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Master Thesis

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VULNERABILITY OF ESTONIAN ELECTRICITY SYSTEM: ECONOMIC IMPACT ASSESSMENT OF A PARAMILITARY CONFLICT IN IDA-VIRUMAA

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I have written the Master's thesis independently. All works and major viewpoints of the other authors, data from other sources of literature and elsewhere used for writing this paper have been referenced.

.... (Signature of the author and date)

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Abstract

The intention of the thesis is to look at the functioning of the Estonian electricity system in a situation where a paramilitary conflict has forced the two biggest power stations in Estonia into a production halt. The hypothetical scenario that the thesis anticipates is developed on an assumption borrowed from literature on critical infrastructure: a government has to assure the functioning of important infrastructure object in the occurrence of a worst case scenario. Given the current unstable situation in international relations and considering opinions that the Russian government could test NATO's integrity by inflicting a military confrontation in the Baltic States, the scenario which anticipates a regional military insurgence taking place in the eastern region of Estonia remains plausible.

The goal is to assess the vulnerability of the Estonian electricity system with a purpose-built model which links the measure of vulnerability to economic losses of a country. The author builds on the general model developed by Edward Christie which intended to measure the economic losses in the case of a gas supply disruption. After making some critical amendments to Christie's model, the author establishes a concrete function to calculate the economic losses in the occurrence of an electricity supply cut.

After testing the model in the case of Estonia, the thesis concludes that due to the high level of interconnectivity and sufficient domestic production options, the losses for Estonian economy deriving from the supply cut are extremely marginal. Thus, the vulnerability of Estonian electricity system is low and can supply end-users even in the occurrence of the hypothetical event.

Keywords: electricity supply, military conflict, vulnerability, expected economic loss.

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Introduction

Energy has become one of the most widely discussed policy areas within the academic as well as political circles in recent years. The subject itself is complex as it includes a number of distinct and different issues – starting from environmental and financial topics and ranging to concerns over security. The latter aspect of energy supply has been the most important factor influencing the official discourse as well as public perception for the European Union (EU) and its individual member states (Ratner et al 2013). Following the gas supply disruptions of 2006 and 2009, the energy supply security has been acknowledged as one of the cornerstones of the EU overall energy policies. In the beginning of 2014, the EU commission launched the EU energy security initiative with the main aim of ensuring the stable and abundant supply of energy. The main reason for developing the strategy was EU's heavy dependence on foreign supplies for meeting the demand of end-users. The issue is even more important, since a number of member states are dependent on a single supplier of gas (European Commission 2015).

EU's heavy reliance on Russian-sourced imports in particular complicates the issue of its overall foreign supply dependence. Although there were indications of Russia being an unreliable partner for the EU already in 2006[1], Russia has enhanced this image with its actions during the military crisis in Ukraine which started in 2014. Though not officially recognized by the Russian government, it is widely argued that the conflict in Ukraine was by a large extent evoked by Russian Federation and that latter supports

[1] During the so-called „gas war of 2006"– a price dispute between Russia and Ukraine – Russia cut its gas supply through Ukraine. Since around 80% of Russian natural gas was transmitted to the EU through Ukraine, many EU member states reported supply cuts and pressure drops within the pipeline infrastructure (Henley 2014)

directly as well as indirectly the separatist forces that have *de facto* annexed the south-eastern part of Ukraine. The crisis in Ukraine has changed the power and security situation within the European vicinity: an ongoing military confrontation has introduced a possibility, which heretofore seemed unrealistic: a military conflict taking place within the EU or its immediate neighborhood.

Every major change of *status quo* in the international security paradigm should be adequately reflected in national (energy) security policies. In the current context – if there is even a distant opportunity of a Russian-backed aggression against one or more EU member states, the opportunity should be considered by national as well as EU-level policy makers. There is reason for concern and the possibility of Russia masterminding a hybrid attack against Baltic States has been voiced even by the former NATO director general Anders Fogh Rasmussen (Evans-Pritchard 2015). Unfortunately, the discussion about the possible targets for such military intervention and the associated costs for Baltic States has remained scarce.

The issue has been transposed into EU level energy policy planning: the European Commission has taken the first precautionary measures to ensure that Russia could not use the "energy weapon" against the EU. In May 2014, the Commission required all EU member states to evaluate their ability to cope with gas supply disruptions form Russia in EU-wide stress tests (European Commission 2014). The previous example demonstrates that on the EU-level, supply cuts by Russia are seen as the biggest security threat. However, the tactics used by Russia in Georgia in 2008 and in a more sophisticated manner in Ukraine in 2014 indicate that in addition to worrying about the supplier-consumer relations between the EU and Russia, attention should be turned on the internal vulnerability of the EU energy system in the face of a paramilitary conflict. Therefore, I believe that the current energy security discourse in Europe has been too one-sided, not taking into account recent developments in international relations.

The growingly aggressive rhetoric of Russian officials towards its western neighbors is definitely alarming to its bordering neighbors. Though Estonia has always been wary of Russia's aggressive policies towards the post-Soviet space, the political as well as academic discourse has not addressed adequately the threats that the Estonian energy system faces. Considering the inherent characteristics of the Estonian energy system, an argument can be made that it is extremely vulnerable to foreign interventions. Therefore, Estonia is the best example for illustrating the need to include the internal vulnerability aspect to the current energy security discourse.

I will take a case-specific approach and analyzes the vulnerability of Estonian electricity system in the context of intra-state armed conflict. Though my intention is to look at this concrete case, the reason behind choosing Estonia as a case study derives from its peculiar energy security situation. Estonia is often portrayed as a country with strong energy security position: it produces around 85% of its electricity from locally sourced oil shale (Eesti Statistika 2014b: 314) and is therefore self-sufficient when it comes to power production.

Due to the low energy density of the resource, oil shale is used mostly locally and is not transported over long distances. This has created a situation where most of the Estonian electricity production comes from a confined area near the border between Estonia and Russia where oil shale is mined. Secondly, the population of this region is not homogeneous: with an overwhelming Russian-speaking majority of 72% of total residents, (Eesti statistika 2015) the region of Ida-Virumaa could be considered as socially unstable in the face of Russian provocations. The interaction of the two factors creates a situation where Estonia's electricity supply security is dependent on the ability to create a stable social environment in a border region which is populated mostly by native Russian speakers.

With an energy dependence level of only 11.9% from total primary energy consumption (European Commission 2015b: 3), Estonian energy security position looks strong. Looking at the extremely concentrated electricity production portfolio, and considering the perspective of a paramilitary conflict, the energy security position of Estonia becomes remarkably weaker. As mentioned, the issue has not been debated in the academic literature nor in the domestic political circles and therefore, I seek to establish an academic and professional discourse on energy security issues, concentrating on the inherent weaknesses of the Estonian electricity system.

While the prevalent energy security discourse has been revolving around the external supply issue, the claim that intra-EU production and transmission infrastructure could seriously suffer from hostile activities remains plausible. I believe that if a government wants to make informed policy decisions, it needs to consider all the associated costs and benefits of a chosen policy path; hence, the worst case scenario should also be analyzed. Unfortunately, there is a lack of debate about the costs that would arise from a targeted attack on Estonian electricity production units located in Ida-Virumaa.

I am concentrating on the measure of vulnerability – a term that is often associated with critical infrastructure in literature. Though there are different options to assess the measure in question, I take a political economy approach and concentrate on the economic side of the issue. My method links the energy security with the overall economic performance of the country. In this sense, the goal is assess how exposed is the domestic economy to electricity supply disruptions. For reaching the goal of the thesis, I look at economic impacts for Estonia that would emerge with the power outages caused by lack of available electricity on the grid. Considering the scope of the research, I use the measure of economic loss as a proxy for illustrating vulnerability of the electricity system. Specific research question is derived from the aforementioned research aim and is formed as follows: **how big would be the expected economic loss for Estonian economy in a case of a serious electricity supply disruption where the major electricity production units located in Ida-Virumaa are offline?** Though not emphasized in the research question, I consider the situation where all the power production units in Ida-Virumaa are offline applicable only to the event where the region (or just the power plants) is controlled by non-state insurgent actors or the region is involved in an active warfare. Technical or human errors cannot create a situation, where all the production units are not operating on the same time.

I take a multi-factor approach to acknowledge the multitude of elements characterizing vulnerability of the Estonian electricity system and its relationship with the overall economic structure of the country. To this date, studies considering this specific issue have remained virtually nonexistent, so there is no opportunity for the author to apply an already tested model to the case of Estonia. Therefore, the first research step is to develop a suitable and methodologically sound model that would consider all the necessary aspects to evaluate the phenomenon in question. I will build on the general model developed by Edward Christie (2009) that links gas supply security with the measure of expected economic loss (EEL). However, due to the different scope of the research, some amendments to the original model has to be made. Whereas Christie looked at the economic dependence on gas supply and developed a general model that assesses economic consequences of the gas supply cut, I intend to do the same for the electricity sector. The topic and research question ultimately call for a political economy approach, since the research mixes security, international relations as well as economic dimensions.

After building a suitable model, the second research step will turn to the proposed research question. The model is put to test in order to evaluate the extent of possible economic losses for Estonia in the case of major/extensive electricity supply cuts. Within the model, I use data from the Estonian electricity transmission operator Elering's annual overviews of Estonian and neighboring electricity markets; also, the national statistic authority of Estonia is a source for secondary data. For the information about the technical nuances of the functioning of electricity system, I conducted a semi-structured interview with an expert of the field. I will use the measure of gross domestic product as a proxy for describing the economic development and will find out the reduction effect that the electricity outage has for the Estonian economy. To test the model and subsequently vulnerability of the Estonian electricity system, I consider two scenarios with different duration – the reasoning behind this will be pointed out in the corresponding section of the paper.

The thesis is organized as follows – the first chapter will provide the theoretical background for the thesis. I will give an overview of previous work on the subject; introduce the main conceptual and theoretical approaches of energy security and vulnerability of critical infrastructure. The chapter offers a justification why the expected economic loss was chosen as an indicator for expressing the vulnerability of energy system. Additionally, I will conceptualize the event of a paramilitary conflict and describe how this suits to the research on vulnerability of infrastructure. The main aim of the chapter is to establish the most important concepts and definitions to give further research a coherent conceptual base.

In the second part of the paper, I will develop a usable model for the cause of the research. As mentioned, the thesis will build on the model of Christie (2009), so a major part of the chapter serves as a critical analysis to Christie's model. The chapter will also refer to alternative approaches introduced previously but only to extent to justify using Christie's model. Second part of the chapter is for model-building purposes; while considering the indicators within the model, the text will refer to the previous chapters. The chapter concludes with pointing out the limits of the used model and recommendations for further work on the model.

Third chapter is the main analytical part of the thesis – it will put the model into the Estonian context and use it for finding the answer to the proposed research question. Before carrying on the analysis, I will introduce the sources for obtained data and the reasoning behind testing the model with two different supply cut period. A discussion part will conclude the findings of the case study and discuss the influence that the hypothetical scenario has on the electricity supply of Estonia. Last chapter of the paper is for concluding the research, pointing out the main findings and deficiencies and proposing recommendations for future research on the subject.

Theoretical background of the thesis

The first chapter is for introducing the theoretical background to the readers in order to establish a coherent and adequate conceptual and theoretical basis for the developed model and case study. The chapter begins by giving an overview on the relevant literature and previous research on the subject. It continues with a look on the critical infrastructure literature – I will justify, why the electricity sector is relevant in the context of critical infrastructures and how my hypothetical scenario relates to this literature. Next, the concept of electricity vulnerability is established and the intention behind using economic losses as a proxy for illustrating the vulnerability is justified. As the case study is based on a hypothetical scenario, a conceptualization of the event is needed: the final part of the chapter is dedicated to establishing a conceptual framework for investigating the event under question.

Previous work on energy and electricity vulnerability

Before establishing definitions to the related concepts and looking at the theoretical background of the thesis, a look into previous research on the subject is appropriate. Though there have been a few recent revelations in this field of study, the academic literature on the vulnerability of electricity system has remained scarce and been mostly revolving around the external vulnerability of the electricity system.

A number of studies have looked at countries' dependence on imported fuels and its relation to the vulnerability of their energy system. Christie (2009) developed a model that concentrates on establishing a connection between the vulnerability of the energy system and state's dependence on gas imports. His model considered the economic losses as a proxy for expressing the vulnerability of the system. Gupta (2008) carried out a similar exercise while considering the vulnerability of oil imports. Christie et al (2012) looked at oil and gas vulnerability of the EU's eastern neighbors (Moldova, Ukraine, Belarus, Georgia, Armenia and Azerbaijan) in the light of cooperation with the EU and concluded that facilitating cooperation is the key to reduce vulnerability.

As the scope of the thesis is the vulnerability of electricity system, an overview of previous work on this distinct subject should also be included in literature review. Nakawiro and Bhattacharyya (2007) analyzed the link between the vulnerability of Thailand's electricity system and natural gas imports. On the same general theme but from a different angle, Bhattacharyya (2009) looked at the fossil fuel prices as a determinant for the vulnerability of electricity system for different countries. His approach considered the electricity bills for consumers to be the proxy for assessing the vulnerability of the electricity system in general. Van der Vleuten and Lagendjik (2010) analyzed the occurrence of blackouts in the EU electricity system and compared how the two prevalent schools of thought – the proponents of centralized EU power system and supporters of the free-market approach with extra emphasis on the transnational power lines – addressed the issue of vulnerability and the future of the EU power grid. Liliestam (2014) compares the vulnerability dimensions for two possible decarbonization scenarios for the EU electricity system – renewable megaprojects (e.g. Desertec) and expanding the use of natural gas.

A different and more substantial set of papers considers the engineering side of electricity vulnerability. Hines et al (2010) looked at the topological metrics of the electricity system in the United States and considered three measures - characteristic path lengths, connectivity loss, and blackout sizes – to describe the vulnerability of the system (Hines et al 2010: 1). Zerriffi et al (2002) analyzed the advantages that a distributed electricity system has over a centralized grid in the occurrence of a military conflict. Tranchita et al (2009) developed a methodology to assess the power system security while considering the possibility of terrorist attacks and taking into account the load and generation factors. Though the studies that consider the engineering aspects of vulnerability do not relate to the current thesis, the example illustrates the multifaceted nature of the concept of vulnerability.

To this date, I do not have knowledge of any studies that look at the inherent vulnerability of the electricity system in the face of a terrorist attack and use a tool that considers economic losses as an indicator for vulnerability. Therefore, the thesis will build on the most similar method. As the setting of current research establishes a link between economics and international relations and looks at the two distinct dimensions within a single research framework, it resembles the approach of Edward Christie (2009), who used economic loss as proxy for describing the vulnerability of the system. Though Christie applied his approach to the gas market, it also suits to the electricity market. In this sense, one of the main tasks for the thesis is to use a method that originally was applied to gas market in order develop a more holistic view of the vulnerability of the electricity systems.

Electricity sector and the literature on critical infrastructure

Since the thesis does not try to evaluate the overall energy security position of a state but rather to concentrate on the functioning of a distinct and extremely important branch of energy system – the electricity sector – the following section looks to develop a coherent conceptual framework for the sector.

Electricity supply is considered to be one of the essential inputs for any economic activity for developed as well as developing countries (Bhattacharyya 2009: 2411). It can be argued that the effective functioning of the electricity sector is a prerequisite for a country to achieve a modern standard of living and economic welfare. An increasing number of academic papers deal with the issue of ensuring the supply of the essential products, services and markets for the society and uninterrupted electricity supply is one of the main research areas for the studies concentrating on this issue. As der Vleuten & Lagendijk (2010) point out, "*In the emerging literature on Critical Infrastructure, electric power grids count among the most 'critical' of all modern infrastructure*" (der Vleuten & Lagendijk 2010: 2053). The European Council Directive 2008/114/EC on European critical infrastructure also acknowledges the importance of electricity generation and transmission facilities and regard them as critical infrastructure (European Council 2008: L 345/81). Since the intention of the thesis is to look at the functioning of the electricity market during an extreme event (e.g. during a paramilitary conflict), I consider the literature on critical infrastructure to be the most suitable for illustrating the main issues of the current research.

Due to the importance of electricity sector to the overall economic development of a state, it should be in the government's best interest to ensure electricity supply to its residents under any condition. Thus the overall functioning of the electricity grid as well as choices for production and transmission infrastructure must be carefully considered. Domestically available resources, electricity interconnectors with neighboring countries, electricity demand characteristics, energy security aspects and growingly, environmental constraints – are all influencing the choices for the electricity system operators. The goals of these individual aspects are often contradicting each other; for instance, if a country has a vast amount of domestically available fossil resources, it could feel reluctant to follow the aspirations of environmentalists for decarbonizing the energy system. The functioning of a system should therefore be balanced and take into account all the concerns of these distinct areas. Liliestam (2014), who compared options for decarbonizing the electricity generation, illustrates the need to find a right balance between different goals by claiming that a decarbonization pathway which makes the system too vulnerable to terrorist attacks should not be realized (Liliestam 2014: 234). This exemplifies the trade-off between different aspects of vulnerability for the electricity system: choices for developing the electricity system are influencing the grid's resilience against unexpected threat factors.

The literature on critical infrastructure points out that terrorists can consider power system as their primary target if their intention is to cause widespread societal and economic damage (National Research Council 2012: 9). Recently, a number of similar incidents have highlighted the issue: in 2014, Yemen had to endure a day-long nation-wide electricity supply cut following a terrorist attack on country's electricity grid and production units (Kelly-Detwiler, 2014). In the beginning of 2015, an attack on Pakistan's main power line left 80% of its population without electricity supply (Williams, 2015). In March 2015, a massive supply cut in Turkey also evoked some opinions that it was caused by terrorist attacks (Porter, 2015). Concerns have been raised of the possibly devastating effects of a terrorist attack on the United States' electricity grid. Given the current international political situation, some experts claim that ISIS poses an imminent threat to the United States' electricity infrastructure (WND, 2014). Therefore, in the context of critical infrastructure studies and current thesis, the terrorist activities remain highly relevant factor for influencing the functioning of the electricity infrastructure.

As is illustrated by Liliestam (2014), the critical infrastructure studies revolve around the issue of system's vulnerability. Before going further, the thesis must establish a concept of vulnerability and its relationship with the functioning of electricity system.

Establishing the concept of vulnerability

The conceptualization of vulnerability is closely related to a vague term in academic and political discourse – "energy security". Even though the term "energy security" itself is widely used in the academic community, there is no consensus over the concrete definition or the precise indicators to use while addressing energy security issues (Kruyt et al, 2009: 2166). Several definitions have emerged over time, ranging from declarative slogans to attempts to concretely conceptualize the term. Daniel Yergin argued in the late 1980's that energy security must „*assure adequate, reliable supplies of energy at reasonable prices and in ways that do not jeopardize major national values and objectives"*(Yergin 1988: 111). Though the definition is overarching and recognized by many scholars, Yergin's approach lacks the clarity on how to carry out a scientific analysis on energy security. Few studies[2] similarly try to form a universal concept for energy security (von Hippel *et al*, 2011: 6720). These approaches are useful, yet if one wants to have an overall understanding about the issue, they also prove to be limited when it comes to measuring the phenomenon as well as applying it in a narrower sector-specific context.

Multitude of approaches and concepts[3] brings forth the problem of measuring energy security and comparing it with other policy objectives (Winzer, 2012: 6). Winzer (2012) also argues that even though there is no consensus regarding the concept of energy security, the academic community generally agrees that *"security is concerned with risks"* (*Ibid*: 37). I recognize the ambiguity of the term and the thesis will not delve into

[2] See, for example APERC (2007); UNDP (2004) for further on this point.
[3] For a comprehensive set of different definitions on energy security, see Winzer 2012.

the discussion about the exact definition of energy security, since there is no particular reason for defining the term. The goal of the thesis is not to assess the overall energy security position of a country, but rather look at a specific aspect within the wider framework of energy security.

I embrace the view that security is interlinked with risks that a system faces directly or indirectly. One of the most important aspects for the security of a system is its exposure to various aspects of risks – if there are a lot of potential threat factors that could negatively influence the functioning of a system, the security position becomes remarkably weaker. The system administrator should therefore guarantee that no extensive and prevalent risk aspects could interfere with the functioning of the system – e.g. it should minimize the vulnerability of the system. Accordingly, the United Nations describes the basic principle of vulnerability as *''the risks of being negatively affected by shocks''* (United Nations 1999 from Nakawiro & Bhattacharyya 2007: 3339). The term "shocks" can also be viewed as unexpected events that the system cannot control; the basic principle of vulnerability is thus alternatively "the risks of being negatively affected by unexpected events". Gnansounou develops a similar definition; according to him, *"the vulnerability of a system is the degree to which that system is unable to cope with selected adverse events"* (Gnansounou 2008: 3735). As the thesis looks at the functioning of the energy system during an extreme case (e.g. paramilitary conflict), the approach echoes the main issue of the paper. Therefore, the above-developed concept of possibly negative unexpected events for the energy system is used throughout the thesis for describing the nature of vulnerability.

Main energy vulnerability concerns for a country could possibly derive from a number of aspects – insufficient energy supply, financial restrictions, technical characteristics, environmental and nuclear non-proliferation issues can all be considered to have an impact on the vulnerability of the energy system (Andrews 2005). Putting this approach into the UN (1999) context, it can therefore be argued that the vulnerability of the energy system is determined by its ability to anticipate and overcome different risk factors. The discussion on vulnerability can be linked with critical infrastructure studies – these risk factors constitute the overall vulnerability of a system and therefore the policies of the national government should seek to minimize the possible negative effects these threat factors pose on the critical infrastructure.

The above-mentioned aspects vary significantly in their normative nature, ranging from purely market-related issues and the overall economic framework (e.g. financial problems) to matters that are beyond the control of a government (for example the global environmental aspects). Accordingly, in analytical framework, these issues need also different tools to recognize the inherent nature and nominal restrictions of the phenomenon. Therefore, studying a concrete phenomenon within the context of energy system vulnerability needs an approach that considers the nature of the phenomenon in question.

Different concepts for measuring vulnerability

As I concluded, the vulnerability of the system is dependent on its ability to cope with adverse actions that could harm the functioning of the system. The wide-ranging spectrum of possible risk factors makes the initial idea of measuring the vulnerability highly case-centric. I will briefly look at different ways for measuring the phenomenon in question, but only to extent as to justify the usage of econometric measuring tool.

As Liliestam (2014) notes, the engineering perspective on risk dominates the critical infrastructure research literature (Liliestam 2014: 236). Since the scope of this paper is to look at the issue from political economy perspective, the current chapter does not concentrate on the methods for measuring vulnerability in engineering research. Therefore, there are only a few previous papers that can be used as a basis for the current paper.

Gupta (2008) looked at oil vulnerability of countries and concluded that there are 3 different risk dimensions that contribute to the overall oil vulnerability of state's economy – market (economic risk), supply risk and environmental risk (Gupta 2008: 1197). By studying the normative nature of these risk dimensions, it also becomes apparent that vulnerability is highly dependent on the concrete goal of a research. A study that considers environmental risks of the energy use – climate change, pollutant emissions etc. – is most likely to use variables that illustrate the environmental dimension; a more market- or economics-oriented research will look at macroeconomic performance indicators of the economy as an indication for the vulnerability of the system. Gupta constructed a composite oil vulnerability index (OVI), which included a linear function of five relevant indicators. He used indicators such as: "domestic oil reserves relative to total oil consumption"; "geopolitical oil risk (consisting of different risk dimensions)"; "GDP per capita" and three indicators that illustrated the influence that oil imports have on respective national economies.

Gnansounou (2008) differentiated between 5 distinct vulnerability dimensions in his effort to create a composite energy vulnerability index for a country. He used the dimensions from different fields of energy research – economic, energy dependence as well as environmental indicators. Christie et al (2012) also attempt to conceptualize vulnerability and conclude that it can be assessed with ten indicators. These indicators are different in their nature and their scope and can be grouped as follows: macroscopic (e.g. overall energy intensity of the economy), diversification (long-term security), resilience (short-term security), and foreign and security policy aspects (relations with suppliers, with third parties) (Christie et al 2012: 23).

While Liliestam (2014) based his study on the case of possible terrorist attacks on electricity infrastructure, he looked at three aspects – diversity, resilience and potential impacts as measures for describing vulnerability of the system. The diversity of electricity supply was assessed via Herfindahl-Hirschmann concentration index; the level of buffers that the system withholds illustrated the resilience indicator and potential impacts looked at the outage size and length.

Though all the methods described above are relevant in the context of the current thesis, all of them lack an important link between the two key variables. Since the intention of the research is to evaluate the economic loss in the presence of a supply cut, the chosen approach needs to link economic activity and electricity consumption. In this sense, Nakawiro and Bhattacharyya (2007) investigated the same relationship: they developed an indicator that considered gas price and the gas intensity of Thailand's economy to be the main factors influencing the degree of vulnerability of the electricity system. Though the approach looks at a link between economics and vulnerability, it does suit to a research which concentrates on investigating the occurrence of a supply cut. Instead, I took Edward Christie's (2009) approach as a conceptual ground for the thesis, since he concretely established the link between supply cut, vulnerability and economic loss. I will turn to Christie's model more thoroughly in the next chapter.

In the current thesis, I also take a holistic approach – in the next chapter, I will develop a model, which mixes different dimensions of energy vulnerability. The intention behind this is to give a more thorough look on the spectrum of issues that must be considered while conducting the current case study. As the main goal for the thesis is to evaluate the economic losses for Estonia in a presence of an electricity supply cut, the research falls within the political economy discourse. The reason for it derives from the proposed research question that looks at a problem that is within the international relations discourse, but assesses it with a tool that is widely used for research in economics. In this sense, I follow the logic of economic vulnerability studies which also look at the exposure of national economy to shocks. The principal difference is that while the former studies look at the country's inherent economic features for describing the vulnerability and assessing economic loss (Briguglio *et al* 2009: 232), the current thesis looks at a very concrete economic sector – electricity – and evaluates the influence that it has on the overall economic performance of a country.

Conceptualizing the extreme event in question – a regional paramilitary conflict

The final part of the theoretical chapter concentrates on conceptualizing the hypothetical event. Ultimately, the thesis sets quite a provocative research problem – how a regional conflict induced and supported by Russia influences the functioning of Estonian electricity system. There are mixed opinions about the possibility of Russia interfering in Baltic States: while some politicians and analysts[4] completey rule out the possibility of a paramilitary conflict in Estonia, I consider it to be a plausible hypothetical scenario,

[4] See, for example Tambur (2015) for comments of Czech president Miloš Zeman, and Nael (2014) for the opinion of the former supreme allied commander of NATO European forces James Stavridis.

as is also recognized by some foreign experts[5]. Considering the above-developed approach to vulnerability – an armed conflict that harms functioning of the energy system will definitely count as an unexpected event and is suitable for the analytical framework of the thesis. The discussion below is designated for deciding, whether the hypothetical event could be applied into the context of critical infrastructure studies.

Before turning to theoretical and conceptual discussion, I briefly streamline the main characteristics of the considered hypothetical scenario. As the comparison was drawn in the introduction between the current events in Ukraine and the possible conflict in Estonia, it should be noted that it was intended to justify the plausibility of the scenario as well as to point out the probable tactics used in the conflict. I consider the two events to have a major inherent difference: while it can be seen that the intention of the insurgent forces in Ukraine is to gain control of the wider region for a long period, the different geopolitical situation for Estonia makes the similar conflict highly improbable. Due to Estonia's NATO membership status, a similar long-lasting military conformation would most probably result in an extremely serious reaction targeted against Russia from Estonia's NATO allies. Therefore, I anticipate that the intention of insurgents is to cause maximum socioeconomic problems for Estonia. The suggested goal of insurgents also coincides with the opinions that Russia could test the NATO's solidarity. Following this, the targeted attack on the Eesti and Balti power plants with an intention to control the operation of the plants for a short period is a plausible scenario.

One of the most complicated issues of the thesis is to conceptualize the actual event in question. The international law applies different rules to conflicts that are international or internal in their nature (Stewart 2003: 313). Thus there is a principal difference between the cases where the actor who imposes military force to a sovereign state can be identified as an institutionalized state actor or a can be considered random insurgent unit with no official affiliations. If a state is under attack by forces which are difficult to identify as a foreign aggressor, the international response would be much more reserved – other states are more reluctant to offer direct military support when the conflict is considered to be an internal affair of a sovereign state. The recent crisis in Ukraine has illustrated the issue as the Ukrainian government has received only limited military

[5] Among others Anders Fogh Rasmussen (see introduction) and Edward Lucas (2014)

support from its allies. Unfortunately, it is increasingly problematic to distinguish the nature of different conflicts since the borders between truly domestic and international conflict have become vague.

As mentioned, the literature on critical infrastructure deals with the threats deriving from terrorist activities. Therefore, the thesis should take look into the actual (not conceptual) contemporary differences between terrorist activities and a military clash in order to decide, whether the event in question can be considered within the critical infrastructure literature. A difficult task is to differentiate between terrorist forces, quasi-state military units, militias or other unidentified units and accordingly, as a number of analysts have highlighted, there are increasingly blurred lines between different types of warfare (Hoffman 2009: 35).

During the recent decade, the "hybrid warfare" concept has become relevant in contemporary security studies. This approach in modern warfare tactics involves a party using different types of force, including terrorism, regular combatants and militia while using non-conventional tactics and information operation to confuse public perception and official acknowledgement of the conflict (Freedman 2014: 11). As a result, the lines between conventional war and terrorism are not so explicitly obvious during a conflict that can be described as an example of "hybrid warfare". During the ongoing crisis in Ukraine, the opposing forces to Ukrainian government have been using the tactics of "hybrid warfare" (Jones 2014). This has made the conceptualization of the Ukrainian conflict difficult – is it a domestic conflict where separatists and terrorist forces are fighting against the central government, or should it be treated as a case of a military interference by another sovereign country?

According to the hypothetical scenario developed in this thesis, an insurgent force with no official affiliation that uses hybrid warfare tactics seizes control of the electricity production units, and is capable of fending off the government forces for a period of time. As pointed out, this derives from the initial intention to cause maximum socioeconomic damage. The initial nature of this kind of hybrid warfare could well be seen more like a terrorist activity not a confrontation between the states. As pointed out by Zerriffi et al (2002), military units and terrorists alike are capable of organizing a coordinated attack on electricity system (Zerriffi 2002: 2). Given the discussion above and the increasingly undistinguishable nature of the hybrid warfare and terrorist activities, I conclude that the hypothetical event can be analyzed within the critical infrastructure literature.

Model for evaluating the vulnerability of the electricity system

The previous chapter clarified the definition of vulnerability and stressed, that the thesis concentrates on the economic vulnerability of electricity supply and thus uses the economic losses as a proxy for vulnerability. In the current chapter, I use the developed concept as a dependent variable within the research framework. The goal of this chapter is to develop a research model that considers the most important variables which are influencing the vulnerability of the electricity system. As pointed out, I consider Edward Christie's model as a base for building my model, so a further look into his model is offered in order to assess its applicability to the current research. Also, I will point to limitations of Christie's model: due to the different scopes of the research, it has some conceptual weaknesses and does not fully relate to the current context. I will point to the shortcomings of Christie's approach and develop a specific model that will be later tested within the current thesis. Of course, I will point to the limitations of my model as well as suggest future work on the model.

Christie's (2009) model on vulnerability

Christie built his model on the premise that the state is ultimately liable for reducing the probability, severity and potential impact of exogenous events that are damaging the welfare of the nation's population (Christie 2009: 276-277). Initially, the term "welfare" is by its very nature a broad concept that historically refers to the efforts to improve the living standard of the population (Coatsworth 1996: 1). The electricity supply has also major impact on the well-being of residents: during the blackouts, the living standards of the population worsen significantly, since people are unable to carry on with their daily routine. The loss of well-being or people's comfort is not easily quantifiable: it depends among other things on the person's attitude, habits, resilience, their ability to adapt in unpleasant situations etc. As pointed out earlier, electricity supply is essential for providing certain goods and services and therefore creating economic activity, or alternatively – creating overall welfare. Latter can be measured with remarkable accuracy using quantitative tools. The economic aspect of welfare gives the research an opportunity to quantify the losses that the population needs to endure while witnessing the power outage.

Christie developed his model to be applicable to gas supply disruptions and the approach follows the logic that the loss of gas supply brings forth a loss of economic welfare in similar proportion. As the main idea behind his method is to look at a country's dependence on foreign suppliers, the model included a diversity index in order to assess how concentrated are natural gas imports for a country. In contrast to other authors, Christie does not use the popular measures of Herfindahl-Hirschman Index or Shannon-Wiener Index[6]. Instead, he borrows a method from financial economics literature and uses the measure of expected shortfall. Ultimately, the measure has been developed as a tool for investment portfolio management and it reflects the average of the worst losses on a predetermined confidence level (Acerbi and Tasche 2001). Christie justifies the choice of method with an intention to factor in the expected loss of worst cases, since human agents tend not to seek to minimize overall expected loss, but instead focus on specific "unacceptable loss" (Christie 2009: 282). The idea to look rather the "worst case scenario" coincides with the point made in the introduction of the current thesis; policy planning of national governments should consider all plausible possibilities and also include worst case scenarios.

The main aim of Christie's work was to develop a functional model that would measure the economic loss for the country in a case of severe gas supply disruption. He concluded that expected economic loss (EEL) is a suitable indicator for describing the vulnerability of the country's energy system in his research setting. As the economic welfare is a significant part of the overall welfare of the state, it makes sense to use this indicator; moreover, if the intention of the study is to specifically find out the monetary value of the supply cuts, the EEL is a suitable tool for investigating the research question. Though Christie did not develop a concrete model, he concluded that EEL should be assessed with a linear function model that follows the general structure of:

[6] Herfindahl-Hirschman Index or Shannon-Wiener Index are measures for ultimately expressing the concentration and diversity of a market respectively. Christie (2009) rejects the two indicators from his model for conceptual reasons: he wanted *„to avoid arbitrary non-linearities in the loss function"* (Christie 2009: 281) and to look at the economic loss for the worst case scenario.

$$EEL = f(\theta, GDP, NID \times es(n))$$

In this equation, a country has a natural gas intensity of gross domestic production (GDP) equal to θ. θ represents the physical volume of natural gas which is consistent with one currency unit of value added generation at the current level. Christie assumes that a physical shortage will obstruct value added generation and while the latter relationship is complex and typically non-linear, the impediment to normal economic activity will depend positively on θ, on GDP, and on the size of the supply shortfall. Expected shortfall (es(n)) is a share of missing foreign supplies so it should be multiplied by net import dependence (NID) to yield the share of the shortfall for domestic end-users (Christie 2009: 283).

Christie used a purpose-built general equilibrium model in order to account for losses through various channels and industries. He observed empirical information from Bulgaria during the time of a two week gas supply disruption in 2009 which was estimated to have cost about 250 million EUR and accounted for around 0.9% of annual GDP of Bulgaria. Christie also called for further research into the Bulgarian supply cut and its relationship with GDP formation in order to develop a more comprehensive specification of the expected economic loss function. It would then help to simulate the effect of future supply cuts for Bulgaria as well as for other countries (*Ibid.* 283).

I also believe that refining the expected economic loss function and further expansion of the discourse would lead to increasing awareness of the possible threats that the energy system faces and the costs for national economy that would arise from supply cuts. Due to the fact that the current thesis has a somewhat different focal point than the Christie's (2009) paper, I also must make some changes to the model. Next, I will build on Christie's general model in order to develop a revised general model which is suitable for assessing expected economic loss in the case electricity supply. After concluding a general model, I will then develop it further into a function, where I have established concrete links between indicators in order to answer to a proposed research question and find out the economic losses for Estonia.

General model for assessing the expected economic loss in the case of electricity disruption – amendments to Christie's (2009) model

I will now turn to the core part of the research – a concrete model for assessing the economic loss in the case of electricity supply disruption will be developed in the following section of the thesis.

As stressed earlier, I will use Christie's general model and make some critical amendments in order for it to be applicable for the intentions of the current thesis. Though the model was developed for gas supply, the relationship between supply cut and its influence on the functioning of economy still holds in the case of electricity. Christie had four key variables that influenced the expected economic loss function: $EEL = f(\theta, GDP, NID \times es(n))$. When "$\theta$" represented natural gas intensity of an economy in Christie's approach, it can easily be transposed into the context of current research. "θ" will be used to represent the electricity intensity of an economy. Electricity intensity is not as widely used as the measure of energy intensity, but for the intention of the current thesis, it is vital to include this variable into the model. The measure itself illustrates, how many units of GDP is created with one unit of consumed electricity.

Electricity intensity is defined and used similarly in Inglesi-Lotz and Blignaut (2011), Mukherjee (2008), Choi and Ang (2003), Sun and Ang (2000). A methodological question remains regarding choosing this indicator as it assumes the relationship between GDP and electricity production to be linear and constant. The indicator looks at overall electricity consumption and does not differentiate between economic and non-economic activities. Therefore, using the indicator does not allow to address adequately the issue of efficiency of electricity use and its relation to GDP creation. To illustrate the issue, I consider an example of a simple system with two electricity consumers A and B; latter represents a household and former an enterprise. The system as a whole generates GDP witch is dependent on the output of A. Electricity intensity of this system is equal to cumulative electricity consumption of A and B divided by the output of A (GDP). I now assume that due to the improvements in efficiency, A can produce the same amount of output with lower electricity consumption. On the same time, B uses more electricity; additional consumption of B is in the exact same amount that was vacated by A with improved efficiency. In a changed situation, overall electricity intensity of the system remains the same, whereas the amount of electricity used for GDP creation is smaller. This illustrates the fact that using the indicator of electricity intensity of the economy on gross national level sometimes fails to address the issue whether the electricity is used for economic activities which generate GDP or for other actions that do not relate to GDP.

The biggest problem in using more sophisticated indicators for measuring electricity intensity and also in accounting for the source of GDP creation relates to data peculiarities. The available data differentiates between industry, households and transport; other sectors are usually considered in one column (see European Environmental Agency 2015). Therefore, it is difficult to separate electricity consumption that is related to GDP creation. Though I recognize the limitations of the indicator, I still use electricity intensity in the model for a few reasons. Most important aspect is the methodological simplicity of the indicator – it is recognized and used within the academic literature and it should not evoke any serious questions about the appropriateness of the indicator. Secondly, the problem of data availability complicates the usage of other measures: it is difficult to find coherent data on electricity consumption on the level of economic sectors; whereas GDP and gross domestic electricity consumption are transparent and easily accessible indicators. Third reason is the intention to look at the issue on an overall system level – I consider the national economy and welfare of the society to be in a common frame with all constituents having equal importance to the functioning of the system.

Next variable in Christie's model – gross domestic product – can be used in any research without much of a need for adaption to a concrete goal of the paper. I also use GDP as a proxy to overall economic development. There are three options for assessing the GDP – production-, income- and expenditure approach (Quang Viet 2009).The current research is based on the first option because of the initial goal of the thesis – to look at the economic loss in the presence of electricity supply cut. Supply cut does not have so direct influence on the income or expenditure of the population. For instance the electricity supply cut does not immediately reduce the income of the people by a concrete amount. Electricity as an input for economic activity has a more straightforward relationship with domestic production output – it can be argued that while the system is unable to assure electricity supply to its customers, an economic agent is unable to carry on with its activities. I anticipate the electricity to be indispensable input for all the economic activities regardless of their nature. Therefore, to observe the direct implications on the GDP formation, the research should follow the production approach of GDP creation.

The last two variables included in Christie's general model need significant amendments before they can be used in current research framework. Both, expected shortfall and net import dependency are in their normative nature indicators that represent the international dimension of Christie's research. As pointed out in the previous section, the expected shortfall (es(n)) describes the worst case scenario in regarding the gas supply cuts; net import dependency is an indicator for measuring the extent to which a country relies on imports to meet its energy demand (IAEA 2005: 83). In the Christie's framework, the two indicators were not used separately. As he notes, the interaction between them is designated for bringing the consequence of supply cuts to domestic end-user level (Christie 2009: 283). Keeping in mind other parameters in Christie's model, net import dependency and expected shortfall are jointly used for expressing the influence of supply cut to national economy.

I will now briefly illustrate the implications that the two variables have on the functioning of the economy with another hypothetical situation. Two countries A and B have same sources for importing natural gas. For the simplicity of the example, I assume that their import portfolios are identical. Following the main assumptions about the nature of expected shortfall, the measure is similar for both countries. Country B has no internal sources for meeting the domestic demand and thus its net import dependency is 100%. Country A has indigenous production and the country satisfies ½ of its gross gas demand with domestic product. Therefore, country A has an import dependency of 50% whilst also having a 50% larger overall domestic gas consumption. In order to exemplify the relationship between severity of supply cut and expected economic loss, I assume that the two countries have an equal efficiency for using natural gas. Therefore, the GDP of country A is two times bigger than that of country B. When anticipating the worst case scenario, country B is unable to generate 100% of its gas-related GDP, whereas country A is still able to use its indigenous resources and 50% of its economic processes will continue. As can be seen, when using Christie's model, the net import dependency and the expected shortfall represent the determining factors for the initial outcome of the model and can be regarded as a measure for expressing the severity of supply cuts to domestic economy.

The measure of net import dependency still has some significant limitations, which Christie has not addressed in his model. IAEA defines net import dependence as "the ratio of net imports to total primary energy supply in a given year" (IAEA 2005: 83). The indicator therefore does not include any information about the availability of resources, efficiency of using the resource etc. and only looks at raw data on production and import volumes. Using it in a model which intends to assess the economic costs of a worst case scenario, limits the opportunities to take a case-specific approach and include factors that could significantly change the outcome of the research.

For illustrating this point, I turn back to the previous example, where country A had indigenous gas resources and its gross internal gas demand was met by 50% with domestic production. I hypothesize that whatever the reason might be (financial, market-related, environmental problems), the country does not fully exploit its gas production ability. In the example, domestic consumption was met by 50% with domestically produced gas, but in reality, the country could satisfy up to 75% of demand with domestic gas. There are no infrastructural constraints and as soon as foreign supply disruptions appear, the import gas can be substituted with domestic product. In this situation, instead of a 50% of gas-related GDP reduction, country A faces a reduction of 25% of GDP generation. Using net import dependency precludes including this context into the model, since the measure does not incorporate any probabilistic dimension. Expected economic loss outcome for country A changes significantly; if instead of import dependency the model would consider the available replacement of foreign supply with domestic production. This paradox should be addressed in the context of current thesis, since the electricity supply cut have a more complex influence on the economic activities due to the specificities of power generation as well as transmission grid functioning[7]. As Christie himself recognizes, the general model could be developed further to include a role of fuel storage (Christie 2009: 283). In the current research, the upgraded version of the model incorporates additional domestic generation capacities and transmission and generation capacities on the neighboring markets. As electricity storage is not yet a mature technology and does not significantly alter the processes on the market, it will not be added to the model.

Christie used its last varirable – expected shortfall – in the model to express the probability of supply cuts happening at the supply source level. The decision to include expected shortfall in the research follows his aim to look at the very worst scenario of gas supply cut. I also embrace the idea not to look at the concentration of a market (as is observed by HHI or SWI), but instead include the very worst case in the research. This derives from the belief that due to the significant importance that the electricity sector possesses to the overall economic functioning of a country, the government should consider worst-case scenarios for ensuring full operational integrity of the electricity system.

Still, different scope of my research in comparison to Christie impedes including the expected shortfall measure in my model. The most important difference is the *ad hoc* nature of current research: I do not intend to include a probabilistic level into the research (e.g. the thesis will not consider the question "How probable is the occurrence of the hypothetical scenario?"), but rather expect the scenario to play out and assess the consequences. In this sense, I follow the logic of Liliestam (2014): he argues that attacks against the system are unknown surprises without meaningfully quantifiable probabilities. (Liliestam 2014: 236). He builds his assumptions on the energy security literature that consider the system to work in ignorance where it is impossible adequately assess the probability of a targeted attack on system (Stirling 2010). The second reason for abandoning the expected shortfall from my research relates to the scope of the research. I do not intend to differentiate between supply cut options. In his example, Christie looked at three distinct sources of supply and deduced the worst case

[7] The main difference being the relative ease of substituting the supply loss – in comparison to the gas sector, the electricity sector usually has far more diversified supply options. On another side, functiong of electricity transmission grid is far more complex and it incorporates the issue of grid tension, which will be explained later in the thesis.

of a supply cut for the hypothetical system. The aim and main assumptions of the current research do not necessitate the use of different supply cut options. Considering the reasons mentioned previously, I do not use the exact measure of expected shortfall.

As is explained beforehand I cannot use the variables “expected shortfall” and “net import dependency” due to some methodological and context-related issues and therefore I abandon these indicators from my model. Still, the general idea behind choosing these indicators – to express the severity of a supply cut – is extremely important for the current research as well. I instead introduce a new variable of “unrecoverable supply cut” (USC) to the general model. The justification and methodological background to this indicator will be offered in next chapter.

Following the discussion above, the revised general model for assessing the expected economic loss in the case of electricity supply cut is:

$$EEL = f\,(\theta, GDP, USC)$$

In the model, θ expresses the electricity intensity of country’s economy; GDP stands for gross domestic product which is calculated using the production approach; USC adds a measure of severity to the model by marking the unrecoverable supply cut. All three indicators have a positive relationship to the expected economic loss (EEL). Next, a concrete function to will be developed in order to assess expected economic loss quantitatively.

Expected economic loss function and electricity supply cut

In the previous section, the general model for expected economic loss in the case of electricity supply cut was developed; the current section goes further and I establish concrete links between the indicators. At first, I will look at the indicators separately, describe their novelty to the research and introduce the way the indicators are measured within the function. The last part of the model-building will provide the main assumptions and generalizations in order to put the research into the correct frame.

As previously stated, the electricity intensity (θ) describes, how much the country's economy uses electricity to produce goods and services. The general form of θ is $\frac{Electricity\ consumption}{Economic\ output}$ and the outcome will tell us, how many units of GDP is produced with a unit of electricity consumed. Since the overall electricity consumption is a reoccurring measure in the model, I will hereinafter refer to it within a model as $Cons_{dom}$; economic output, which represents the national gross domestic production, will be referred to as "GDP". Keeping in mind that the thesis assesses economic loss, I assume that every unit of electricity that cannot be consumed, brings along a reduction of GDP that is equal with the volume of θ. The unrecoverable supply cut (USC) is for expressing the gravity of the supply cut and it quantifies the electricity that cannot be supplied to domestic consumers. Therefore, θ should be multiplied with the USC – the function now takes a following form:

$$EEL = \frac{Cons_{dom}}{GDP} \times USC$$

An important step in the research is to ascertain the magnitude of USC. Since the model is designated for a situation, where large power producing units are deliberately offline, an important aspect is a loss of production (LP) from these units. Usually, the electricity system has some buffers to overcome unexpected failures in transmission and generation facilities. I use the measure of recoverable supply (RS) to express the nominal and technical capacity of the electricity system to substitute failed power production.

A general model for calculating USC is:

$$USC = LP - RS,$$

Where: $USC \in [0, Cons_{Dom}]$

The limitation excludes the possible peculiarity where the unrecoverable supply cut is larger than the domestic consumption. As the intention of the model is to look at the supply cut for the domestic users that use electricity as an input for their economic activities, by definition the supply cut cannot exceed the domestic consumption. A hypothetical scenario, where this limit is applied, relates to an electricity system with low domestic consumption level and a single major power producing unit, whose output significantly surpasses the domestic consumption. In a normal situation excessive electricity is exported. In this hypothetical scenario, the ability to export electricity significantly exceeds the ability to import electricity from other systems. When the facility falls offline, it creates a nominal USC which exceeds the domestic consumption.

The USC itself has a complex nature, since it needs a detailed look into the functioning logic of the electricity system. I will first turn to the measure of loss of production. The model looks at economic losses for a country and it is designed to be applied on a country level. Reality of the electricity market complicates using the model – in an open and interconnected electricity market, the origin of electricity is less important and moreover, is difficult to identify. Following this point, I make the first assumption: regardless of whether the produced electricity will be exported or consumed domestically, the same share of production loss will be applied to both dimensions. This means that LP is calculated as follows:

$$LP = Cons_{dom} \times P_{loss}$$

In the equation, $Cons_{dom}$ marks overall domestic electricity consumption and P_{loss} the share of domestic electricity production deriving from the facilities that are modelled to suffer from supply halt. P_{loss} has a 0≤1 scale within the model.

In the measure of RS, the information about the transmission and available generation capacity of neighboring countries as well as the domestic power production should be included. In the further developments of the model, the level of electricity storage should also be considered, but as the technology is still in developmental stage and cannot make much difference on the substitution of the production, it will not be included in the current research. There is quite extensive information available about the nominal capacities of power generation and transmission and using this information allows to deduct the volume of substituting capacities. The functioning of the system is also related to technical issues and it requires an investigation on an engineering level. One of the most important factors to take into account is the ability to maintain the tension in the grid in the case where large units are unable to produce electricity. This is one the key elements that significantly changes the outcome for the measure of recoverable supply; also, it also gives the function a highly case-centric nature. It means that before applying the EEL model to any electricity system, a researcher must look at the functioning logic of the grid from an engineering perspective to determine the system's ability to maintain tension in the grid.

The functioning logic of the electricity market obliges us to make some generalizations. The two most important factors for describing the overall electricity consumption are peak demand and overall domestic consumption. Unfortunately, the relationship between the two is not straightforward and addressing the issue requires establishing further assumptions about the interactions of the two indicators. The peak demand usually occurs during the cold winter days, where the excessive consumption will cover the higher need for heating (Karnau 2012). As already noted, I consider the economic system to operate as a whole and do not differentiate between separate electricity end-user groups. Following this logic, covering peak demand is essential for guaranteeing the well-being of the population as well as maximizing the output of economic agents at any given time.

The problem lies with the issue that while electricity demand and infrastructure capacities are measured in watts, the consumption is expressed in watt-hours. Consumption is dependent not only on the level of demand, but also on the demand-cycle, meaning that timing of electricity use is also an important factor. In order for the model to exactly mirror the reality, it should take into account the production and consumption-cycles, as well as possible amendments to consumption in the presence of a supply cut (e.g. the consumption management of end-users) but due to the restraints of the thesis, I will make a significant generalization in order to make the measures of electricity consumption and unrecoverable supply cut simultaneously useable.

I assume the relationship between peak demand and overall electricity consumption to be linear: for every watt supplied below the domestic peak demand level, the overall consumption of electricity decreases by a designated amount. In order to find out the relationship, I make a simple division between overall consumption and peak demand and find out how big is the reduction of end-user consumption. The goal is to determine the magnitude of a loss if the peak demand is not met. The calculated measure will be multiplied with available substitution capacity to find out the recoverable supply.

The equation for calculating the RS is:

$$RS = \frac{Cons_{dom}}{peak\ demand} \times available\ substitution\ capacity^{*};$$

Where: $available\ substitution\ capacity^{*} \in [0, peak\ demand]$

The justification for using the limitation is similar as presented previously, when I discussed the USC. As the mode looks at the domestic level, any distortion that does not relate to domestic consumption should be excluded. Therefore – if the physically available substitution capacity is larger than the peak demand, the excessive capacity will not be counted within the model.

Compiling the two equations, the USC will be:

$$USC = Cons_{\ dom} \times P_{loss} - \frac{Cons_{dom}}{peak\ demand} \times available\ substitution\ capacity^{*}$$

The discussion above concentrated on the EEL that occurs due to loss of economic activity from sectors that use electricity as an input. As mentioned, the thesis evaluates the EEL as a loss of production and accordingly, I took the production approach for calculating the GDP. Since electricity generation can also be considered as an individual sector for the creation of GDP, the loss of electricity production as an economic activity must also be included in the model in order to have a complete overview of all the associated costs from the halt in power generation. Therefore, I include a second dimension in the model – GDP loss from electricity production as an individual economic activity; I will refer to it as GDP $Loss_{electricity}$. Instead of bringing the previously determined indicator of loss of production (LP) into the equation, I look at all available domestic production units (minus the ones that are modelled to be offline) and assume that in the case of severe supply disruption, the loss of production is substituted to the maximum extent with installed domestic controllable production capacity and import sources are used only when the domestic capacity is exhausted. Therefore, I get a measure of $P_{supply\ cut}$, which illustrates the available domestic production units in the case of supply disruption. I cannot include recoverable supply (RS) in the equation, since the measure of RS does not differentiate between domestic and international level; it looks at overall opportunities to substitute supply. Considering the GDP formation, only domestic production is relevant and thus it calls for including a measure of $P_{supply\ cut}$ to the model. Controllable production in this context refers to the facility, where the operator can without any reservations control the production of electricity. It differs from wind, wave and photovoltaic power production, since the output of these power producing facilities cannot be controlled and the output is dependent more on the weather conditions. I use a *ceteris paribus* approach for the "uncontrollable" power production ($P_{uncontrollable}$) – meaning that I anticipate the production of uncontrollable electricity to remain constant.

As the EEL illustrates the deviation from normal functioning of economy, the measure of GDP $Loss_{electricity}$ (calculated as a contribution of the electricity production sector to GDP creation in the case of supply cut) must be subtracted from the contribution of the electricity sector to GDP creation in a normal situation. I anticipate that in normal situation, the electricity production is P_{normal}; adding this level to the measure GDP $Loss_{electricity}$, gives us following equation:

$$GDP\ Loss_{Electricity} = P_{normal} - (P_{supply\ cut} + P_{uncontrollable})$$

As I measure GDP on a production basis, electricity generation should also be expressed on a final-product basis. I anticipate that even though the supply disruption could affect market prices and thus also the generated GDP by electricity sector, the GDP created from electricity production remains constant on a single unit level. This means that the measure (GDP per unit of electricity produced) is similar in the normal situation as well as in the supply cut scenario. Therefore, I must multiply the $GDP\ Loss_{Electricity}$ indicator with a constant of GDP per unit of electricity produced; the equation now takes a form of:

$$GDP\ Loss_{Electricity} = \left[P_{normal} - (P_{supply\ cut} + P_{uncontrollable})\right] \times \frac{GDP_{electricity}}{P_{normal}}$$

In this equation, $GDP_{electricity}$ accounts for a GDP that is created by electricity production. Also, since the supply cut created a significant production deficit, I assume that added domestic production units work at their full capacity during the supply cut in order to satisfy domestic demand.

Adding the dimension of electricity sector as an independent GDP component, the function of EEL is:

$$EEL = \theta \times USC + GDP\ Loss_{electricity}$$

Since the model is based on a hypothetical scenario, it incorporates a level of uncertainty. The outcome of the model is thus dependent on the data included and the rules for using the data. Even if the model uses the latest available data, the outcome could still significantly differ from reality. One of the main reasons is the significant level of generalization which is needed in order to have a common frame for the research.

The final step for concluding the model is to add a dimension of longevity to the equation – I will refer to the duration of the supply cut as "n" in the model. Since the duration is measured in days, I will bring all the data on the same basis. I acknowledge that the creation of GDP as well as electricity consumption may vary significantly seasonally, but due to the constraints of the thesis as well as limitations of available data, I will not use any seasonal adjustment coefficients to address the issue. This generalization level is also needed for the simplicity and academic integrity of the research.

After including the dimension of duration, the final form of the EEL function is as follows:

$$EEL = \left(\frac{\theta \times USC + GDP\ Loss_{electricity}}{365}\right) \times n$$

It should also be added that I anticipate other facilities to be able to work on full capacity and that there are no accidents or infrastructural, market-related or political constraints that hinder the free flow of electricity on the grid.

Limitations of the model and suggestions for further work

As already argued above, there could be significant discrepancies between outcome of the model and actual economic loss. The model cannot predict future, since the outcome of the supply cut in reality is heavily dependent on the current economic situation, improvements in the efficiency of electricity use, the GDP composition of a concrete country etc. The generalized level of the model is still able to give an indication of country's economic vulnerability to electricity supply cut in extreme situation. In the current section, the limitations of the model will be briefly streamlined and amendments and future developments of the model will be suggested in order to make it more corresponding to reality.

The most noticeable limitation is method's inability to differentiate between electricity used for economic activities and for activities which does not have a direct influence on the GDP. The problem with this issue is the data availability – it is difficult to find coherent data that gives the electricity consumption on basis of an economic sector of final consumer. More concretely, the consumption data does not differentiate between the electricity used for business- and for public services. The second problem that impedes using the more sophisticated indicator is methodological – even if it would be possible to make the differentiation between economic and non-economic activities, it is difficult to make the same distinction on a level of economic actors. In a simplistic example – if a company is using electricity for lightning the office space, it can be argued that this amount of used electricity does not directly contribute to economic activity. Therefore, there are no workable options for solving this peculiarity and the electricity consumption should still be viewed on an overall system level.

The second problem derives from the conceptually difficult nature of electricity sector: when consumption, production, supply and demand of other commodities can be measured in same units, the inherently different indicators for expressing electricity demand and consumption complicates the issue of measuring and comparing the two. The approach taken in the thesis to link the peak demand and overall consumption is quite straightforward and it does not mirror the reality to full extent. The rare occurrence of peak demand and the fact that it is mostly influenced by climatic conditions makes the relationship between economic activity and peak demand highly questionable. The model suggests that if the peak demand is not met, the overall consumption would decrease accordingly; in reality, the relationship is more complex and depending on the severity of supply cut, its duration and the period of its occurrence, the actual influence on the consumption could be extremely marginal. Since the thesis looks on the issue on an overall system level and anticipates the worst case scenario, the assumed relationship is still used. Further developments of the model should include establishing a more sophisticated indicator that would observe the electricity demand-cycle and its relation to value added economic production. An additional option is to apply different seasonal coefficients for the supply cut: since the GDP creation as well as electricity consumption could potentially be dependent on the season, it could add accuracy to the outcome of the model.

A separate problem derives from the issue of price of electricity – following free market logic supply deficit should increase the prices on market. The model does not include this dimension to the equation since I anticipate that the increased prices on market do not lead to decision by the economic agents (who use electricity as an input to their production) to stop their activities. It is assumed that the increased prices will instead lead to higher price of final product and following the main assumptions of value added production method and a *ceteris paribus* principle, the GDP value remains constant. The price issue remains relevant when considering electricity production as an individual GDP component, where the outcome of the indicator is closely connected with prices on market. In the case of current research, it remains less relevant since the prices on the market are not determined by the facilities which go offline, but rather by neighboring markets (Oja 2012). The prices on Estonian market most likely will not change so drastically as to have a major impact on the indicator. And even if so happens, the direction of the relationship between market prices and the indicator that considers electricity production as an individual GDP component remains vague and should be investigated thoroughly. Nevertheless, the addition of price dimension could be useful in a case of a different electricity system and therefore could be included in the future adaptions of the model.

Case study: testing the model in the case of Estonia

In the final core section of the thesis, I concentrate on the case of Estonia: I will put the empirical data about Estonian electricity system into the pre-developed model in order to decide its vulnerability. As already emphasized and explained earlier, I will use expected economic loss as a proxy for describing the vulnerability of the system. Before applying the model to the case, I will briefly introduce the background of the Estonian electricity system. In order to understand the plausibility of the scenario or the importance of the issue, a closer look into the functioning logic of the Estonian electricity system is useful. Next, I will turn to the indicators identified in the model; comment on their origin and novelty to the research.

The main sources for acquired data include the Statistics Estonia and Eurostat for the macroeconomic data of Estonia; Nordpool Spot and Elering for the information about the Estonian and Scandinavian electricity system and the capacities of currently intact infrastructure. Key information was obtained via a semi-structured interview with the Estonian electricity transmission system operator – Elering – official which allowed me to establish an understanding of the technical issues that relate to the case study and the Estonian electricity system.

I test the model in the case of electricity supply disruptions with two different longevities: in the first case, the supply disruption would last for 15 days. This gives an opportunity to compare the event in question with the gas supply cuts to Europe in 2009. As pointed out earlier, the incident had a particularly grave effect on the functioning of some European countries – the similar duration of the event would help to understand, how the gas supply cut that induced Christie to develop his model would relate to the functioning logic of electricity sector and its influence on Estonian economic activity. The thesis already established the intention of the insurgent terrorist forces and following the logic presented, I will add a longer dimension to the model – 60 days. As the motivation of the terrorist forces was not to gain control of the region for a long time, but instead to cause widespread socioeconomic damage to host country, the longer timeframe would serve as a potential duration of the insurgence. I also anticipate that 60 days is a too short period for the government to adequately address the supply deficit situation (e.g. the government is unable to establish new generation or transmission infrastructure).

The following chapter will first turn to all the indicators within the model. In the second part I will play out both scenarios and assess the losses of either of the two scenarios for the Estonian economy. The chapter will also include a discussion about the vulnerability of Estonian electricity system and its influence on the economy of Estonia.

Main characteristics of Estonian electricity system

Since the thesis is case-centric, the readers should be acquainted with the contextual background of the thesis in order to understand why the system is vulnerable to a regional paramilitary conflict as hypothesized. In the next section I will briefly introduce the main characteristics of the Estonian system by focusing on the power generation and transmission infrastructure, demand characteristics and Estonia's involvement in the regional Nordpool Spot electricity market.

Figure 1 summarizes the most important characteristics of the Estonian electricity system. As can be seen by analyzing the table, Estonia enjoys remarkable electricity supply security position – production of electricity has exceeded the domestic consumption by a landslide during the last 10 years. While the consumption has been increasing steadily, the production took a downward turn during the economic crisis of 2008, but soon recovered and has remained at high levels. The growing trend of import and export can be explained by the development of the regional Nordpool market – Estonia has been the transit country for electricity between Scandinavia and other Baltic states.

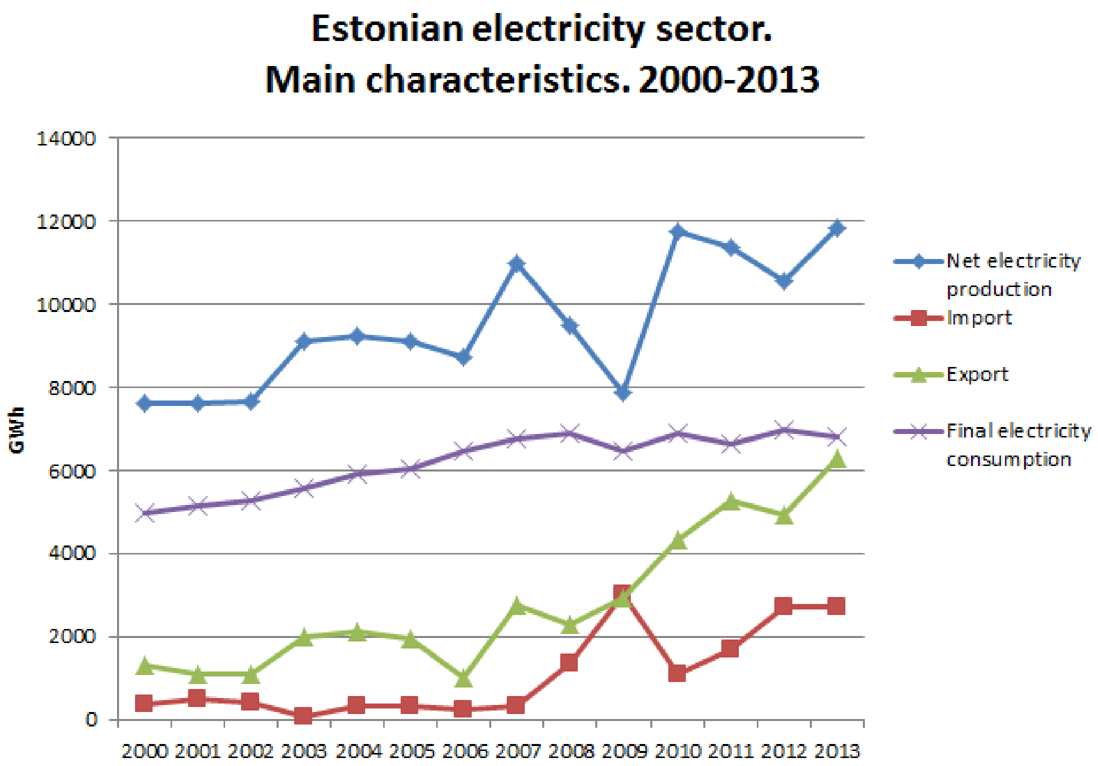

Figure 1. The main characteristics of Estonian electricity sector. *(Source: Eesti statistika 2015, Eesti statistika 2015e)*

The second important aspect of every electricity system is its ability to cope with domestic peak demand. Estonian Electricity Development Plan until 2018 framed the principle that has guided the strategic planning of Estonian electricity system. According to the “110% principle”, domestic net production (without the internal consumption of power plants), has to amount to 110% of the peak demand during winter months (Majandus- ja kommunikatsiooniministeerium, 36). This requirement in addition to the substantial physically available interconnection capacity[8] with neighboring countries, gives the Estonian system a substantial supply security during the peak demand. Figure 2 illustrates the fluctuations of Estonian peak demand and the applicability of the 110% rule.

[8] Interconnectors with Finland – Estlink 1 and 2 – have a combined capacity of 1000 MW (accordingly 350 MW and 650 MW) (Elering 2015); Estonia-Latvia connection capacity is 879 MW (Elering 2014, 9). Though Estonia-Russia has an interconnection with a capacity of 950 MW, there is no physical electricity trade between the two countries and therefore the capacity is considered to be 0 (Energiatalgud, 2015b)

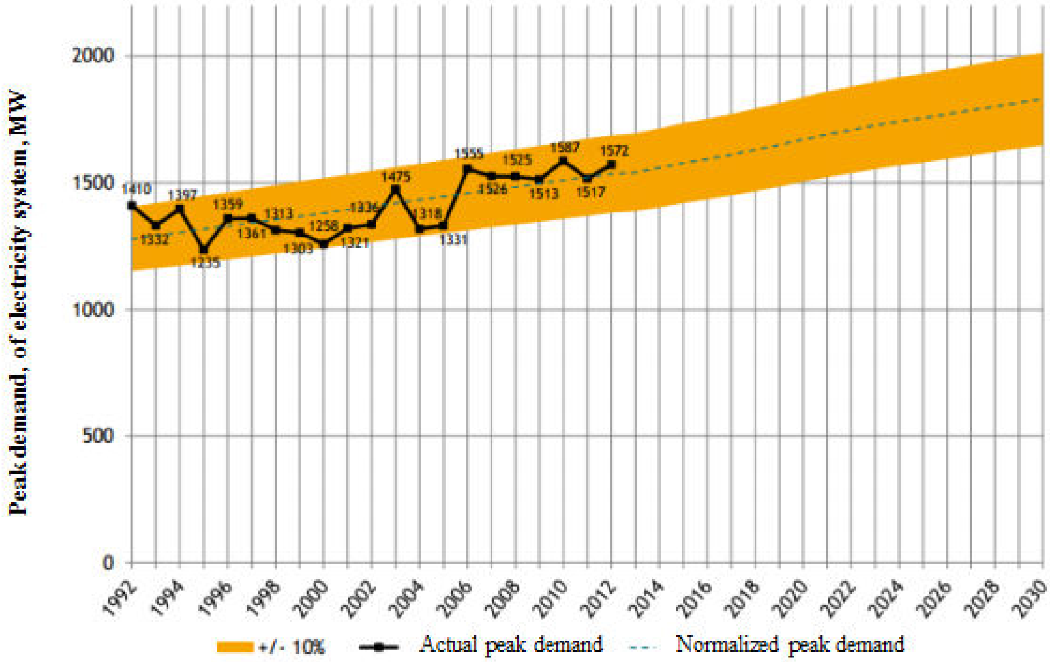

Figure 2. Peak demand of Estonian electricity system. *(Source: ENMAK 2030+, 33)*

Figure 2 shows that in order to cope with the 110% rule, Estonian grid operator has had to ensure the domestic electricity generation capacity of around 1600 MW. The actual installed capacity has surpassed the level substantially – in 2013, the installed net capacity of the electricity system was 2739 MW and available capacity during the peak demand was 2071 MW (Elering 2013, 4).

Due to the data peculiarities, which only distinguishes between electricity, produced from different sources and does not collect statistics on single plant level I cannot use the official and publicly available data about the actual production numbers of concrete power plants. The statistics differentiate between electricity produced from different sources (e.g. wind, hydro, oil shale, coal, gas, biogas etc.) and according to the official information, in recent years, over 80% of Estonian electricity production comes from using oil shale (Eesti statistika 2015b). Oil shale is used only in 2 power plants – Eesti power plant (with installed capacity of 1369 MW) and Balti power plant (612 MW) (Energiatalgud, 2015). So it can be deducted that at least 80% of the overall power production originates from these two power plants. This number does not reflect the reality to full extent, since these power plants also use additional fuels to produce electricity. Therefore, the actual estimated number of the electricity produced by the two power plants is around 90% (*Ibid.*, Eesti Energia 2015).

Final important aspect for the scope of the research is the geographic positioning of the electricity generation capacity in Estonia. Since I anticipate an "Ukrainesque" scenario to take place in Estonia, the location of the power plants is an important factor for justifying the plausibility of the hypothetical scenario. The actual location of the two major plants – Eesti power plant and Balti power plant – is pointed out with red dots on figure 3. As can be seen, both major power plants are located just next to the border with Russia and they are situated just 15 km from each other. Therefore, there is a strong reason to anticipate that in the case of a regional paramilitary conflict, the strategic nature of power stations makes them a primary target for the insurgent forces.

Figure 3. Map of Ida-Virumaa and the location of the two power stations. *(Source: Delfi 2015)*

The values for the used indicators

The current section concentrates on the indicators within the model: I will point out the concrete values for each indicator in the case of Estonia. In addition, I provide the necessary background to explain where I gathered the information, how I processed the data and what amendments and assumptions I had to make for the data to be useable for the model as well as for the issue under question.

The first variable that the model includes is electricity intensity (θ). Data about the electricity consumption as well as economic output is easily accessible from the national statistics agency website. I used the measure of GDP at current prices as a proxy for describing economic output. There are a number of options for expressing the GDP and the problem with chosen method is its inability to effectively compare the measure in time. It does not consider the purchasing power, nor is it anchored to a benchmark year in order to address the issue of inflation. Since neither of the two is relevant in the current context, I can exclude the more sophisticated methods and use the measure of GDP at current prices. Additionally, there is a particular reason why it is necessary to use the current market prices method: later in the chapter, I include an indicator for electricity production as an individual GDP component to the model. The data about this indicator is only available on the basis of a current year; therefore, I also use the similar data about the overall GDP – it gives us the compatibility between the two indicators. I use the net inland final electricity consumption in the model; the measure excludes the internal electricity consumption of power plants. As pointed out above, the peak demand measure is linked with the peak consumption of the electricity end-users. Thus there is a concrete established relationship between the net final consumption and peak demand and I will use this in the model. Secondly, as the electricity used in power plants does not relate to the creation of final product by the end-users who use the electricity as a production input, the amount of this type of electricity is also irrelevant for the indicator.

I use the latest available data for the two indicators but since I apply the model on a concrete calendar year, an important aspect is also using data from the same year for all the indicators. The latest available data about the Estonian electricity consumption is of

2013. Therefore, 2013 serves as a basis for all the used data[9]. In 2013, Estonian GDP amounted to 18 739 million EUR (GDP) on current prices (Eesti statistika 2015d) and final electricity consumption was 6802 GWh ($Cons_{dom}$) (Eesti statistika 2015e).

The second individual variable is unrecoverable supply measure (USC). Determining this indicator is significantly more challenging than the previous indicator and it requires a more in-depth look into the electricity system. I will look step-by-step on all the sub-indicators and their interaction in order to generate a concrete measure for the USC.

First, I will determine the gravity of a supply cut for the Estonian electricity system. As the model suggests, I have to find measures for the two distinct factors – electricity consumption and level of production from the Eesti and Balti power plants – and multiply them for calculating the supply loss. Again, I use the measure of net final inland electricity consumption. Unfortunately, there is no reliable official data that differentiates electricity production on a power plant basis; I instead ground the indicator on secondary information. This gives the indicator lower precision, since the secondary data has a more generalized level of information on the actual production from the two power plants that are modelled to suffer from paramilitary conflict as hypothesized. I have introduced the domestic consumption measure ($Cons_{dom}$ – 6802 GWh); the second indicator illustrates the lost production (P_{loss}) and is measured as the percentage of inland electricity production generated in Eesti and Balti power stations. As already pointed out in the previous section of the thesis, it is estimated that around 90% of Estonian electricity production comes from these two plants.

For calculating the recoverable supply (RS) measure, I must first determine the reduction effect on inland end-user consumption if the peak demand is not met by available generation and transmission capacity. It should be noted that the measure "peak demand" is extremely volatile and the concrete peak demand for a year is dependent on many factors, most importantly, on climatic conditions. But as the thesis

[9] When considering the electricity infrastructure, I look at the current situation and not 2013. It should be noted that the outcome of the research could change immensely, if instead I would have looked at the situation of 2013. Since then, a new key infrastructure object, an interconnector Estlink 2 has been opened. It has the capacity of 650 MW, which changed the *status quo* on the electricity market and security situation for Estonian electricity sector significantly.

established a direct link between the peak demand and final energy consumption, I have to look at actual data for a concrete year. Since the basis for other data is 2013, I use the same year for peak demand measure. The peak demand in 2013 occurred during winter months and was at 1510 MW (Elering 2014, 4).

The second step for establishing the measure of recoverable supply calls for a look into the available capacity of production and transmission infrastructure. Additionally, the production and consumption characteristics of neighboring countries must be considered. First, I turn to additional domestic production capacities: as Elering (2014) have observed, there are 605 MW of available controllable domestic production capacities excluding Eesti Elektrijaam and Balti Elektrijaam, which in my scenario are modelled to be offline (Elering 2014:6).

While considering the availability of import capacities, the research also has to include the actual production capacity and domestic consumption of other countries. The current situation in Finland perfectly illustrates the case: though Estonia has a 1000 MW of transmission capacity with Finland, the latter operates in energy deficit (e.g. cannot satisfy its peak demand with domestic production). According to Elering (2014), Finland has a peak demand of 13600 MW, of which it can supply 12710 MW with domestic production (*Ibid.* 7). As the scenario considers the "worst case scenario", Finland is unable to supply Estonia if the peak demand occurs simultaneously on both countries and Estonia works in a production deficit. I should then look at other linked markets. Sweden has a supply surplus of 4700 MW during the peak demand and therefore is able to export its excessive production to the countries which does not have sufficient available domestic production capacity (*Ibid.* 7). Finland and Sweden have two transmission lines with combined import capacity of 2700 MW to Finland (Elering 2014: 9). As can be seen, the import capacity from Sweden can satisfy the deficit of Finland (890 MW) as well as contribute to meeting the peak demand of Estonia in a supply cut situation. Therefore I can add 1000 MW as an available substitution capacity for Estonia originating from Finland.

Additionally, Estonia is able to import electricity from Latvia – an interconnection with import capacity of 879 MW could potentially transfer the excessive production (500 MW from Latvia and 480 MW from Lithuania) to Estonia (Elering 2014). Therefore, while considering all the available substitution opportunities, it can be concluded that due to the extensive import capacities and the fact that the neighboring markets are not working in a supply deficit, Estonia can cover most of its electricity demand with imported electricity. While also taking into account the domestic production capacity, I argue that recoverable supply for Estonia exceeds the peak demand. The restriction for the recoverable supply indicator dictates that in this case, I will use the peak demand (1510 MW) as a measure for expressing recoverable supply.

As pointed out in the previous chapter, not only nominal import and production capacities are needed in order to determine unrecoverable supply, a closer look into the system characteristics is also needed. One of the most important problems for an electricity system which loses a significant amount of its production is the system's ability to maintain tension in the grid. The discussion on this particular issue is too technical for the current study and falls out from the competences of the author and instead of exhaustively working through relevant literature on the engineering-side of electricity grid, I conducted a semi-structured interview with an expert on the field to understand the technical issues accompanying the supply cut. Erkki Sapp, energy market analyst from Estonian electricity system operator Elering confirmed that even though the reliability of the Estonian electricity system would suffer in the hypothesized case (e.g. the extreme weather events as well as other emergencies could have a more severe effect on the electricity supply), the grid is *ceteris paribus* still able to satisfy the domestic peak demand and keep the needed tension in the grid (Sapp, 2015).

The third variable that I included in the model uses the electricity production as an individual GDP component. I used data about the added value in electricity production as a proxy for illustrating the measure. The approach where added value is used for expressing the GDP is a common option used extensively in literature. The approach not only gives an opportunity to track the overall performance of the whole economy, but also provides data for the analysis of the productivity of each economic activity and changes in the structure of the economy (Quang Viet 2009: 6).

The first determined indicator is electricity production in normal situation (P_{normal}). I use the data about overall electricity production in the reference year 2013. I excluded the electricity produced for internal use of power stations, since I anticipate that it does not contribute to value added production. The reason being that most probably the electricity used within the company is not sold on market, but rather used in a facility without any direct influence on GDP. The used measure is therefore net electricity production, which amounted to 11823 GWh in 2013 (Eesti statistika 2015). As established in the previous chapter, I consider the uncontrollable electricity production to remain constant – e.g. in the presence of a supply cut, Estonia is unable to artificially enhance the production of wind, photovoltaic and hydro power. In order to determine the production from these uncontrollable electricity sources ($P_{uncontrollable}$), I combine two distinct measures (electricity from wind and from hydro power plants). I exclude the measure of photovoltaic electricity production for two reasons: firstly, the Statistics Agency does not measure independently the production of photovoltaic power; secondly, the capacity has remained virtually nondescript[10] and therefore does not have a significant effect on the outcome of the model. The combined production of hydro and wind power amounted to 555 GWh in 2013 (*Ibid.*); this serves as a measure of $P_{uncontrollable}$ for the model.

The third sub-measure illustrates the electricity production in the presence of supply cut. I assumed that the lost electricity supply is to maximum extent substituted with additional available domestic production capacities, which in Estonia's case amounts to 605 MW. During the supply cut, the domestic facilities are anticipated to work at full capacity throughout the crisis. It should also be noted that while deciding the measure of $P_{supply\ cut}$, I assume these facilities to work throughout the year (since the measure is on year-basis); in reality, the emergency power station in Kiisa (250 MW) could not be able to work for such an extensive period, since it is designed to work only in the case of emergency (Elering 2014: 6). Later, when I use the temporal factor in the model, this limitation is singled out: the duration of the two time periods under consideration in this thesis is not so extensive as to have a major impact on the functioning of the Kiisa facility. Keeping in mind the assumption of maximum exhaustion of domestic production facilities, I find the total domestic production by multiplying the production capacity with 365 (days) times 24 (hours). Given the assumptions, the gross domestic production during the peak demand is 5300 GWh ($P_{supply\ cut}$).

[10] To illustrate the small capacity of Estonian photovoltaic installations, the combined production of these was around 0,1 GWh during the first 3 months of 2014 (Kuul 2015).

Finally, I will find the generated GDP from electricity production and apply it on a GWh basis. For deciding this measure, I use the data of electricity production and value added from electricity production from 2013. P_{normal} was already pointed out; $GDP_{electricity}$ as a measure for expressing the volume that electricity production contributed to GDP was 216 million EUR (Eesti statistika 2015c).

Expected economic loss in the case of supply disruption

In the previous section, I presented the data needed for testing the model; in the current section, I will complete the model and calculate the losses that would occur with the electricity supply cut. I will apply the model for two different time periods: explanations for choosing 15 days and 60 days as the temporal factors were presented in previous parts of the thesis.

In order to ensure transparency and to better acquaint readers with the calculating mechanisms of the model, I will calculate all the indicators individually and then apply the temporal factors to calculate the overall economic loss

First variable in the model is the level of electricity intensity of the economy (θ).

$$\theta = \frac{Cons_{dom}}{GDP} = \frac{6802\ GWh}{18739\ EUR_{million}} = 0{,}363\ \mathrm{GWh}/EUR_{million}$$

The measure reveals that 0,363 GWh of electricity contributes to generating 1 million EUR of gross domestic product. Deriving from this, I calculated that using 1 GWh of electricity generates 2,75 million EUR worth of GDP in the form of final product. To test the relationship, I also looked at the electricity consumption/GDP ratios of previous years and though the indicator fluctuates and has shown a downward trend (indicating that Estonian economy has become less electricity-intensive) it still falls within the same general gap (between 0,36-0,47 in 2006-2013). It would require an additional regression analysis to fully understand the significance of the relationship between the two indicators, but since this falls out of the scope of the current research, an inquiry into this subject will not be pursued.

The second variable needs a more careful management – a number of sub-indicators must be calculated before it is possible estimate the level of unrecoverable supply cut (USC). USC consisted of two indicators – loss of production (LP) and recoverable supply (RS); the first step is to calculate the LP

When calculating the loss of production (LP), I multiply the 2013 net inland final electricity consumption of 6802 GWh with the percentage of inland electricity production generated at Eesti and Balti power stations; the latter indicator has a scale of 0≤1 in the model (since the indicator is measured in percentages).

$$LP = Cons_{dom} \times P_{loss} = 6802\ GWh \times 0{,}9 = 6122\ GWh$$

The recoverable supply (RS) measure indicates how much of the 6122 GWh of lost production could be substituted. As I introduced the values for used indicators in the previous chapter, I can now put the data into the model.

$$RS = \frac{Cons_{dom}}{peak\ demand} \times available\ substitution\ capacity^{*} =$$
$$= \frac{6802 GWh}{1510\ MW} \times 1510\ MW = 6802\ GWh$$

Since I established and justified the used limit which prescribes that available substitution capacity is always considered only in a capacity to satisfy the peak demand, the two measures single each other out and can be deleted in the case of Estonia. The measure of RS shows that Estonia can cover its peak demand and ensure supply for domestic consumers even if the two power plants are not able to generate electricity.

Unrecoverable supply cut (USC) as a second major indicator within the model is calculated as a difference between the loss of production and recoverable supply:

$$USC = LP - RS = 6122\ GWh - 6802\ GWh = -680\ GWh$$

Since I applied a limitation to this indicator, in order to exclude the possible unrealistic outcomes for the overall model, the USC measure used in the model is 0 GWh.

The last major indicator in the model expresses the contribution of the electricity production as an independent sector to the overall GDP. For calculating it, a following equation must be solved:

$$GDP\ Loss_{Electricity} = \left[P_{normal} - (P_{supply\ cut} + P_{uncontrollable})\right] \times \frac{GDP_{electricity}}{P_{normal}} =$$

$$= [11823\ GWh - (5300\ GWh + 555\ GWh)] \times \frac{216\ 000\ 000\ EUR}{11823\ GWh} =$$

$$= 5968\ GWh \times 18269 \frac{EUR}{GWh} = 109\ 032\ 225\ EUR$$

From the calculation above, I can conclude, that if the supply cut would last for a whole calendar year, the economic loss for Estonia from only the decreased electricity production would be around 110 million EUR.

For finalizing the model, I will now add the temporal factor in order to find the economic losses for Estonia in the presence of supply cut with different durability. In the first scenario, I use 15 days as longevity of a supply cut. The intension behind this is to make a comparison between the hypothesized event and a gas supply cut to Europe that happened in reality in 2009.

$$EEL = \left(\frac{\theta \times USC + GDP\ Loss_{electricity}}{365}\right) \times n =$$

$$= \left(\frac{0{,}363 \frac{\text{GWh}}{EUR_{million}} \times 0\ GWh + 109\ 032\ 225\ EUR}{365}\right) \times 15 =$$

$$= \frac{109\ 032\ 225\ EUR}{365} \times 15 = 4\ 480\ 776\ EUR$$

In the case of a short supply cut as hypothesized in the current thesis, the economic losses for Estonia remain nondescript; the 4,5 million EUR as a direct influence on the GDP creation is a marginal amount compared to 770 million EUR of estimated total GDP created during the 15-day supply cut.

The second time span considered in the case study is 60 days: the longer period should reflect a situation, where due to the ongoing conflict; the facilities are offline and

Estonia is facing a longer supply cut. 60 days should reflect a time period, which is too short for the government to adequately act on the issue (e.g. to implement new measures and infrastructure for meeting the domestic demand).

$$EEL = \left(\frac{\theta \times USC + GDP\ Loss_{electricity}}{365}\right) \times n =$$

$$= \left(\frac{0{,}363 \frac{\text{GWh}}{EUR_{million}} \times 0\ GWh + 109\ 032\ 225\ EUR}{365}\right) \times 60 =$$

$$= \frac{109\ 032\ 225\ EUR}{365} \times 60 = 17\ 923\ 105\ EUR$$

Again, the virtually nonexistent loss for Estonian economy proves that according to the premises of this model and empirical information obtained about the functioning of the electricity system, Estonian system is resilient against the supply cut induced by a paramilitary conflict in Ida-Virumaa.

Discussion

The model reveals that Estonian electricity system is well-protected against the supply cut – the economic losses would be limited only to decreased domestic electricity production and the sector's individual contribution to overall GDP creation. Estonian system is able to satisfy the demand of its residents even if the two biggest power plants are offline for a longer period. This is due to the improvements in the electricity transmission infrastructure as well as recent additions to domestic production capacity. It is important to note, that even though the Estonian electricity system is more vulnerable to power outages deriving from other unexpected events (weather- or emergency-related issues) during the hypothetical event, the system can maintain the needed tension in the grid. If the research would have been conducted a few years earlier, when the extensive transmission infrastructure did not exist, the outcome of the research would have been extremely different.

Considering the discussion above and findings from the model, the straightforward answer to the proposed research question would be that economic losses for Estonia are virtually nonexistent in the case of paramilitary conflict in Ida-Virumaa which results in a supply halt from Eesti and Balti power stations. The economic losses of 5 million EUR and 17 million EUR deriving from supply cuts with duration of 15 and 60 days accordingly is a proof of the low level of economic vulnerability that threatens Estonia in the case of the hypothetical event.

Bringing the discussion on a political level, the situation where Estonia is in deep domestic production deficit is definitely alarming. In this situation, neighboring countries are guarantors of Estonian electricity supply and if any of the import transmission lines or the power production unit on neighboring markets goes offline, the Estonian economy would face a real deficit of electricity and the government is forced to limit electricity supply for end-users. Moreover, since the reliability of the domestic transmission grid would suffer in the case where Eesti and Balti plants are offline, the problems with meeting the domestic demand could become significant, if the hypothetical event coincides with extreme weather conditions. If the latter results in damaged transmission grid, it would harm the integrity of the Estonian electricity system as a whole. Therefore, the hypothetical event *per se* does not result in a noticeable supply disruption; if it coincides with other infrastructure malfunction or with an extreme weather conditions, the consequences could be extremely dire.

Given the premises of current thesis and the approach taken to assess the economic losses, the vulnerability of Estonian electricity system remains low. It should still be carefully considered by the policy-makers, whether the extreme concentration of Estonian power production capacities to Ida-Virumaa is a threat for the functioning of domestic economy.

Conclusion

The intention of the thesis was to assess the vulnerability of Estonian electricity system in a hypothetical situation where the two biggest power plants (Eesti and Balti elektrijaam), which are located near the border with Russia, would suffer from a regional paramilitary conflict. I anticipated that an insurgent military force, whose intention is to cause maximum socioeconomic problems for Estonia blocks the electricity production from the two power plants leaving the Estonian electricity system in a significant supply deficit situation. A Russian-backed military confrontation taking place in the region remains as a plausible scenario considering the growing tensions between Russia and NATO. In this sense the current Ukrainian conflict serves as a justification for the plausibility of the scenario as well as it illustrates the probable tactics to be used by an insurgent force.

One of the main assumptions within the thesis suggested that due to the extreme importance to the welfare of the country and its residents, a government should ensure the electricity supply even during the worst case scenario. I therefore follow the logic of the critical infrastructure literature which also emphasizes the need to protect the integrity of critically important infrastructure systems and objects. Since there are numerous risks that the energy system faces, the aim of the government should be to minimize the vulnerability of the electricity system.

In the theoretical part of the thesis, a concept of vulnerability was first developed. As the bulk of the literature connected vulnerability to system's ability to cope with unexpected events, the thesis also followed the same general idea. It is apparent that the considered scenario suits into the framework of vulnerability – the military attack is definitely an adverse event with huge implications on the functioning of the system. While the concept of vulnerability is quite straightforward, deciding how to assess the vulnerability of the electricity system is very context-related issue. Since the aim of the thesis was to look at the influence of electricity supply cut to the overall economic performance of a country, the relationship between economic losses and vulnerability was assumed and expected economic loss used as a proxy for vulnerability. After introducing the relevant literature and different options for measuring vulnerability, I concluded that there are a few previous studies that have linked the economic and vulnerability dimensions and measured it with quantitative tools.

The research question of the thesis looked to quantify the losses for the Estonian economy in the event where the two power stations are unable to operate and produce electricity. The chosen method called for developing a concrete mathematical function model that would link all the relevant variables in order to find the losses on the monetary level. The model was built on the suggested general model of Edward Christie (2009). Since Christie looked at the natural gas system and developed a model to assess its vulnerability to foreign supply cuts, I had to make some critical amendments to his model in order to make it applicable to electricity system and the intention of the thesis to look at the inherent vulnerability of system and exclude the international dimension. The purpose-built model for the chosen case included three distinct variables – electricity intensity of economy, unrecoverable supply cost and electricity production as an individual GDP component. The model considers the functioning logic of electricity market by including the level of buffers that compensate the supply deficit: interconnectors to neighboring markets and additional domestic production are taken into account while calculating the unrecoverable supply cut. An additional dimension reckons the electricity production as an individual GDP component to help mirror the reality more accurately.

As it was the first effort to quantify the economic losses in the presence of a supply cut, I do not deny the deficiencies of the model. Future work on the model should most importantly include a better method for accounting the relationship between the electricity consumption of end-users and available supply capacity. Also, seasonal coefficients could be used to account for the seasonal difference of electricity consumption as well as GDP creation. A dimension of electricity market prices could also help to refine the model, but since it includes a whole new level of prognosis, adding this dimension should be carefully considered and methodologically justified.

After testing the model for the hypothetical scenario, the thesis concludes that the economic losses for Estonia would remain nondescript thus implying the low level of vulnerability of the Estonian electricity system given the premises of the research. Due to the recent additions to electricity transmission infrastructure as well as domestic production capacity, the system is able to satisfy the end-user demand at all times. Thus there are no limitations for economic production that use electricity as an input and given the chosen production approach of calculating GDP, there are no losses for the national economy. Only marginal losses arise from the variable of electricity production as an individual GDP component, but since these account for an imperceptible part of the overall GDP, I can make an argument that virtually no losses would emerge for Estonian economy in the occurrence of an electricity supply cut which is caused by a military conflict in Ida-Virumaa.

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