. DH PRICE REGULATION

Estonian regulator – Estonian Competition Authority (ECA) – is responsible for price regulation for natural monopolies (electricity, DH, gas, and water networks). The regulation follows ex-ante principle, so the utilities have to apply and justify their tariff applications. They have approved more than 130 DH prices [11]. ECA uses traditional cost-plus pricing method to regulate the utilities [12]. This method is simple to use, flexible for many situations and easy to administer, but the downside is that it does not incentivise efficiency investments by utilities and there is a risk to inflate costs [13]. Moreover, Estonia is among small number of countries where DH tariffs can only be single one-component price for all the customers in one DH system, regardless of their consumption volume or load profile or other criteria. This is clearly the simplest tariff system, but as is described in Section V, in comparison with alternative heat sources it does not give right feedback about actual costs for customers of different nature.

Moreover, contrary to the decreasing volume, growing risk, and increasing responsibility of DH, the regulated return is dropping. This has been dropping continuously since 2004, when it was at its peak (11,7%), to 5,55% in 2016. The profitability of DH operators continues to drop during the coming years, unless the regulation principles are changed.

V. DH IS CHALLENGED BY NEW HEATING SOLUTIONS

In 2013, the average DH price in Estonia was 55,51 €/MWh, about half of the price in Denmark (100,08 €/MWh), a bit more than in Finland (53,28 €/MWh), and almost 5 times more expensive than in Iceland (11,30 €/MWh). DH prices in the Baltic region did not vary too much [14], [15]. In this comparison we could see that Estonian DH is not the most competitive, but the prices are not too different from those of neighbours. Still, these are only the average tariffs, and in each individual network the price may vary a lot. That is because the cost of DH depends on many factors: asset base, fuels used, production and distribution efficiency, load profiles, consumption density, labour costs, and many more. Some of those are by its nature variable (i.e. dependant on consumption volume) like fuel, and others are fixed (i.e. do not depend on consumption) like capital, labour and other costs.

Salesmen of alternative solutions have used one-component DH tariff to their benefit. They compare this full price of DH to the fuel cost of the alternatives. As customers are not aware that full energy supply cost is not just monthly energy carrier bill, they often disregard separate bills for investment or loan payment, as well as maintenance and repairs. Thus, full cost of DH is competing with the variable cost of alternative solutions, which usually are cheap base load solutions neither able to cover peak loads nor having reserves. In this regard competitors to DH are HP-s, but sometimes even wood pellets or local gas boilers have been installed. It is easy to tell that one's electricity cost for HP with seasonal coefficient of performance (SCOP) of nominal working conditions (air 7C/water 35C) is lower that DH price.

As the DH pricing model is inflexible in comparison to free pricing of alternatives, it sends misleading signals to customers who are not financial or energy specialists. There is no price for reserve kept by DH nor difference between periods of high and low demand nor any other differentiation by consumption volume or load. That is potentially further reducing the competitiveness of DH.

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VI. POLICIES AND MEASURES

General energy policy is described in Estonian Energy Sector Development Plan for 2030 (ENMAK-2030) [16], which foresees significant energy savings and growth in supply efficiency as well as introduction of more renewables.

However, this policy change was already enforced in 2009 when Electricity Act was amended to reward renewable production and cogeneration. This boosted investment into wind power and local and biofuel CHP-s. During last decade also DH network and heat production reconstruction have been supported. Right now DH, electricity market, and gas market legislation are undergoing another round of amendment processes. The target is to liberate price regulation and motivate efficiency and renewable energy investments, but it is a hard political debate because energy is also considered to be a major social issue.

Also energy performance targets for buildings are in place from the same time, with last change in 2013. According to those, new apartment buildings must have calculated energy performance indicator (EPI) not higher than 150, older buildings shall not exceed 180 after renovation [17]. As EPI, weighed energy use (WEU) is calculated similarly, the only difference being that this term reflects that it is based on actual consumption data. As described in Section II old apartment buildings with total energy use of 180...250 kWh/m^2/a are having WEU level of 210...300. These figures include all energy purchase in buildings, excluding energy that is generated on-site, corrected with weighted values for each fuel and energy. Weights for electricity, fossil fuels and DH are 2,0; 1,0 and 0,9 respectively.

In EU investment support scheme for periods of 2010-2014 and 2014-2020 there are two major areas related to energy – building renovation and DH rehabilitation.

According to building reconstruction conditions, the maximum amount of support (40%) is awarded for buildings estimated to reach EPI level of 150 [12]. The support conditions require, among other measures, to install heat recovery ventilation or EAHP. The latter is cheaper, because there is no need to install inlet ventilation ducts for all apartments. Sometimes, in order to comply with the target, solar panels or solar collectors are added to reduce energy purchase.

During 2010-2014 more than 600 apartment buildings received this support. In the period of 2014-2020 the planned support funding for improving energy efficiency is 102 million euros. About 1000 buildings were expected to be renovated. In March 2017, there are already applications for 50 million euros for 233 buildings, 85% of those targeting at highest support rate, most of those planned to install EAHP.

At the same time the state is supporting DH sector to install renewable production and renovate networks to reduce environmental impact and improve efficiency. The amount for those measures is 72 million euros.

VII. FOLLOW-UP OF BUILDINGS RENOVATED WITH GRANT

Related study of following up building energy use before and after the renovation [6] is already printed. It is summarised in this Section.

Exhaust air of the building is the only source allowed for HP according to DH law. However, sometimes outside air to water HP-s (AWHP) have been qualify for support because of lacking inspection. According to the theoretical modelling in study [3] EAHP is expected to cover nearly 100% of domestic hot water demand and about 63% of the heating demand of a typical apartment building in Estonia. Altogether that is about 73% of the total heat demand, which means DH is needed only to provide 27% of heat demand. Papers [3] and [5] conclude that in addition to volume drop of purchased heat the EAHP causes DH return temperature to rise. That in turn means higher loss in DH return pipe and lower efficiency of heat production, especially when flue gas condenser is used.

Having those theoretical impacts in mind, an analysis of 12 buildings that have installed heat pumps using grants during 2010-2016 was carried out under author 1 supervision and participation. Figure 1 illustrates heat performance of a very well renovated 5-floor 60-apartment building. After major renovation during summer of 2014 normalized heat need dropped from about 125 to 93 kWh/m^2/a i.e. by 25%. Installed EAHP produces 50...54 kWh/m^2/a using purchased electricity (about 20 kWh/m^2/a) and recovered heat from ventilation (30…35 kWh/m^2/a). Its share is about 60% of total heat need. Only about 40...42 kWh/m^2/a (about 40%) is purchased from DH. SCOP of this EAHP was varying in range of 2.6...2.9, so electricity use of HP was about 20 kWh/m^2/a.

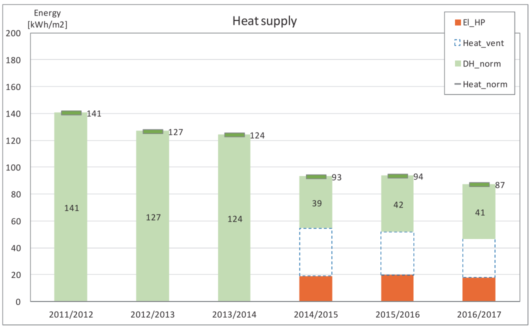

Fig. 1. Changes in heat supply of a well renovated building

Adding the electricity consumption in apartments and the common use of 30 kWh/m^2/a (weight 2.0), the WEU will total at 130. This was one of the 2 buildings out of 12 analysed that actually fulfilled the target of 150.

In other researched buildings additional insulation accounted for 20...30% of consumption decrease. After renovation heat pumps covered about 55...65% of heat need, leaving only 35...45% for DH. The WEU values ranged between 165…185, what is significantly higher (10…23%) than target. The exceptions were buildings with ordinary AWHP which did not have the limitations of exhaust ventilation air volume. That allowed higher heat output, but on

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the other hand the system became more sensitive to drops in air temperature. With lower air temperature, the AWHP output and COP will drop dramatically. As a result, during mild winters AWHP covers the need for heat and DH is hardly used, but if cold winter will hit, the share of DH will rise significantly. AWHP-s were able to supply 80...90% of heat during recent rather mild winters, leaving DH contribution to only 10...20%.

For all EAHP systems SCOP ranged between 2,5...3,0. This is much lower than assumed value used for decision making (3,0…3,6). It is important to note that the return temperature rise has been obvious in all the buildings where this data was available.

So, unfortunately, in most cases the actual savings from the renovation were 10…20% lower than calculated beforehand. This is due to over estimating the impact of energy savings, problems in planning and carrying out the actual renovations, unprofessional operation of installed systems, inadequate consumer behaviour, and other reasons.

Environmental impact of utilisation of HP-s in DH systems is analysed in paper [19]. That concludes that CO2 emissions from energy production are the highest if AWHP used in buildings, followed by systems with EAHP.

Based on that, the economics and environmental benefits of EAHP can be questioned. Provided that DH is produced from renewable fuels and is available at a competitive price. The feasibility of EAHP installation for customers shall be analysed in separate studies.

VIII. IMPACT OF HEAT PUMPS TO DH PRICE

For quantifying the impact of extensive installation of EAHP-s in buildings for DH price and viability of DH investments simple pricing model was developed to calculate DH prices at different assumptions.

A. *Calculation model assumptions*

Pricing model was built in accordance with the price approval methodology of ECA [20]. The model can be used for every DH area, but since smaller DH networks are more vulnerable to changes those were modelled.

Even if only few buildings install EAHP, or even worse, illegal AWHP-s, then consumption drop of 20...30% could be a real thing. So, a typical, not the smallest town, is taken as an example. The population of this town is about 2000-3000 inhabitants, it has a DH system with consumption of 10 000 MWh per year. DH is supplied via a natural gas plant and DH network have been there for some time, but have been kept in good condition. There are usually about 30...50 apartment buildings and some public buildings (kindergarten, school, etc.). As network is assumed to be in well maintained condition, the heat loss is assumed to be 1800 MWh, resulting in relative loss of 15.3%.

To improve the existing situation of the DH, the investment into a new baseload biofuel heating plant with capacity of 2,0 MW is also modelled. According to standard heat load curve it will produce about 85% of heat needed at 85% fuel efficiency. Biofuel plant investment varies a lot, depending on site, configuration of fuel storage, and other local conditions. Here the value is assumed to be 450 €/kW. Estonian government is supporting investments for installation of DH biofuel boilers in the amount of up to 50%, so ideal case with this maximum level of support is assumed in the model.

Network and production assets are assumed to be halfway through their economic lifetime, delivered gas and biofuel prices are assumed to be 33 €/MWh and 14 €/MWh, and production efficiency on gas is 93%. All prices are calculated without VAT. 20% of VAT is added to end customers, but companies can redeem the tax. In order not to make the model too technical three important simplifications were assumed for all cases: boilers efficiency will not change, biofuel share will remain at 85%, and return temperature rise is disregarded. Other basic assumptions are also typical for such DH system.

B. *Results from the DH model*

Using these assumptions, an existing DH network with heat production on natural gas (cases “Gas”) was modelled for 3 consumption scenarios. First one is the situation before any changes. Second one is assuming that DH is losing 25% of the volume to HP-s. Total need for DH is assumed to remain at 7500 MWh. This scenario is refered as “-25%”. With the DH network remaining the same, the loss being 1800 MWh, the relative loss of will now translate to 19,4%. And that is in case when the return temperature rise is disregarded. It is clear that the increase in relative loss will cause increase of fuel cost in DH price. Also, there is no way to avoid capital cost of already installed system and the operation and maintenance (O&M) has to be kept at the previous level. That means fixed cost per sold unit will rise. The third one being more theoretical case where almost every building is fully renovated causing consumption to drop by 50% (“-50%“ added to case name). To examine if the installation of new biomass plant would improve the situation, these same scenarios were calculated with new base load biofuel plant in place (cases “Bio”).

Results are presented in Figure 2, where columns “Gas”, “Gas-25%“, “Gas-50%“, “Bio”, “Bio-25%“, and “Bio-50%" represent DH price before and after the rehabilitation of buildings and installing HP-s. The results show that investment into biofuel base load plant at initial consumption level will result in significant price decrease (more than 9 €/MWh, about 16%) for customers, but the split between variable and fixed costs will change dramatically. Gas-fired DH variable cost account for 74% and fixed cost only 26% of the total. Adding the biofuel plant will decrease variable cost share to 52% while fixed cost rises to 48% of total price. Drop of DH consumption will cause significant rise of the tariff, not just caused by dividing constant fixed costs by lower volume, but also by unchanged amount of fuel burned for compensating the same DH network loss, which is also now divided by lower consumption volume. So, when volume changes, both fixed and fuel cost per unit of consumption will change. The difference between fuels is that biofuel system with higher asset base will have quicker growth ratio and the gap between two fuels is closing gradually. Still, at volume drop to half from initial one the biofuel system remains cheaper by almost 5%. Consumption decrease even further would cause equilibrium.

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Before installation of HP-s, the DH system was properly maintained and functioning normally to provide all the need, with price of DH depending on fluctuating price of natural gas. The switch to biofuel would make DH more competitive. However, if the alternative local heat sources will be installed, the DH system will soon be uncompetitive for full heat supply and remain more and more responsible for peak load at even growing tariffs.

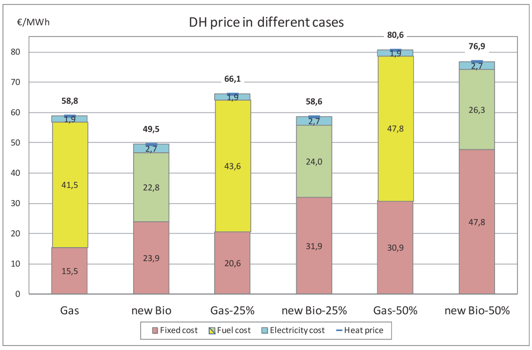

Fig. 2. DH price components for different scenarios

IX. NEED FOR CHANGE

As the building owners are supported to install local EAHP-s, it creates major distortion in single one-component DH pricing that is not dependent on the consumption volume and load profile of customers. This is creating odd situation for customers using only DH. They will have to take responsibility for the costs of keeping up the system for not just themselves but partly also for the customers with alternative supply. At the same time, customers who are utilising their HP-s as the first priority, but still requesting full availability of DH at any time, will pay only a fraction of related cost to keep DH up and available, thus delegating part of the responsibility for costs to the customers who remain using only DH. That neither sends the right signal to both customer groups nor reflects the real costs related to the respective customers. Further, the competitiveness of DH will be jeopardised because lower volumes will cause the rise of the tariff. In this case, variable cost of alternative local heating solutions seems to be even more competitive, although these will often be able to supply only the base load.

For DH operators this highly probable new situation with a dramatic decrease in consumption, and still having to take full responsibility for unpredictable consumption, even during peak loads, is very challenging. These developments reduce efficiency of DH system and lower CHP potential, which is often supplied by renewable fuels. Some of the renewable DH will be replaced by electricity generated by fossil fuels. Moreover, the regulated return of natural monopolies depending on decreasing interest rates of German bonds results in decreasing return levels year after year. That, under conditions of growing uncertainty, is not motivating proper investments into DH systems.

So, the tariff system with single one-component price that was once a good solution to drive development, is now causing stagnation and inequity between customers. The pricing system must be developed into dynamic one able to reflect actual costs for each customer segment and motivating DH operator for investment into efficient solutions.

There multiple different pricing models used in different countries. Those are described and analysed in [21], [22], [23]. From those papers and discussions in seminars and workgroups some ideas for alternative pricing are:

- differentiation of single-component fee by consumption volume (or cumulative steps);
- implementing two- or three component pricing with energy, capacity (or flow rate) and service fees;
- applying different energy fees for different seasons (winter, spring-fall, summer);
- real-time pricing according to smart meters;
- bonuses for low return temperature.

From the listed methods two-component pricing has proved its viability in Nordic and in some Eastern European countries, but lately seasonal tariffs have been added to that and sometimes even more sophisticated tariff systems are tested.

From environmental perspective, the use of heat pumps in DH system operating on renewable fuels can have adverse effect, because renewable heat from DH is partly substituted by non-renewable electricity [19]. Negative impact is extended by the fact that lower DH demand results in lower electricity generation from CHP-s using renewable fuels.

This odd development would not take place if the energy policy, energy efficiency policy and environmental policy would be synchronised as well as DH pricing system would reflect real costs for the customer.

X. CONCLUSIONS

The flat one-component DH pricing system together with targets for energy efficiency of buildings and support policy create an odd situation, when energy installations in buildings are causing inefficiency of DH system and a potential rise of environmental impact of energy consumption.

As Estonian government is targeting the reduction of environmental impact of energy system and energy efficiency, it is supporting both buildings to lower energy consumption as well as DH to increase efficiency and use renewable fuels. For DH this has been quite a success, as in all major towns the production has already been converted to local or renewable fuels. Smaller networks are undergoing the change.

From the other hand, the customers are also motivated by the support system to renovate their buildings. To get maximum support level they must achieve low energy performance indicator which takes into account only the purchased energy. Installation of heat pumps or other heat recovery systems is demanded. That means that in some cases some of the heat normally supplied by renewable DH would be replace by heat generated by HP using non-renewable electricity. To avoid this adverse effect the energy and

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efficiency policies should be synchronised at system or even country level to achieve the lowest environmental impact.

Further, DH pricing system has not been developed to cope with the change. It has remained the same as it was created more than 20 years ago – regulated single one-component price for all customers. As modelled in section VII, the price of DH will increase as the penetration of HP-s in the system grows. These major price increases have the most adverse impact on those customers who rely fully on DH as they will, through increasing prices, take responsibility of the costs related to keeping up the DH system also for the customers with HP-s. So, the latter ones are living partly on behalf of the other customer group. Therefore, it is important to develop new and more flexible pricing methods for DH. This will be a challenge for regulating authorities and DH companies, as it is very important that the process of developing and implementing new price system is clear and well communicated to customers, so that they will see that those new pricing models are also in their benefit and reflect costs adequately.

Analysis of suitable pricing models and their implementation in context of Estonian DH market shall be carried out separately. Optimal solution would be the one reflecting real costs to each customer as well as keeping customers and DH sector motivation to continue developing sustainable energy systems.

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