An interdisciplinary assessment of energy security risks in the Finnish energy market

Jaakko J. Jääskeläinen
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A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at the lecture hall E of the Undergraduate Centre (Otakaari 1) on 22 March 2019 at 12:15.

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Abstract

Climate change is currently one of the most compelling global threats, and energy sector accounts for almost two thirds of all emissions related to the climate change. Therefore, national energy systems face conflicting pressure to supply the ever-increasing demand for energy while decarbonising energy production. Under this pressure, concern over energy security has increased. The most topical energy security concerns in the Finnish energy market are generation adequacy and import dependence. This dissertation examines these themes along with other market-related energy security risks in the Finnish context.

This dissertation analyses energy security in the Finnish energy system by examining various scenarios in investment, the future of combined heat and power (CHP) production, the impacts of a severe drought, and import dependence. The research is done in collaboration with multiple researchers from other disciplines such as law and environmental and political sciences.

Generation adequacy in the Finnish energy system is analysed by using the EnergyPLAN simulation tool. The impacts of a severe drought on the Finnish energy system are analysed by combining hydrological and energy system modelling. Generation capacity investment prospects, particularly those of biomass-based CHP production, are analysed by applying the net present value (NPV) and levelised cost of electricity (LCOE) methods. Energy security issues related to a plausible decrease in the Finnish CHP capacity are analysed on a city-level (Helsinki) by applying quantitative modelling, and on national and international levels, by qualitative assessment.

Finland’s dependence on Russian energy import currently is analysed by applying the interdependence framework, and the future development of the energy-trade is studied by developing and analysing energy policy scenarios until 2040.

The results indicate that the Finnish energy system is currently well prepared against technical faults. Despite the public concern, challenges with generation adequacy due to technical reasons are improbable. A severe, multiyear drought in the Nordic area could affect generation adequacy in Finland particularly via reduced availability of electricity import during peak demand periods. Despite the high thermal efficiency of CHP production, the Finnish energy system would most probably function even if the capacity decreased notably in the 2020s. Finland’s notable import dependence on Russian energy import has so far not resulted in any disruptions in security of supply, and the dependence is likely to decrease in the future. However, energy trade between the countries goes beyond techno-economic aspects, and it is difficult to predict the energy security implications of geopolitical and societal trends.

Keywords energy security, energy system analysis, generation adequacy, import dependence

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P.s. Thanks for the neat cover photo, bro

Valencia, 14 October 2018
Jaakko Juhana Jääskeläinen
Table of Contents

Acknowledgements................................................................................... i
Table of Contents.................................................................................... iii
List of Abbreviations and Symbols.......................................................... v
List of Publications................................................................................ vii
Author’s Contribution........................................................................... viii
1. Introduction................................................................................... 1
   1.1 Background.............................................................................. 1
   1.2 Scope and structure ............................................................... 2
   1.3 Novelty of the dissertation ..................................................... 4
2. Literature review .......................................................................... 5
   2.1 Energy security ...................................................................... 5
   2.2 The Finnish energy system .................................................... 7
      2.2.1 Demand ........................................................................... 7
      2.2.2 Supply ........................................................................... 8
      2.2.3 The record-high demand peak ....................................... 10
      2.2.4 System reserves ............................................................... 11
      2.2.5 Finnish energy strategy and energy policy goals .......... 13
3. Methods and Materials ................................................................ 15
   3.1 Energy system simulations .................................................... 15
      3.1.1 The stress test................................................................. 16
      3.1.2 Scenario analysis ............................................................ 17
      3.1.3 Limitations of the energy system simulations .............. 18
   3.2 Investment profitability analysis ........................................... 19
      3.2.1 Weighted average cost of capital ................................... 20
   3.3 Materials and data ................................................................. 21
4. Results ........................................................................................ 23
   4.1 Generation adequacy ............................................................... 23
      4.1.1 Generation adequacy in the current system ................... 24
      4.1.2 Generation adequacy in the future................................. 26
# List of Abbreviations and Symbols

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>aFRR</td>
<td>automatic frequency restoration reserve</td>
</tr>
<tr>
<td>CAPEX</td>
<td>capital expenditures</td>
</tr>
<tr>
<td>CDA</td>
<td>capacity delivery agreement</td>
</tr>
<tr>
<td>CHP</td>
<td>combined heat and power</td>
</tr>
<tr>
<td>CRP</td>
<td>country risk premium</td>
</tr>
<tr>
<td>DM</td>
<td>debt margin</td>
</tr>
<tr>
<td>EBIT</td>
<td>earnings before interest and taxes</td>
</tr>
<tr>
<td>EC</td>
<td>European Commission</td>
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<tr>
<td>ENTSO-E</td>
<td>European Network of Transmission System Operators for Electricity</td>
</tr>
<tr>
<td>EU</td>
<td>the European Union</td>
</tr>
<tr>
<td>EUA</td>
<td>European emission allowances</td>
</tr>
<tr>
<td>EUE</td>
<td>expected unserved energy</td>
</tr>
<tr>
<td>FCF</td>
<td>free cash flow</td>
</tr>
<tr>
<td>FCR-D</td>
<td>frequency containment reserve for disturbances</td>
</tr>
<tr>
<td>FCR-N</td>
<td>frequency containment reserve for normal operation</td>
</tr>
<tr>
<td>FiT</td>
<td>feed-in tariff</td>
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<tr>
<td>GHG</td>
<td>greenhouse gas</td>
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<tr>
<td>HOB</td>
<td>heat only boiler</td>
</tr>
<tr>
<td>IRENA</td>
<td>International Renewable Energy Agency</td>
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<tr>
<td>LCOE</td>
<td>levelised cost of electricity</td>
</tr>
<tr>
<td>LNG</td>
<td>liquefied natural gas</td>
</tr>
<tr>
<td>mFRR</td>
<td>manual frequency restoration reserve</td>
</tr>
<tr>
<td>MRP</td>
<td>market risk premium</td>
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</tbody>
</table>
NESA  the Finnish National Emergency Supply Agency
NPV  net present value
OPEX  operational expenditures
PV  photovoltaic
RES  renewable energy source
SG  steam generator
TSO  transmission system operator
VOLL  value of lost load
VRE  variable renewable energy
WACC  weighted average cost of capital

$\beta_A$  beta coefficient for asset
$\beta_E$  beta coefficient for equity
$C_T$  costs in year T
$E_T$  electricity production in year T
$n$  estimated time span of an investment
$R_D$  required return on debt
$R_E$  required return on equity
$R_F$  risk-free rate
$T$  time in years
$t_c$  corporate tax rate
$x_D$  proportion of debt
$x_E$  proportion of equity
List of Publications

This doctoral dissertation consists of a summary and of the following publications, which are referred to in the text by their numerals:

I. Jääskeläinen, Jaakko; Zakeri, Behnam; Syri, Sanna. Adequacy of Power Capacity during Winter Peaks in Finland. IEEE Xplore, 14th International Conference on the European Energy Market (EEM), Dresden, 6–9 June 2017. DOI: 10.1109/EEM.2017.7981883.


VI. Jääskeläinen, Jaakko; Höysniemi, Sakari; Syri, Sanna; Tynkkynen, Veli-Pekka. Finland’s Dependence on Russian Energy – Mutually Beneficial Trade Relations or an Energy Security Threat?. MDPI. Sustainability 2018, Volume 10 Issue 10, 3445. DOI: 10.3390/su10103445.
Author’s Contribution

Publication I: Adequacy of Power Capacity during Winter Peaks in Finland

Jaakko Jääskeläinen prepared the EnergyPLAN model for Finland with the help of Behnam Zakeri, prepared the input data, conducted the simulations, and wrote the manuscript with reviews and comments from Sanna Syri and Behnam Zakeri.

Publication II: Trouble Ahead? An Interdisciplinary Analysis of Generation Adequacy in the Finnish Electricity Market

Jaakko Jääskeläinen developed the EnergyPLAN model for Finland, prepared the input data, and conducted the energy system simulations and the investment profitability analysis. Kaisa Huhta conducted the legal analysis. The authors planned the work and wrote the manuscript together.

Publication III: Energy security impacts of a severe drought on the future Finnish energy system

Jaakko Jääskeläinen developed the EnergyPLAN model for Finland using the hydrological data provided by Noora Veijalainen as input and carried out the energy system simulations and energy system analysis. Noora Veijalainen conducted the hydrological analysis and simulations and Mika Marttunen assessed the environmental impacts of the drought. Jaakko Jääskeläinen, Noora Veijalainen and Mika Marttunen wrote the manuscript, with guidance, reviews and comments from Sanna Syri and Behnam Zakeri.

Publication IV: Ensuring Generation Adequacy in Finland with Smart Energy Policy – How to save Finnish CHP production?

Jaakko Jääskeläinen prepared the data for the investment profitability analysis with Jenny Lehtomäki and conducted the investment profitability analysis. Kaisa Huhta conducted the legal analysis. Jaakko Jääskeläinen and Kaisa Huhta planned the scope of the work and wrote the manuscript.
Publication V: Energy Security Impacts of Decreasing CHP Capacity in Finland

Kristo Helin and Jaakko Jääskeläinen planned and wrote the manuscript together. Kristo Helin wrote Sections I and III, and Jaakko Jääskeläinen wrote Sections II and IV. Section V and editing were done in collaboration between the two. Kristo Helin performed the related modelling work. Sanna Syri commented on the manuscript. All authors were involved in the planning and clarification of the scope of the work.

Publication VI: Finland’s dependence on Russian energy – mutually beneficial trade relations or an energy security threat?

Jaakko Jääskeläinen carried out the analysis on the technological and economic aspects of the Finnish-Russian energy trade and sketched the development of the energy trade in the future scenarios. Sakari Höysniemi conducted the literature review on energy security, analysis on the political aspects of energy trade and the analysis on Russia’s energy strategy. All authors participated in planning of the scope. Jaakko Jääskeläinen and Sakari Höysniemi wrote the manuscript with guidance, comments and reviews from Veli-Pekka Tynkkynen and Sanna Syri.
1. Introduction

1.1 Background

Climate change is one of the most compelling global threats in the modern era due to the severity and ambiguity related to its future impacts [1]. Moreover, there have been evident challenges in finding a global consensus with regard to the measures to address climate change mitigation. Global energy consumption accounts for up to two thirds of all the greenhouse gases (GHG) related to the accelerating climate change [2]. Consequently, the energy sector is under great pressure to be decarbonised in the decades to come. This has launched a so-called energy transition in the 2010s, i.e. a pathway towards a decarbonised energy system by 2050 from the current fossil-based one. The transition has comprised inter alia an exponential penetration of variable renewable energy (VRE), such as wind and solar energy.

However, in addition to decarbonisation and supplying the rapidly increasing demand for energy particularly in the developing countries, energy systems comprise a variety of other essential factors to be monitored. Issues such as system balance, self-sufficiency, system costs and generation adequacy\(^1\) are equally important for national economies. Furthermore, the energy transition has brought challenges of its own. All these dimensions together with the underlying issues of decarbonisation and supplying the increasing global demand for energy are attributes of energy security. Energy security is hence a complex and multidimensional concept that is characterised by various trade-offs. That is, apart from increasing energy efficiency, improving one dimension typically comes with a cost in another dimension. For example, improving the system resilience through additional reserves increases system costs, and reducing emissions and import dependence via VRE production can undermine the system balance.

The European Union (EU) imports more than half of its consumed energy [3]. Consequently, the European Commission (EC) has set energy security as one of its key targets. In response to the European gas supply concerns in 2006 and 2009, the EC released an Energy Security Strategy in May 2014 [4]. In order to improve energy security in Europe, the strategy proposes inter alia increasing energy efficiency and energy production within the Member States, development of an integrated European energy market, speaking with one voice.

\(^1\) Generation adequacy refers to the ability of the totality of generating units to meet demand at all times.
in external energy policy, and reducing the dependence on one supplier, particularly on Russia [4].

In terms of energy security, Finland is an interesting country. Energy consumption per capita in Finland is among the highest in the world [5] and, apart from peat\(^2\), the country holds practically no fossil fuel reserves of its own. Thus, Finland is strongly dependent on energy import – both primary energy and electricity particularly during demand peaks. Furthermore, a majority of the import originates in Finland’s neighbour in east, Russia. In line with the new Energy and Climate Strategy of Finland [8], Finland hence faces pressure to decarbonise its energy sector, improve its self-sufficiency in energy while advancing the European energy market integration, and to maintain the level of system costs and security of supply reasonable through the transition. This dissertation aims at recognising and analysing the current and foreseeable energy security issues in Finland in this context.

1.2 Scope and structure

This dissertation analyses energy security in the Finnish energy system. The focus is on phenomena related to Finland’s current and future energy system, particularly in electricity and heating markets, and the system’s ability to supply the demand for energy under different circumstances. The research presented attempts to address the following research questions:

Q1. What are the most relevant current and foreseeable market-related energy security threats in the Finnish energy system?

Q2. How resilient is the Finnish energy system against these threats?

The most topical energy security issues were identified via dialogue with different energy authorities and officials in Finland, following the energy-related political discourse and media, analysing the current energy market trends both in Finland and globally, and analysing the Finnish energy system in order to find vulnerabilities related to its energy supply. Overall, this dissertation summarises the methods, analyses and results of the associated publications. Figure 1 presents the main topics of this dissertation and the themes that each publication addresses, and Table 1 presents the research questions and applied methods in the individual publications.

\(^2\) Peat is a debated energy source, as it does renew faster than the fossil fuels (2-4 mm/a [6]), but its CO\(_2\) emissions surpass even those of coal (93.2 g/MJ for hard coal and 107.6 g/MJ for milled peat [7]).
Figure 1. Research topics of this dissertation and the themes that each publication addresses.

Table 1. Research questions and applied methods in the individual publications in this dissertation.

<table>
<thead>
<tr>
<th>Publication</th>
<th>Research questions</th>
<th>Methods</th>
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<tbody>
<tr>
<td>I: Adequacy of Power Capacity during Winter Peaks in Finland</td>
<td>Is the Finnish electricity system currently prepared enough against technical faults?</td>
<td>Simulation of different stress factors with EnergyPLAN simulation tool.</td>
</tr>
<tr>
<td></td>
<td>What measures does the current legislation allow in terms of subsidisation of generation capacity in order to avoid generation inadequacy?</td>
<td>Doctrinal analysis of the Finnish and EU energy market legislation.</td>
</tr>
<tr>
<td></td>
<td>What is the outlook of investment in power capacity in Finland?</td>
<td>Investment profitability analysis.</td>
</tr>
<tr>
<td>III: Energy security impacts of a severe drought on the future Finnish energy system</td>
<td>How would a severe drought (in Finland and in the Nordics) affect the Finnish energy security?</td>
<td>Simulation of a drought similar to that in 1939–1942 in the current and future Finnish energy system.</td>
</tr>
<tr>
<td></td>
<td>How does generation adequacy develop until 2030 in different energy market scenarios?</td>
<td>Simulation of drought and generation adequacy in the Finnish energy system with EnergyPLAN simulation tool in different energy market scenarios.</td>
</tr>
<tr>
<td></td>
<td>What measures does the current legislation allow in terms of subsidising cogeneration through a plausible era of low electricity market prices?</td>
<td>Doctrinal analysis of the Finnish and EU energy market legislation.</td>
</tr>
<tr>
<td>V: Energy Security Impacts of Decreasing CHP Capacity in Finland</td>
<td>What are the energy security implications (local, national and international) if a notable amount of CHP capacity is replaced with heat only production in Finland?</td>
<td>A case study of Helsinki: least-cost investment analysis of the system with no CHP production.</td>
</tr>
<tr>
<td></td>
<td>-Qualitative assessment of national and international energy security impacts of decreasing CHP capacity in Finland.</td>
<td>-Analysis of the trade relations through the Interdependence framework.</td>
</tr>
<tr>
<td>VI: Finland’s dependence on Russian energy – mutually beneficial trade relations or an energy security threat?</td>
<td>Is Finland’s notable dependence on Russian energy an energy security threat to Finland?</td>
<td>Literature review.</td>
</tr>
<tr>
<td></td>
<td>How is the dependence likely to develop in the future?</td>
<td>-Analysis of the trade relations through the Interdependence framework.</td>
</tr>
</tbody>
</table>
This dissertation is structured as follows. Section 2 reviews the existing literature on energy security, particularly that related to Finland, and the Finnish energy system. Section 3 presents the methods and materials used in the research, and Section 4 introduces the main results of the publications. Section 5 presents a summary and discussion of the results, limitations of the research, and recommendations for future research.

1.3 Novelty of the dissertation

The findings and results of this dissertation serve the existing literature by providing further insight and knowledge as follows.

**Case studies:** This dissertation provides insight into some of the currently most discussed issues in the Finnish energy market, such as generation adequacy, the future role of cogeneration in Finland, and the risks related to the notable import dependence. Finland is an intriguing country with regard to the abovementioned phenomena. First, Finland is facing challenges with generation adequacy despite or due to its liberal energy-only market model. Secondly, Finland is an energy-intensive country with very limited domestic fossil fuel resources and hence strongly dependent on energy import from its neighbour in east, Russia. The issues are studied via simulation of different stress factors, e.g. technical faults in the system during a peak demand period or the impacts of a severe drought in the current system, and the development of plausible future scenarios. The research is tied to the existing infrastructure, legislation and energy policy goals in Finland.

**Universality of the results:** Due to the unique nature of each national energy system and its surroundings, generalisation of results in energy security related research is challenging. However, this dissertation provides tools and approaches that are applicable in energy security related research particularly in countries with strong import dependence and a trend of decreasing generation adequacy under the ongoing energy transition.

**The interdisciplinary approach:** This dissertation is a part of a larger interdisciplinary project on water-food-energy nexus, security and resilience in Finland, From Failand to Winland. Most publications in this dissertation are a result of collaboration between researchers from different disciplines, such as energy system analysis combined with law research (University of Eastern Finland, Law School), hydrological and environmental research (Finnish Environment Institute) or political research (University of Helsinki, Department of Social Research). The interdisciplinary approach is essential in order to understand the studied phenomena in this dissertation, such as the nature of Finnish-Russian energy trade and the impacts of a severe drought.
2. Literature review

2.1 Energy security

Energy security is a multidimensional and evolving concept. Studies on energy security have expanded from their beginnings following the 1970s oil crises and concerns on fossil fuel import dependence to encompass increasingly diverse and interdisciplinary issues, inter alia affordability, social acceptance, and environmental impacts. Consequently, energy security is an increasingly popular research subject.

A large body of research concentrates on defining and measuring energy security, e.g. [9]–[13], but no academic consensus has been reached in either composing a clear definition or a comprehensive indicator that would be useful in political decision-making. With regard to the lack of a clear definition, however, there is no lack of attempt, and Ang et al. [9] found 83 different definitions for energy security in academic literature. For instance, Cherp and Jewell [14] define energy security as ‘low vulnerability of vital energy systems’, and Ren and Sovacool [15] define it as ‘equitably providing available, affordable, reliable, efficient, environmentally benign, proactively governed and socially acceptable energy services to end-users’. International Energy Agency, on the other hand, defines energy security as the ‘uninterrupted availability of energy sources at an affordable price’ [16]. The lack of a comprehensive and useful indicator, on the other hand, has to do with the complex nature of energy security. Energy security comprises dimensions that are very difficult to compare with each other, such as system balance, self-sufficiency and the long-term impacts of climate change. As Böhringer and Bortolamedi [17] puts it, a money-metric translation of changes in energy security indicators that could make these amenable for a rigorous economic cost-effectiveness assessment is missing.

A common way to encompass the different dimensions of energy security is the four A’s: availability, accessibility, affordability and acceptability [18]. However, the approach has also been criticised for not addressing the following three questions, which derive from the proposition that energy security is an instance of security in general [14]:

- Security for whom?
- Security for which values?
- Security from what threats?
A framework developed for future scenarios by Jewell et al., on the other hand, examine energy security through three different perspectives: sovereignty, robustness and resilience [19]. Sakari Höysniemi elaborates on these perspectives more in Section 2 of Publication VI. Ang et al. [9] found seven major themes that repeated in most energy security related studies: energy availability, infrastructure, energy prices, societal effects, environment, governance, and energy efficiency. However, few studies comprise all these dimensions.

This dissertation applies the framework developed by Cherp and Jewell that defines energy security as the low vulnerability of vital energy systems. The three abovementioned perspectives, sovereignty, robustness and resilience, are embedded in the framework as the plausible sources of risks. The framework is depicted in Figure 2.

![Energy security as the low vulnerability of vital energy systems](image)

In line with the most recent Finnish Energy and Climate Strategy [8] and energy security related issues present in media and in political discourse, the most topical energy security aspects in the Finnish energy system are generation adequacy, self-sufficiency and system costs, with the underlying pressure to decarbonise the energy system. Table 2 presents the vital energy systems and analysed vulnerabilities in each publication of this dissertation.
Table 2. Vital energy systems and analysed vulnerabilities in each individual publication.

<table>
<thead>
<tr>
<th>Publication</th>
<th>Vital energy systems and the analysed risks and vulnerabilities</th>
</tr>
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<tbody>
<tr>
<td>I: Adequacy of Power Capacity during Winter Peaks in Finland</td>
<td>The vital energy system is the Finnish energy infrastructure and its adequacy in supplying the demand. The analysed risks are technical in nature (robustness perspective), with the underlying unpredictable (resilience perspective) climate-related stress.</td>
</tr>
<tr>
<td>II: Trouble Ahead? An Interdisciplinary Analysis of Generation Adequacy in the Finnish Electricity Market</td>
<td>The vital energy systems are the Finnish energy infrastructure, energy-related legislation, and the current market model, and their capabilities in ensuring generation adequacy. The analysed risks are economic and technical in nature (robustness perspective), with the underlying climate-related stress. The vulnerability is connected to the resilience perspective through the unpredictability factor.</td>
</tr>
<tr>
<td>III: Energy security impacts of a severe drought on the future Finnish energy system</td>
<td>The vital energy system is the Finnish energy infrastructure and its adequacy in supplying the demand. The analysed risk is a climate-related stress in Finland and in the neighbouring countries. The vulnerability is connected to the resilience perspective through the unpredictability factor. Moreover, the paper analyses both sovereignty and robustness of the Finnish energy sector via analysing the national energy policy goals until 2030.</td>
</tr>
<tr>
<td>IV: Ensuring Generation Adequacy in Finland with Smart Energy Policy – How to save Finnish CHP production?</td>
<td>The vital energy systems are the Finnish energy infrastructure, energy-related legislation and their capabilities in ensuring generation adequacy in Finland. The risks are economic and political in nature and the vulnerabilities are connected to decreasing flexibility, diversity and sovereignty in the Finnish energy system.</td>
</tr>
<tr>
<td>V: Energy Security Impacts of Decreasing CHP Capacity in Finland</td>
<td>The vital energy system is the Finnish energy infrastructure and its adequacy in supplying the demand. The risks are economic and political in nature and the vulnerabilities are connected to decreasing flexibility, diversity and sovereignty in the Finnish energy system.</td>
</tr>
<tr>
<td>VI: Finland’s dependence on Russian energy – mutually beneficial trade relations or an energy security threat?</td>
<td>The vital energy systems are energy resources and energy flows that support the critical functions of the society. The analysed risks are economic and intentional actions (sovereignty perspective). The vulnerability is connected to Finland’s lack of sovereignty through the notable import dependence.</td>
</tr>
</tbody>
</table>

2.2 The Finnish energy system

The Finnish energy system along with its security aspects have been studied widely. The studies comprise inter alia analyses of single energy forms, such as nuclear power [20], bioenergy [21] or peat [22], studies on integration of renewable energy sources\(^3\) (RES) into the Finnish energy system [23], [24], and Finland’s energy trade with Russia [25]. Moreover, a large body of research analyses the Finnish energy policy [26]–[29]. However, at the time of writing this dissertation, no studies have comprehensively addressed the questions presented in Section 1.2. In order to lay out the foundations for the findings in this dissertation, the following sections introduce the demand, supply, system reserves and energy policy goals in the Finnish energy system, respectively.

2.2.1 Demand

Finland has substantial energy consumption per capita due to its cold climate and energy-intensive industry. The most significant sectors of (primary) energy consumption are industry (45%, 2016 figures), space heating (26%) and transport (17%) [30]. Figure 3 presents the Finnish primary energy

\(^3\) Renewable energy refers to energy sources that replenish within a human timescale. In the context of this dissertation, renewable energy comprises wind power, solar energy, hydro-power and bioenergy.
consumption and energy sources in 2007–2016 [30], 2020 and 2030 [8]. Primary energy consumption is expected to reach 418 TWh by 2030 [31].

![Figure 3. Primary energy consumption and energy sources in Finland in 2007–2016 [30], 2020 and 2030 [8].](image)

Annual demand for electricity has remained at around 82-85 TWh in Finland in the 2010s. During the past decade, the demand has been lower than expected due to the financial crises and exceptionally warm weather. However, the annual electricity demand peaks in Finland have grown, reaching an all-time high in early 2016. The peak is analysed in Section 2.2.3 in more detail. The main sectors of electricity consumption are industry and construction (47%, 2016 figures), residential and agriculture (27%), and the public sector (23%), with transmission and distribution losses covering 3% of electricity use in 2016 [30]. In 2030, the Energy and Climate Strategy estimates an annual electricity consumption of 93 TWh and an upper limit of 16,235 MWh/h for the annual demand peak in Finland [31]. Demand-side flexibility in the day-ahead (Elspot) market is estimated to be 200-600 MW [32], and it is more likely to increase than decrease in the future. Demand flexibility in the spot market is assumed to be 400 MW in the publications related to this dissertation.

In addition to the high demand for electricity and space heating, a noteworthy feature in the Finnish energy system is the role of district heating and cogeneration in particular, which will be discussed more in Section 4.3. Demand for district heat was approximately 33.6 TWh in 2016, i.e., 46.1% of total space heating [33]. Approximately 70% of the district heat was based on combined heat and power (CHP) production. Demand for district heat is expected to remain approximately at its current level until 2030 [31].

### 2.2.2 Supply

As illustrated in Figure 3, the most important primary energy sources in Finland are biomass (25.9%, 2016 figures), oil (23.2%) and uranium (18.2%) [30]. Apart from peat, Finland imports practically all of its fossil fuels, and a vast majority
of the import comes from Russia. In total, import comprised 64.0% of the total primary energy supply in 2016, of which the majority originated in Russia. The import is analysed in more detail in Section 4.5. The most notable domestic primary energy sources in Finland are biomass (71%, 2016 figures), peat (15%) and hydropower (10%) [30]. Figure 3 presents the development of primary energy supply in Finland in 2007–2016 and the political targets for 2020 and 2030.

The Finnish electricity system is a part of the Nordic wholesale power market, Nord Pool, and hence connected with its neighbouring countries’ power markets. Furthermore, Finland is heavily and increasingly dependent on cross-border electricity trade. During the past few years, electricity supply in Finland has been distributed between thermal power (29.6%, 2016 figures), nuclear power (26.2%), hydropower and wind power (21.9%), and net import (22.3%) [34]. Installed power capacity in Finland in early 2018 was approximately 17,400 MW [35]. However, as some of the capacity is allocated in system reserves and the availability of e.g. wind and hydropower vary according to external conditions, the highest electricity production peak in Finland in e.g. 2016 was approximately 11,600 MW [36]. This corresponds to the estimate of Fingrid, the national transmission system operator (TSO), regarding the available domestic power capacity during the winter peak demand period in 2016 [30]. Thus, Finland is highly dependent on electricity import particularly in supplying the annual demand peaks. The cross-border transmission capacities from Sweden, Russia and Estonia are approximately 2,700 MW, 1,400 MW and 1,000 MW, respectively, resulting in a total import capacity of 5,100 MW. This is more than one third of the record-high demand peak. Of these connections, Sweden and Estonia are included in the common electricity market. Interconnection capacities in the Nordic power system are illustrated in Figure 4.
2.2.3 The record-high demand peak

In 7 January 2016, the Finnish power system witnessed an all-time high demand for electricity, 15,105 MWh/h [36]. The highest peak took place at five o’clock in the afternoon and the consumption-weighted outside temperature in Finland was minus 25 degree Celsius [38]. Demand for electricity surpassed the Finnish production capacity by more than 3,500 MW and, consequently, Finland imported approximately 4,230 MWh of electricity during the hour. However, despite the record-high demand, no shortages in power supply were experienced. Moreover, no reserve capacity was activated and the electricity spot price in the Finnish bidding zone remained moderate, at 99.94 EUR/MWh [39]. Despite the relatively low wind power production (approximately 16% of the installed capacity), the market conditions were generally favourable: hydro reservoirs were above average [40], there were no noteworthy technical disturbances in the system, and a national holiday in Russia ensured the abundance of import from Russia at a moderate price level. Table 3 shows the installed power capacity [35], estimated available capacity [30], and actual production during the peak demand hour [36] in Finland. The most notable development in the capacity between early 2016 and late 2018 is that the Finnish wind power capacity has more than doubled. Figure 5 shows the electricity supply and demand during the peak demand day.
Table 3. Installed power capacity, estimated available capacity and actual production during the peak demand hour of 2016 in Finland.

<table>
<thead>
<tr>
<th>Production type [MW]</th>
<th>Installed capacity</th>
<th>Estimated available capacity during the peak</th>
<th>Production during the peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydropower</td>
<td>3,180</td>
<td>2,550</td>
<td>2,235</td>
</tr>
<tr>
<td>Nuclear power</td>
<td>2,780</td>
<td>2,780</td>
<td>2,776</td>
</tr>
<tr>
<td>Condensing power plants</td>
<td>2,160</td>
<td>960</td>
<td>638</td>
</tr>
<tr>
<td>Combined heat and power, total</td>
<td>6,985</td>
<td>5,250</td>
<td>4,790</td>
</tr>
<tr>
<td>CHP district heating</td>
<td>4,170</td>
<td>3,250</td>
<td>3,134</td>
</tr>
<tr>
<td>CHP industry</td>
<td>2,815</td>
<td>2,000</td>
<td>1,656</td>
</tr>
<tr>
<td>Wind power</td>
<td>1,005</td>
<td>60</td>
<td>161</td>
</tr>
<tr>
<td>Other</td>
<td>-</td>
<td>-</td>
<td>274</td>
</tr>
<tr>
<td>Total</td>
<td>16,110</td>
<td>11,600</td>
<td>10,874</td>
</tr>
</tbody>
</table>

Figure 5. Electricity supply and demand during the peak demand day in 7 January 2016.

Even though the electricity system indicated no signs of emergency, the peak raised awareness and spurred debate on generation adequacy and import dependence in Finland. Sections 4.1 and 4.5 aim to address whether the concerns over these issues are in fact justified, respectively.

2.2.4 System reserves

The Finnish energy system has a variety of fail-safe mechanisms to cope with unexpected faults and stressful market situations. To maintain the system security, the Finnish and other Nordic countries use the N-1 criterion, i.e. the systems are dimensioned to withstand any common faults in the grid components without an interruption in electricity supply or secondary failures. After responding to a fault in the system, Fingrid strives to restore the readiness to respond to the next possible fault as quickly as possible. Moreover, Fingrid and Nord Pool have a variety of instruments in order to maintain generation adequacy in Finland in case the markets fail to solve the situation. First, in case an intersection between supply and demand curves is not achieved after the
market-based demand-side flexibility, Nord Pool effectuates one or more of the following measures [41]:

- Activate peak load reserves;
- Ask the TSO about the possibility to adjust the trading capacity;
- Block orders that increase curtailment;
- Deduct orders on a pro rata basis until a point of intersection is achieved.

The peak load reserves are offered to the Elspot market in case the supply and demand curves do not intersect otherwise. The reserve for the period from 1 July 2017 to 30 June 2020 is 729 MW and it comprises four power plants and two heat pumps for demand response [42]. The peak load reserve was increased from 299 MW in the period of 2015–2017. However, the reserve has not been activated to address generation adequacy since the entry of the Capacity Reserve Act in 2011. In addition to the peak load reserves, Fingrid controls different frequency restoration reserves, which comprise approximately 1,000 MW of capacity with a starting time of 10-15 minutes [43]. These reserves are mainly fuel oil powered gas turbines. However, as mentioned earlier, the primary function of the frequency reserves is to cope with unexpected faults in the power system and they operate completely outside the Elspot market. Different frequency containment and restoration reserves and their capacity obligations are presented in Table 4.

### Table 4. Fingrid’s frequency containment and restoration reserves.

<table>
<thead>
<tr>
<th>Reserve product</th>
<th>Obligation [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Containment Reserve for Normal operation (FCR-N)</td>
<td>about 140</td>
</tr>
<tr>
<td>Frequency Containment Reserve for Disturbances (FCR-D)</td>
<td>220-265</td>
</tr>
<tr>
<td>Automatic Frequency Restoration Reserve (aFRR)</td>
<td>70</td>
</tr>
<tr>
<td>Manual Frequency Restoration Reserve (mFRR)</td>
<td>880-1,100</td>
</tr>
</tbody>
</table>

In addition to operating the frequency reserves, Fingrid coordinates the communication between different power market stakeholders, ensures that all available capacity is activated in case of power supply shortage, and blocks bids in the intraday market (Elbas) or the whole market if needed [44]. If demand for electricity is not met with all the aforementioned measures, Fingrid will apply rolling blackouts in the Finnish power system. However, this procedure has yet to be tested. The Finnish energy system has traditionally not had any major issues with regard to generation adequacy or system balance, partly because of the notable hydropower capacity in the Nordics.

In addition to the different capacity reserves, there are also reserves for primary energy supply in Finland. The Finnish legislation on imported fuels (28.11.1994/1070) obliges parties importing or utilising coal or natural gas to store fuel for three months’ consumption and parties importing or utilising oil to store fuel for two months’ consumption. However, in practice natural gas storages are substituted via storing fuel oil. Uranium is excluded from the legislation, but nuclear power producers store uranium for 1-2 years’ consumption. In addition to the obligations for importers and producers, the
Finnish National Emergency Supply Agency (NESA) has emergency fuel storages.

2.2.5 Finnish energy strategy and energy policy goals

In November 2016, the Finnish government published a new National Energy and Climate Strategy [8], which presents a roadmap to achieve the national energy policy targets. The goal is to systematically set a course for achieving an 80-95% reduction in GHG emissions, which is delineated in the Finnish Energy and Climate Roadmap 2050 from 2014 [45]. The main targets of the strategy by 2030 are the following:

- Increase the share of RES to 50% of final energy consumption;
- Increase self-sufficiency in energy production to 55% of final energy consumption;
- Halve the use of imported oil for energy comparing to the level of 2005;
- Phase out coal in normal energy use;
- Increase the share of RES in transport sector to 40% by e.g. increasing the amount of electric vehicles to 250,000 by 2030.

A key tool in the strategy work was calculating possible energy market development via assessing two different scenarios, the Basic scenario and the Policy scenario. Rather than predictions, the scenarios are built on certain assumptions projecting different possible future outcomes. The Basic scenario assumes that no additional energy policy actions are implemented after the actions taken in spring 2016 or earlier. The scenario sets the baseline with which the required policy actions are compared and the impacts of any new measures on the energy and climate targets can be determined. The share of RES will increase in the Basic scenario, mainly due to an increase in the use of forest chips and waste liquors from forestry. Moreover, the use of heat pumps is estimated to increase with the current trends, while the strong increase in wind power production between 2010 and 2017 will slow down significantly without new policy measures. Final energy consumption is estimated to converge around 315 TWh/a, of which RES should cover approximately 47%. This falls 3 percentage points short from the government’s target for 2030. With regard to the targets on energy self-sufficiency and halving the energy use of oil, the Basic scenario falls short 4 percentage points and 12 TWh, respectively [31].

The Policy scenario includes policy measures with which to achieve the national targets set in the strategy. Some of the measures are still intangible and mentioned to be specified later on. However, some measures are described briefly, inter alia:

- Technology neutral tendering processes will be organised in 2018–2020 in order to increase RES utilisation in electricity production in the most cost-efficient way;
- Increasing the obligation for the share of biofuels in road traffic to 30%;
• Coal will be phased out by taxation and subsidies for domestic substitutes in CHP production;
• Investment support and tax exemptions for e.g. small-scale distributed energy generation.

Finland aims towards zero net electricity import by 2030 [8]. However, two new cross-border transmission lines are being planned and constructed between Finland and Sweden, and Finland’s dependence on imported electricity to supply the annual demand peaks might hence even grow by 2030. In addition to the new transmission lines and the aforementioned policy targets, the most significant foreseeable change in the Finnish energy system by 2030 is the deployment of two new nuclear power plants, Olkiluoto 3 (1,600 MW) and Hanhikivi 1 (1,200 MW).
3. Methods and Materials

3.1 Energy system simulations

The energy system simulations in Publications I–III are carried out using a publicly available simulation tool, EnergyPLAN (version 12.5), which is developed and maintained by the Sustainable Energy Planning Research Group at Aalborg University [46]. The tool simulates national energy systems on an hourly basis, including electricity, heating, cooling, transport and industry sectors. The algorithms of the model are not presented in this dissertation, but are thoroughly documented in Reference [47]. Inclusion of the heating sector is essential in the Finnish energy system, as the heating and power markets are strongly connected via CHP production and heat pumps. EnergyPLAN has been widely used for modelling systems with a high share of CHP production, e.g. [23], [48].

EnergyPLAN is a deterministic input-output simulation tool with an hourly time resolution of a full year (8784 hours). The model inputs are inter alia annual energy demands, technology specifications of production facilities, and annual profiles of inflexible production methods. All annual profiles are input as deterministic hourly distribution patterns. Output of the simulation consists of hourly system operation, fuel consumption, and system costs. Figure 6 shows the flow diagram of the major components in the EnergyPLAN model. Energy sources are depicted with white background, conversion technologies with yellow, storage and exchange with blue, and demands with orange.
EnergyPLAN has two different simulation modes: technical and market economic. The technical simulation mode prioritises all available domestic production in the dispatch order before importing any electricity, whereas the market economic mode prioritises imported electricity in case its price is lower than the short-run marginal costs of domestic production. The latter portrays the dynamics of a liberal electricity market more accurately. Furthermore, the market economic scheme reflects the nature of dammed hydropower as a market-balancing instrument more accurately, whereas the technical strategy distributes flexible hydropower production evenly throughout the year. The market economic mode hence reflects the dynamics of the Nord Pool market more accurately and, therefore, it is applied in the publications related to this dissertation.

3.1.1 The stress test

In order to analyse generation adequacy under different stress factors in the Finnish energy market, a stress test is applied in the EnergyPLAN simulations in Publications I–III. The test assumes the hourly demand profile of 2016 for electricity and heating and similar external conditions for wind, hydropower and solar energy production. In Publication III, demand and supply are scaled to match the estimations of the Finnish Energy and Climate Strategy for 2020 and 2030 in different scenarios. Emphasis of the test is on the first week of January, when the Finnish energy system experienced the record-high demand peak described in Section 2.2.3. Publications I and II analyse the resilience of the Finnish energy system against technical faults in the system in order to address the concerns on generation adequacy currently. Publication III, on the other hand, aims to assess the development of generation adequacy until 2030.
and the implications that a severe drought would have on generation adequacy. Results of the publications are presented in Section 4.

### 3.1.2 Scenario analysis

All publications related to this dissertation analyse energy security threats through different scenarios and case studies. Publications I and II analyse scenarios with outages in technical power system components during a peak demand period and Publication III applies the hydrology of the worst drought during the past century to different energy policy scenarios in Finland. Publications IV and V analyse the development of CHP investment prospects in different price scenarios and energy security impacts in a scenario, where the price level is inadequate to encourage investment in CHP plants, respectively. Publication VI analyses the development of Finnish-Russian energy trade in different global energy policy scenarios. Instead of predicting the future or the likelihoods of different outcomes, the scenarios work as thought experiments [49] to map out plausible energy security threats. Table 5 summarises and elaborates on the analysed scenarios.
Table 5. Different scenarios and their purposes in this dissertation.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Explanation</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Publications I and II</td>
<td>January 2016 demand peak with a forced outage in SE1-FI transmission line</td>
<td>Used to assess the severity of the debated stress regarding generation adequacy in Finland during the 2016 demand peak. The scenarios are named with numerals in the publications, but are referred to with more informative names in Section 4 of this dissertation. The scenarios have an incremental amount of technical faults in order to assess the sufficiency of the existing fail-safe mechanisms in the system.</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>January 2016 demand peak with a forced outage in SE1-FI transmission line and Olkiluoto 1 power plant</td>
<td></td>
</tr>
<tr>
<td>Scenario 2</td>
<td>January 2016 demand peak with a forced outage in Fenno-Skan 2 transmission line and Olkiluoto 1 and 2 power plants</td>
<td></td>
</tr>
<tr>
<td>Publication III</td>
<td>Basic</td>
<td>A baseline scenario in the Finnish Energy and Climate Strategy to which the impacts of the planned policy actions are compared</td>
</tr>
<tr>
<td>Policy</td>
<td>A scenario with all the planned policy actions in the Finnish Energy and Climate Strategy</td>
<td>Used to analyse the development of generation adequacy in Finland until 2030 with the national energy policy goals.</td>
</tr>
<tr>
<td>Alternative</td>
<td>A scenario with pessimistic assumptions regarding the development of generation and transmission capacity in Finland</td>
<td>Used for sensitivity analysis; would the absence of e.g. Hanhikivi 1 power plant and a new transmission line between Finland and Sweden cause generation inadequacy in the future?</td>
</tr>
<tr>
<td>Publication IV and V</td>
<td>Low price</td>
<td>Electricity spot price and EUA prices remain at around 30 EUR/MWh and 10 EUR/t until 2045, respectively</td>
</tr>
<tr>
<td>Intermediate price</td>
<td>Electricity spot price and EUA prices are the average of those in Low and High price scenarios</td>
<td>Used to analyse the future of Finnish CHP production with an intermediate price development in Publication IV</td>
</tr>
<tr>
<td>High price</td>
<td>Electricity spot price and EUA prices develop according to the estimations in the Finnish Energy and Climate Strategy</td>
<td>Used to analyse the future of Finnish CHP production with the price development assumptions in the Finnish Energy and Climate Strategy in Publication IV</td>
</tr>
<tr>
<td>Publication VI</td>
<td>Market trends</td>
<td>Based on decided and implemented energy and climate policy actions globally; results in global warming of 3-3.5 degrees Celsius</td>
</tr>
<tr>
<td>Low carbon</td>
<td>Assumes strong global consensus and political will to tackle climate change; results in a global warming of 2 degrees Celsius</td>
<td>Used to assess the future development of Finnish-Russian energy trade in a scenario with strong will to decrease the use of fossil fuels globally</td>
</tr>
<tr>
<td>High carbon</td>
<td>A scenario where the ongoing energy transition stagnates and global climate goals are abandoned</td>
<td>Used to assess the future development of Finnish-Russian energy trade in a pessimistic scenario regarding climate change mitigation</td>
</tr>
</tbody>
</table>

3.1.3 Limitations of the energy system simulations

The EnergyPLAN tool was chosen for the energy system simulations as it suits for the comprehensive analysis of an energy system including both heating and electricity sectors. However, EnergyPLAN is not an optimal tool for the analysis of a set of national energy systems with a complex web of interconnections, and the deterministic nature of the tool excludes stochastic analysis. Therefore, the indirect impacts of drought via reduced availability of electricity import in Publication III were based on a more qualitative analysis. EnergyPLAN does not allow the analysis of sub-hour events, as its time resolution is one hour. Sub-hour resolution grows more important with the increasing share of VRE, and it is particularly important for analysing system balance and frequency restoration after unexpected faults in the system. However, countrywide simulations are typically done with an hourly resolution, which is sufficient in providing insight in the phenomena studied in this dissertation. Moreover,
EnergyPLAN’s time span for simulations is one year whereas the analysed drought lasted for over three years, the tool lacks an option for temporal restrictions in import capacity of electricity, and the tool does not consider ramp-up rates of power plants. Nevertheless, the simulations provided the desired insight on the resilience of the Finnish energy system currently, the impact of a severe drought on generation adequacy in Finland, and the development of generation adequacy in the scenarios presented in the new Energy and Climate Strategy.

3.2 Investment profitability analysis

A common method for analysing the feasibility of an investment is the net present value (NPV) method [50]. The method discounts all cash flows resulting from an investment to their present day values using a given interest rate. As power plant investments are highly capital intensive and create cash flows for up to 70 years, the applied interest rate warrants attention. A widely accepted method used by investors to determine the interest rate for an investment is the weighted average cost of capital (WACC) method [50]. This reflects the minimum yield required by a company to invest in a project, taking into account the capital structure, i.e. the proportion of debt and equity, and all risks associated with the project. The nominal post-tax WACC is defined as follows:

$$WACC = (1 - t_c) * x_D * R_D + x_E * R_E$$

Where $t_c$ denotes the corporate tax rate, $x_D$ and $x_E$ the proportions of debt and equity, and $R_D$ and $R_E$ the required returns on debt and equity, respectively. The required returns are defined as follows:

$$R_E = R_F + \beta_E * MRP + CRP$$

$$R_D = R_F + DM$$

Where $R_F$ denotes the risk-free rate, $\beta_E$ beta coefficient for equity, i.e. the unsystematic risk, MRP market risk premium, CRP country risk premium, and DM debt margin. Furthermore, the beta coefficient for equity is defined as follows:

$$\beta_E = \beta_A * (1 + (1 - t_c) * \frac{x_D}{x_E})$$

Where $\beta_A$ denotes the beta coefficient for the whole asset. The WACC method discounts the free cash flow (FCF), i.e. the annual cash flow available to both equity holders and lenders, using the calculated WACC. The following approach is used to estimate the FCF in this dissertation:
Revenue
- Operating costs
- Depreciation
= EBIT (earnings before interest and taxes)
- Tax on EBIT
+ Depreciation
- CAPEX (capital expenditures)
- Increase in working capital
= FCF

The NPV is now calculated by discounting the FCF of each year using the WACC:

$$NPV = \sum_{t=0}^{n} \frac{FCF_t}{(1 + WACC)^t}$$

Where T is the time in years and n is the estimated time span of the investment. Finally, the levelised cost of electricity (LCOE) is calculated. LCOE is the average price of electricity throughout the lifespan of the power plant required to result in an NPV of zero. In addition to enabling economic comparison of different power production methods, the LCOE method provides a clear indication of the required average wholesale electricity price to ensure the feasibility of an investment. The LCOE is defined as follows:

$$LCOE = \frac{\sum_{t=0}^{n} \frac{C_T}{(1 + WACC)^t}}{\sum_{t=0}^{n} \frac{E_T}{(1 + WACC)^t}}$$

Where C_T includes all costs, i.e. CAPEX, OPEX (operational expenditures, excluding fuel costs) and fuel costs, in year T and E_T the electricity production in year T. The unit of LCOE is hence EUR/MWh. LCOE calculations are applied in Publications II and IV.

### 3.2.1 Weighted average cost of capital

Publications in this dissertation with investment profitability analysis assume project financing, i.e. the project is analysed as a separate entity and it needs to be able to meet its financial covenants per se. A 70% debt proportion is assumed to ensure the project’s capability to repay its loan. A nominal WACC is applied, as future electricity and fuel price projections generally use nominal values. Debt margins vary significantly according to the perceived risks related to the project and project owner at hand. The debt margin used in the calculations reflects the creditworthiness of a major utility in Finland rather than the risks related to a certain power plant project. Table 6 shows the assumptions and key parameters used to calculate the WACC.
Table 6. Assumptions for calculating the weighted average cost of capital.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corporate tax rate ((t_C))(^1)</td>
<td>20%</td>
</tr>
<tr>
<td>Proportion of debt ((X_D))(^1)</td>
<td>70%</td>
</tr>
<tr>
<td>Risk-free rate ((R_F))(^2)</td>
<td>0.5%</td>
</tr>
<tr>
<td>Debt margin ((D_M))(^1)(^2)</td>
<td>2.0%</td>
</tr>
<tr>
<td>Beta coefficient for asset ((\beta_A))(^3)</td>
<td>0.9</td>
</tr>
<tr>
<td>Return on equity ((R_E))(^4)</td>
<td>14.8%</td>
</tr>
<tr>
<td>Return on debt ((R_D))(^4)</td>
<td>2.5%</td>
</tr>
<tr>
<td>Beta coefficient for equity ((\beta_E))(^5)</td>
<td>2.6%</td>
</tr>
<tr>
<td>Country risk premium ((C_RP))(^6)</td>
<td>0.1%</td>
</tr>
<tr>
<td><strong>Market risk premium</strong> ((M_RP))(^6)</td>
<td>5.3%</td>
</tr>
<tr>
<td><strong>WACC, nominal post-tax</strong></td>
<td>5.7%</td>
</tr>
</tbody>
</table>

\(^1\) bold values are calculated


\(^3\) Reflects the relatively low systematic risk connected with investment in power production in Finland.

\(^4\) Based on A. Damodaran’s analysis, rounded up to the nearest tenth of a per cent, available at pages.stern.nyu.edu/~adamodar/ (last accessed on 12 June 2017).

\(^5\) Based on the difference between risk-free rate and long-term stock index growth, which is based on the PWC report ‘Equity Market Risk Premium (EMRP) on the Finnish stock market’, June 2015.

Thus, a WACC of 5.7% is applied in the calculations in Publications II and IV.

### 3.3 Materials and data

Power capacity data in the Finnish energy system is derived from the Finnish Energy Authority’s power plant register, which includes all power plants with a capacity of at least one MVA [35]. Data on cross-border transmission capacity and estimated availability of generation capacity during winter peaks comes from Fingrid. The energy system simulations use realised hourly consumption and production data collected by Fingrid [36], which also estimates the market-based demand-side flexibility in the day-ahead market. Must-run hydropower production is estimated to be the running daily minimum of the realised total hydropower production and the rest is flexible, dammed hydropower. The hourly heating demand pattern is based on the running five-hour average production profile of non-industrial CHP electricity production. Electricity market prices and hydro reservoir levels are drawn from publicly available data on the Nord Pool website [39], [40], and power plant cost data is based on Energienet.dk’s report [51]. Demand response and peak load reserves are not included in the simulations, but are taken into account in the analysis of the simulation results. Overall, the EnergyPLAN models are calibrated to reflect similar market conditions as described in Section 2.2.3 as accurately as possible.
4. Results

4.1 Generation adequacy

Generation inadequacy is an energy security risk with very tangible implications. Estimations for the value of lost load (VOLL) range between 5,000–20,000 EUR/MWh [52], which surpasses the price cap in the day-ahead market notably. In addition to the apparent economic losses related to the expected unserved energy (EUE), generation inadequacy also decreases affordability for all end-users who are served their expected energy, as the approaching generation inadequacy is reflected in a steep increase in the price of electricity. The vital energy system is thus the energy flows that support critical social functions.

The Finnish energy system has traditionally had no major issues regarding generation adequacy. However, as described in Section 2.2.3, Finland is increasingly dependent on electricity import to meet the annual demand peaks, whereas the estimated available capacity during winter peaks in Finland still exceeded the demand peaks in the early 2000s [31]. However, concurrently with the growing amplitude of the annual demand peaks, more than 2,000 MW of thermal capacity was decommissioned or mothballed in Finland during the past decade due to lack of economic competitiveness. Moreover, the last commercially operative condensing coal power plant, Meripori, was partly allocated in the Finnish peak load reserve in July 2017 and thus removed from the market.

Due to the developments described above and the record-high demand peaks in Finland and in Nord Pool area in early 2016, generation adequacy has become a common theme in political discourse and in media. Moreover, the European Network of Transmission System Operators for Electricity (ENTSO-E) published a Mid-term Adequacy Forecast in late 2017 [53] with a bleak outlook on Finnish generation adequacy, which revived the concerns after the milder winter in 2017. However, Fingrid together with the other Nordic TSOs published a report in April 2018 that corrected some of the estimations in the forecast by ENTSO-E, stating that the generation adequacy in Finland is in fact much better.
than that estimated by ENTSO-E [54]. Sections 4.1.1 and 4.1.2 aim to address whether the concerns over generation adequacy in Finland are in fact justified.

4.1.1 Generation adequacy in the current system

Publications I and II analyse generation adequacy in the Finnish energy system in 2016. The adequacy is analysed via applying different technical stress factors, such as faults in the most significant power plants and transmission lines, during circumstances described in Section 3.1.1. Publication I concluded that the system had enough available capacity during the demand peak to cope with a fault in the most significant single source of power supply, i.e. the transmission line between northern Sweden and Finland (SE1-FI, 1,100 MW), without any intervening measures. Moreover, the fault would have moved the point of intersection between the supply and demand curves, increased the electricity market price and, thus, alleviated the stress by lowering the demand. With regard to the short-term effects of an abrupt fault of this severity in the power system, Fingrid would have needed to activate frequency restoration reserves to maintain or restore system stability. Scenarios where two and three simultaneous faults occur are analysed next, respectively.

Faults in SE1-FI transmission line and Olkiluoto 1 power plant:
This scenario simulates simultaneous failures in the SE1-FI transmission line and Olkiluoto 1 power plant during a similar market situation as the first week of 2016. Publication I assumes that the forced outages have occurred separately before the peak demand day and action has been taken to deal with the short-term effects. Therefore, the resulting lack of generation capacity is already included in the aggregated supply curve in the day-ahead trade for the peak demand day. As Figure 7 shows, there is a shortage of supply throughout the day. The highest shortage occurs between 17.00 and 18.00 and is approximately 700 MW.
This shortage coincidentally corresponds to the sum of available peak load reserves and the estimated available demand flexibility in the spot market in 2016. Therefore, Nord Pool would not have had to resort to cutting the demand curve. However, this scenario already reflects a severe stress in the power system and the activation of peak load reserves indicates that there are no more market-based supply bids in the electricity market. The price in the Elspot market could hence reach the ceiling price of 3,000 EUR/MWh, which is roughly one hundred times the average day-ahead market price in Finland in 2016. This could have encouraged higher demand response than the estimated 400 MW, as the estimate applies in short-term situations. Price futures indicating prolonged elevated electricity prices could encourage greater flexibility in, for example, industrial electricity use. As the forced outages are not interdependent, the probability of this scenario to materialise is approximately 0.042%.

**Faults in Fenno-Skan 2 transmission line and Olkiluoto 1 and 2 power plants:**
This scenario simulates simultaneous forced outages in Olkiluoto 1 and 2 power plants (880 MW each) and a fault in Fenno-Skan 2 transmission line (800 MW) during a market situation described in Section 3.1.1. Again, the stress factors have occurred separately before the peak demand day and measures to deal with the short-term effects have been taken. Therefore, the lack of capacity is included in the day-ahead trade for the peak demand day in 7 January 2016. As shown in Figure 8, there is a severe shortage of supply throughout the day. The highest shortage of capacity is between hours 17 and 18 and it is approximately 1,280 MW.
Figure 8. Electricity supply during the peak demand day with faults in Fenno-Skan 2 transmission line and Olkiluoto 1 and 2 power plants.

This scenario reflects a severe and unlikely situation of three major power system components failing during a record-high demand peak. After demand flexibility and activation of the peak load reserves, there is still a shortage of 580 MW during the highest peak, and Nord Pool would thus have had to cut the demand curve. This situation has yet to materialise in Finland and the detailed procedures are hence to be tested. However, Fingrid has sufficient reserves to supply the demand, but it is a matter of prioritising whether the reserves are held up for yet another fault in the system. As in the case with two simultaneous faults, prices in the Elspot market would be close to the ceiling price throughout the day, encouraging higher demand-side flexibility than the estimated 400 MW. As none of the faults is interdependent, the probability of this scenario to materialise during the demand peak is approximately 0.0026%.

It should be noted, however, that despite the unlikelihood of the scenario, a corresponding set of faults did in fact materialise in July 2018 [55]. A transmission line between Finland and Russia was under maintenance while both Olkiluoto 1 and 2 power plants experienced forced outages. However, this occurred during the summer when the demand for electricity was much lower than that in early 2016.

4.1.2 Generation adequacy in the future

Although the estimated completion of Olkiluoto 3 nuclear power plant in 2019 should alleviate the stress related to generation adequacy, the debate continues: up until 2018, the low level of electricity wholesale prices since 2012 seemed to
continue in Finland. However, in contrast with the market expectations, electricity prices in the Nord Pool area soared in summer 2018 due to the combination of a very dry summer, record-high European emissions allowances (EUA) price and the high price of coal. Before the increase in the wholesale price in 2018, the price level encouraged utilities to replace retiring CHP capacity with heat only boilers (HOB). The uncertainty regarding the amount of decreasing thermal capacity in the 2020s combined with controversial views regarding the development of electricity peak demand in Finland have kept the debate alive. Section 4.2 aims to address briefly the current concerns related to feasibility of investment in power capacity in Finland.

Publication III analysed the development of generation adequacy until 2030 in the scenarios of the new Energy and Climate Strategy of Finland. Moreover, in addition to the Basic and the Policy scenarios, an Alternative scenario with pessimistic assumptions regarding the development of generation capacity in Finland was developed. The Alternative scenario assumes prolonged low level of electricity prices throughout the 2020s and a corresponding lack of willingness to invest in new generation capacity. Most of the retiring CHP plants are replaced with HOBs due to the lack of economic feasibility of CHP electricity production. Moreover, Hanhikivi 1 nuclear power plant investment does not materialise. Neither Balticconnector nor growing liquefied natural gas (LNG) markets manage to restore the economic feasibility of natural gas in Finland. Therefore, its utilisation keeps its declining trend, resulting in an additional reduction of 485 MW in the available CHP capacity during winter peak by 2030. Moreover, investment in the third transmission line between northern Finland and Sweden does not materialise. Meri-Pori condensing coal power plant is assumed to stay in the peak load reserves for the remainder of its technical lifetime. With regard to demand for electricity, electric vehicles develop faster than predicted in the Energy and Climate Strategy, increasing the annual electricity demand by one TWh by 2030. Development of the demand peaks and estimated available power capacities during the peaks are presented in Table 7. Figures in the table are elaborated in Publication III. The demand peak and the estimated available power capacity in 2016 were 15,105 MW and 16,700 MW, respectively.

Table 7. Development of generation adequacy in Finland until 2030 in different scenarios.

<table>
<thead>
<tr>
<th>Scenario [MW]</th>
<th>2020</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Demand peak</td>
<td>Available capacity during the peak</td>
</tr>
<tr>
<td>Basic</td>
<td>15,440</td>
<td>16,120</td>
</tr>
<tr>
<td>Policy</td>
<td>15,440</td>
<td>16,235</td>
</tr>
<tr>
<td>Alternative</td>
<td>15,440</td>
<td>17,665</td>
</tr>
</tbody>
</table>

4 Electricity price futures indicated stagnating electricity price level until the deployment of Olkiluoto 3, which should have decreased the price further.

5 For differing estimates, see the background report for the Finnish Energy and Climate Strategy and Gaia Consulting Oy in ‘Tehomarkkinaselvitys’ (‘Capacity market study’), 30 December 2016.
As the strategy was published in late 2016, no notable differences in the Basic and Policy scenarios have yet occurred by 2020. The Alternative scenario, on the other hand, has 565 MW less capacity available during the demand peak due to Meri-Pori condensing coal plant being allocated in peak load reserves. However, the commercially available generation and transmission capacity after supplying the demand during the peak still amount to more than 2,200 MW in the scenario. Overall, generation adequacy is better in each of the simulated scenarios comparing to that in 2016 due to the expected deployment of Olkiluoto 3 nuclear power plant.

As shown in Table 7, the simulations in Publication III result in a notable improvement in generation adequacy by 2030 in the Basic scenario, slight improvement in the Policy scenario, and an alarming drop in the Alternative scenario, from 2,225 MW to 160 MW. The difference between the scenarios Basic and Policy is caused by the phase-out of coal in energy use and the assumption that most coal fired district heating CHP plants are replaced with HOBs in the Policy scenario. Main reasons for the improved availability of capacity are explained via the deployment of Hanhikivi 1 nuclear power plant and the two new transmission lines between Finland and Sweden (800 MW + 400 MW). The difference between the scenarios Policy and Alternative comes from the absence of Hanhikivi 1 and the 800 MW transmission line between Finland and Sweden. Moreover, the Alternative scenario assumes a stronger trend in decreasing CHP capacity due the lack of competitiveness of natural gas in power production. Figure 9 illustrates electricity demand and supply in the Policy scenario in 2030 during market conditions described in Section 3.1.1.

Figure 9. Electricity demand supply during the peak demand in 2030 in the Policy scenario.

---

6 In addition to the new 800 MW transmission line, Fenno-Skan 1 will be replaced with another transmission line with a capacity of 800 MW, resulting in a net increase of 400 MW.
Kaisa Huhta from University of Eastern Finland analysed the legal instruments and State-driven financing options available to address the apparent lack of investment in generation capacity in Publication II. Her conclusion was that State financing to subsidise investment in the interest of generation adequacy in this case is unlikely to comply with EU law.

Future development of generation adequacy is tied to a variety of factors, such as the development of demand-side flexibility, price development of wind and solar power, and the impacts of the increasing cross-border transmission capacity between the Nordic countries and Central Europe. Moreover, factors such as the future of Swedish nuclear power production and Estonia’s plans to replace the retiring Narva power plants in the 2020s inevitably affect the availability of electricity import in Finland.

4.2 Generation capacity investment prospects

Publication II analysed the investment prospects in generation capacity in Finland. As described in Section 2.2.5, Finland aims to phase out coal in energy use by 2030. Furthermore, the utilisation of natural gas in energy production has decreased significantly during the last decade due to uncompetitive prices, and oil is only used as a back-up fuel in electricity production due to its high price. Therefore, investment in coal, oil or natural gas fuelled generation capacity is highly unlikely. Investment in hydropower is also excluded from the analysis because, apart from some repowering investments, there is very little potential for new hydropower investment in Finland [56].

As described in Section 2.2.1, CHP production accounts for a large share in the Finnish energy system. As CHP plants produce both heat and electricity, calculating the production cost of electricity is less straightforward. In this dissertation, the production cost of electricity in a CHP plant is derived as the incremental cost of investing in a CHP plant instead of HOB with equal heating capacity. Demand for district heating is predicted to stabilise or even decrease due to improvements in buildings’ energy efficiency and the development of competing heating methods, inter alia heat pumps and solar collectors [53]. Therefore, it is assumed that the only viable investments in CHP are replacement investments in retiring capacity. Against this background, the feasibility of investment in onshore wind power, nuclear power, bio-CHP and solar power is analysed next, using the methods described in Section 3.2. Table 8 presents the input data and assumptions used in the profitability analysis of Publication II, and Table 9 shows the results of the calculations.

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7 Natural gas utilisation in Finland has decreased from 41.3 TWh in 2010 to 20.8 TWh in 2016 [30].
Table 8. Input data for calculating the economics of different power production methods in Finland.

<table>
<thead>
<tr>
<th>Item</th>
<th>Wind power</th>
<th>Solar power</th>
<th>Nuclear power</th>
<th>Bio-CHP2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technical assumptions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacity [MW]</td>
<td>21</td>
<td>0.85</td>
<td>1,200</td>
<td>35</td>
</tr>
<tr>
<td>Capacity factor</td>
<td>33%</td>
<td>9.8%</td>
<td>90%</td>
<td>68.5%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>37%</td>
</tr>
<tr>
<td>Construction time [a]</td>
<td>1.5</td>
<td>1</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>Technical lifetime [a]</td>
<td>25</td>
<td>30</td>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>Annual output degradation</td>
<td>0.5%</td>
<td>0.75%</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td><strong>Commercial assumptions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAPEX [EUR/kW]</td>
<td>1,600</td>
<td>1,050</td>
<td>5,600</td>
<td>1,343</td>
</tr>
<tr>
<td>OPEX [EUR/kW/a]</td>
<td>40.0</td>
<td>11.6</td>
<td>148.9</td>
<td>37.1</td>
</tr>
<tr>
<td>Fuel cost [EUR/MWhfuel]</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>22.5</td>
</tr>
<tr>
<td>Decommissioning cost [% of CAPEX]</td>
<td>1%</td>
<td>1%</td>
<td>10%</td>
<td>1%</td>
</tr>
</tbody>
</table>

1 Excluding interests during construction.
2 Figures for bio-CHP are based on recent realised projects in Finland.
3 A wind farm with six 3.5 MW turbines is analysed.
4 The same capacity as the planned Hanhikivi 1 power plant in Finland.
5 Based on the average of all new wind power plants in Finland between May 2014 and May 2017. The Finnish Energy Authority provides data for power plants registered in the feed-in tariff scheme in the SATU system, available at tuotantotuki.emvi.fi/Installations (last accessed on 2 June 2017)
6 Typical value in southern Finland.
7 Based on realised capacity factors in Finland, available at www.world-nuclear.org/information-library/country-profiles/countries-a-f/finland.aspx (last accessed on 2 June 2017).
9 Uranium is not traded on the open market and contracts are negotiated privately. However, based on e.g. www.world-nuclear.org, the price is approximately 2 EUR/MWh.

Table 9. Results of the investment profitability analysis for power production in Finland.

<table>
<thead>
<tr>
<th>Plant type</th>
<th>LCOE [EUR/MWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind power</td>
<td>65.30</td>
</tr>
<tr>
<td>Solar power</td>
<td>120.80</td>
</tr>
<tr>
<td>Nuclear power</td>
<td>96.90</td>
</tr>
<tr>
<td>Bio-CHP (incremental)</td>
<td>61.00</td>
</tr>
</tbody>
</table>

The results indicate that, even without any subsidies, wind power was among the most competitive electricity production methods in Finland in 2017. Moreover, together with solar power, it is expected to experience the strongest price reduction in the future [57]. However, the calculated LCOE of wind power is still more than double the average day-ahead market price of 2016 in Finland [39]. Therefore, the rapid growth in the Finnish wind power capacity in the 2010s is explained via the high feed-in tariff (FiT). It should be noted, however, that due to the notable electricity wholesale price increase in 2018 and the improving cost-efficiency of wind power production, market-based investment in wind power production has started to occur in Finland after the publishing of Publication II. The resulting LCOE of wind power is in line with a recent study on wind power production costs in Finland, averaging at 60-70 EUR/MWh [58]. However, the estimated lifecycle costs of wind power plants have a notable variance, ranging between 45 and 90 EUR/MWh.

Bio-CHP was the most competitive electricity production method in Finland according to the analysis in Publication II with an LCOE of 61.00 EUR/MWh.

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8 Laid down in section 23 of the Finnish Feed-in-tariff Act, Laki uusiutuvilla energialähteillä tuotetun sähkön tuotantotuesta (1396/2010).
However, the LCOE is still approximately twice the average electricity day-ahead market price in 2016. Due to the topicality of the issue and the concerns over the future of CHP production in Finland among the industry experts, the economics of bio-CHP production are analysed in more detail in Section 4.3.

Solar power is the most expensive production method analysed in Publication II, exceeding the average wholesale electricity market price of 2016 by approximately 88 EUR/MWh. Nonetheless, there is increasing investment in solar photovoltaic (PV) systems in Finland. The resulting LCOE of solar power is in line with e.g. International Renewable Energy Agency (IRENA) [59], which estimates a LCOE of approximately 120 USD/MWh (~105 EUR/MWh) for a commercial PV system and 150 USD/MWh (~132 EUR/MWh) for a residential one in Germany. Solar power systems are currently built for companies’ or households’ captive consumption. Together with wind power, solar power is expected to experience the most rapid decrease in production costs in the future.

The LCOE of nuclear power calculated in Publication II is 96.90 EUR/MWh. This seems optimistic compared with recent nuclear power plant projects in Europe: for example, a FiT of approximately 106 EUR/MWh (92.5 GBP/MWh) is paid to Hinkley Point nuclear power plant in the UK. Therefore, the underlying financial assumptions indicate that investment in a new nuclear power plant in Finland is not economically feasible.

### 4.3 The future role of cogeneration

CHP production accounts for a large share of Finnish electricity production and it is expected to continue doing so under the Finnish Energy and Climate Strategy [8]. However, several simultaneous trends set the future of Finnish CHP production on an ambiguous path. First, demand for district heat is stagnating, as described in Section 4.2. Secondly, a large share of district heat in Finland has traditionally been produced with either coal or natural gas. However, the former is planned to be phased out and the latter has lost its economic competitiveness during the past decade [60]. Thirdly, electricity price level of 2012–2017 encourages replacing retiring CHP capacity with HOBs, which practically excludes the possibility of electricity production at the site for decades to come. Concurrently, there is a consensus among industry experts that a significant reduction in the Finnish CHP capacity would have negative impacts on energy security.

The main argument for CHP production is its evident thermal efficiency comparing to separate heat and power production. It can reach a thermal

---

9 The Hinkley Point feed-in tariff is estimated to be approximately 92.50 GBP/MWh. Financial Times, ‘Why EDF’s Hinkley Point deal is potentially so lucrative’, available at www.ft.com/content/70b9a0ea-6493-11e6-a08a-c7ac04ef00aaa (last accessed on 19 June 2017).
efficiency of up to 90%, as the excess heat from electricity production is utilised as heat in the district heating network. However, condensing power plants have already left the Finnish power market due to the lack of competitiveness in the past decade, and with the current market trends, non-industrial CHP production is next in line. Publications IV and V aim to address the concerns related to the future of CHP production in Finland. In line with the Energy and Climate Strategy of Finland, the most probable energy sources for new CHP production are biomass and peat. However, as peat is a debated fuel with prominent CO₂ emissions, the following analysis concentrates on biomass-based production. Biomass is the most abundant domestically available fuel in Finland and it is considered carbon neutral. The sustainability of biomass utilisation in different timescales is a highly complex issue and extremely relevant for the Finnish energy system and economy. However, a thorough analysis of the issue is outside the scope of this dissertation and hence a subject of future research.

4.3.1 Economics of biomass-based thermal production

As in Section 4.2, costs of CHP plants’ electricity production are derived as the incremental cost of investing in a CHP plant instead of a HOB or a steam generator (SG) with equal heating capacity. Investment in a SG instead of a HOB would leave an option for a turbine investment at the site in case electricity prices reached an adequate level to spur investment in the future. However, such an investment is dubious both technically and economically under the current market uncertainty, and it is hence highly unlikely that an energy company would commit to such an investment without any additional incentives.

Publication IV analysed the economics of biomass-based thermal production and the legal instruments and State-driven financing options available to address the apparent lack of investment in CHP plants. Furthermore, the publication analysed whether an investment in a SG instead of a HOB could be justifiable in different electricity price development scenarios. Economics of the production were analysed applying the methods introduced in Section 3.2. The analysis concentrated on a district heating system that has demand for 200 MW heating capacity. The options were to invest in a HOB, SG or a CHP with 90 MW electrical capacity. It should be noted that the heating capacity of the SG is overdimensioned comparing to the demand for heat, as it is dimensioned to have 200 MW heating capacity after the turbine investment later on. Table 10 presents the input data for the investment profitability analysis, and Table 11 shows the results of the calculations, omitting the FiT for biomass-based electricity production.
Table 10. Input data for calculating the economics of biomass-based thermal generation in Finland with a heating capacity of 200 MW.

<table>
<thead>
<tr>
<th>Item</th>
<th>HOB</th>
<th>SG</th>
<th>CHP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technical assumptions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacity [MWe]</td>
<td>-</td>
<td>-</td>
<td>90</td>
</tr>
<tr>
<td>Operation hours [h/a]</td>
<td>6,000</td>
<td>6,000</td>
<td>6,000</td>
</tr>
<tr>
<td>Efficiency</td>
<td>88.5%</td>
<td>87.0%</td>
<td>86.0%</td>
</tr>
<tr>
<td>Construction time [a]</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Technical lifetime [a]</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Annual degradation</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td><strong>Commercial assumptions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAPEX [EUR/MWth]</td>
<td>0.686</td>
<td>1.019</td>
<td>1.142</td>
</tr>
<tr>
<td>OPEX [EUR/MWhfuel]</td>
<td>3.71</td>
<td>4.60</td>
<td>4.53</td>
</tr>
<tr>
<td>Fuel cost [EUR/MWhfuel]*</td>
<td>22.5</td>
<td>22.5</td>
<td>22.5</td>
</tr>
</tbody>
</table>

*until 2025, an increase of 1% per annum after that

Comparing to a CHP plant investment, the additional CAPEX for making the turbine investment with an existing SG separately afterwards is 5 MEUR. All the plants are assumed to use wood chips as fuel.

Table 11. Results of the investment profitability analysis for biomass-based thermal generation.

<table>
<thead>
<tr>
<th>Plant type (200 MW heating capacity)</th>
<th>LCOE [EUR/MWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat only boiler (HOB)</td>
<td>43.06*</td>
</tr>
<tr>
<td>Steam generator (SG)</td>
<td>49.82*</td>
</tr>
<tr>
<td>Incremental HOB → CHP, 90 MWe</td>
<td>54.35</td>
</tr>
<tr>
<td>Incremental SG → CHP, 90 MWe</td>
<td>40.97</td>
</tr>
</tbody>
</table>

*For heat only production

LCOE of the CHP plant is 54.35 EUR/MWh, which is much higher than the average price during the past years. However, the LCOE of the analysed 90/200 MW\(^{10}\) plant is notably lower than that of the 35/100 MW plant analysed in Section 4.2, with an LCOE of 61.00 EUR/MWh. It should be noted that the average annual spot price in Nord Pool is calculated without taking into account the amount of electricity consumed per hour [39]. Therefore, an average MWh bought from the spot market in 2016 was actually 2.7% more expensive than the annual average price of electricity (calculated by taking into account the hourly electricity demand in 2016 [36]). Moreover, district heating CHP production emphasises on hours with lower temperatures and higher consumption and, consequently, higher electricity price. Therefore, an average MWh produced with district heating CHP in fact yielded 5.3% more revenues in 2016 than what the average spot price would indicate. This should be taken into account when comparing the results of the LCOE calculations with annual average electricity spot prices. Despite the higher yield, decisions by Finnish utilities to replace retiring CHP plants with HOBs are currently economically justifiable if no major subsidy scheme is implemented to encourage investment in CHP plants.

Publication IV analysed a least-cost investment strategy for an investor in a market with demand for 200 MW heating capacity. The analysis is based on finding the highest NPV in three different price scenarios. Subventions for biomass-based CHP electricity production are assumed to continue according to the current law on RES subvention in Finland (30.12.2010/1396) 25 §. The

\(^{10}\) A CHP plant with 90 MW electrical capacity and 200 MW heating capacity.
following three scenarios with different electricity and EUA prices were analysed:

- **Low price scenario**: electricity and EUA prices remain at 30 EUR/MWh and 10 EUR/t until 2045, respectively;
- **Intermediate price scenario**: electricity and EUA prices are the averages of those in the Low and High price scenarios;
- **High price scenario**: electricity and EUA prices develop according to the Finnish Energy and Climate Strategy (42.5 EUR/MWh and 15 EUR/t in 2020, 57.5 EUR/MWh and 22.5 EUR/t in 2025, and 62.5 EUR/MWh and 30 EUR/t from 2030 onwards [31]).

The best investment strategy in the Low price scenario is to invest in a HOB. Despite the FiT of 18 EUR/MWh for CHP electricity production for the first 12 years of operation, the investment is not economically justifiable. In the High price scenario, the highest NPV is achieved via a direct investment in a CHP plant. Taking into account the FiT and the higher value of CHP production comparing to the average spot price, the electricity sales price surpasses the calculated LCOE already in the first year of operation. The Intermediate price scenario, on the other hand, deserves a more thorough scrutiny. Investment in a CHP plant results in a slightly negative NPV (-5.2 MEUR, in comparison with the -52.6 MEUR in the Low price scenario), and an increase of one EUR/MWh in the average spot price throughout the plant’s technical lifetime would already make the investment feasible. However, an initial investment in a SG with a turbine investment later on would still not be feasible in the Intermediate price scenario. The current FiT for bio-CHP decreases as the EUA price increases, and the rising EUA price is one of the main components that could cause an increase in the average price of electricity in the Nordics.

Kaisa Huhta from University of Eastern Finland analysed the legal instruments and State-driven financing options available to subsidise CHP in Publication IV. Her conclusion was that State financing to CHP or SG in the interest of generation adequacy in this case is unlikely to comply with EU law.

### 4.3.2 Energy security impacts of decreasing CHP capacity

The impacts of decreasing CHP capacity in Finland are often absent from the debate among politicians and industry experts. Publication V aimed to address this issue on three levels: local (a case study of Helsinki), national, and international (the Northern European power market). The publication analysed a scenario where the average wholesale price of electricity remains at around 30 EUR/MWh throughout the 2020s, which results in a sharp decrease in the Finnish CHP capacity. Kristo Helin from Aalto University modelled the energy system of Helsinki until 2030 in the scenario, and the decreasing CHP capacity in Helsinki would most probably be substituted with biomass-based (pellets in this case, as the availability of forest fuels is limited in the capital region [61]) HOBs. The most tangible energy security impacts of the decreasing CHP capacity on a local level would therefore revolve around risks related to the
storability [62], availability, cost level and sustainability of biomass [63]. Supplying the current heat demand with biomass in Helsinki would already notably surpass Finland’s potential and visions for domestic pellet production, and most of the fuel would therefore need to be imported. Moreover, carbon neutrality of biomass is to some extent theoretical with the timescale of a few decades and the underlying urgency related to climate change mitigation. These perspectives are in contrast with the most common arguments for biomass utilisation, i.e. self-sufficiency and environmental friendliness.

The main concerns related to the decrease in the Finnish CHP capacity on a national level are generation adequacy, flexibility, inertia, and self-sufficiency. The issues regarding generation adequacy were analysed in Section 4.1, and the planned new nuclear power plants and transmission lines should compensate for a notable decrease in the Finnish CHP capacity. With regard to flexibility and inertia, there are currently no clear price signals indicating a scarcity of either. Price spikes are rare enough not to encourage investment in peak power production and the significant hydropower capacity in the Nordics has so far balanced the market well. The implications of decreasing CHP capacity on inertia, i.e. the amount of kinetic energy in the power system, have also raised concerns. However, should the two new nuclear power plants in Finland be deployed, their rotating mass should compensate for the decreasing thermal capacity in Finland [64]. Both flexibility and inertia, however, are issues that warrant attention in the future with the integrating European power market.

Self-sufficiency in power production is a two-sided issue. One side is the self-sufficiency regarding capacity, i.e. generation adequacy, which was discussed in Section 4.1. The other side is self-sufficiency regarding primary energy supply. Despite the increasing self-sufficiency, Finland still imports almost two thirds of its primary energy (the import dependence will be discussed further in Section 4.5). The decommissioned CHP capacity in the scenario analysed in Publication V is mainly based on coal and natural gas, both of which Finland imports in its entirety. Therefore, the decreasing capacity would not increase Finnish primary energy import. Imported electricity is regarded as a source of primary energy without taking into account the losses in production. Consequently, importing electricity produced with a certain fuel instead of the fuel per se would technically only decrease Finland’s primary energy import.

Demand for electricity is generally inelastic and thus not greatly affected by the existence Finnish CHP production or the lack thereof. Moreover, Nordic electricity production has generally low marginal costs, e.g. hydropower, wind power and nuclear power. This means that these carbon-neutral technologies are prioritised in the merit order, i.e. they are dispatched even with lower demand and price level. Therefore, without additional investment in power capacity, a decrease in Finnish CHP production would not be replaced with any of the above-mentioned technologies, and it would not notably decrease electricity demand either. Instead, electricity would be imported from countries that have available production capacity, which in this case is mostly thermal production. This view is in line with the past. In the 2000s, production deficits (due to outages in Swedish nuclear power units and low hydropower
production) have eventually been compensated by increases in thermal production in inter alia Finland and Denmark [65], [66]. However, as thermal power capacity in Finland (along with that in Denmark) decreases in the scenario of Publication V, the compensating production will eventually take place in other countries, such as Poland, the Baltics or Germany. These countries have condensing power capacity with a capacity factor well below 100% and therefore potential to increase production. Thus, as long as CHP production in Finland eventually replaces separate heat and power production based on fossil fuels, CHP production is clearly the more environmentally friendly option. That is, a decrease in the Finnish CHP capacity has the potential to increase fossil fuel use and CO₂ emissions in the North European level. The net impact on the international level should not be ignored when analysing energy security, especially when it comes to sustainability and acceptability issues.

4.4 Energy security impacts of a severe drought

4.4.1 Background

The Finnish and Nordic power systems rely heavily on hydropower production. Despite hydropower being among the most flexible production methods in the short-run, there can be significant differences in annual production volumes based on the hydrological conditions. Therefore, the interdependence between generation adequacy in Finland and the hydrological conditions in the Nordics deserves a thorough scrutiny. As in Sections 4.1, 4.2 and 4.3, the vital energy system is thus the energy flows that support critical social functions and the embedded economic implications to end-users due to stresses in supply.

Noora Veijalainen from the Finnish Environment Institute analysed the history of Nordic droughts in Publication III. Severe droughts in the Nordics are rare, but some notable droughts have occurred once every few decades [67]. The worst drought of the past century took place in 1939–1942, during which the precipitation was well below average for over three consecutive years. Year 1941 was the driest year of the century and, consequently, hydropower production during the year was only around half of that in e.g. the late 1930s [68]. However, comparing the hydropower production of 1941 directly to the present day is not sensible, as a large proportion of Finland’s hydropower capacity was built only after 1946. In order to analyse the impacts of a similar drought in the Finnish energy system currently and in the future, Veijalainen modelled the hydrological conditions of 1939–1942 with the current hydropower capacity. Using observations of temperature, precipitation, wind speed and relative humidity of 1938–1942 provided by the Finnish Meteorological Institute, she modelled the discharge at locations of the current hydropower plants using Finnish Environment Institute’s Watershed Simulation and Forecasting
Results

In addition to weekly power production, she estimated the maximum production during peak demand. This data was used as input in the energy system simulations, of which results are presented next. The indirect impacts via reduced availability of cross-border transmission capacity are based on analysis of realised, less severe droughts in the 2000s.

### 4.4.2 Implications of a drought in Finland

The hydrological simulations of the drought situation result in a significant reduction in annual hydropower production. For example, the annual production with the current hydropower capacity using weather conditions of 1942 is 56% lower than that in 2016 (6.9 TWh/a vs. 15.6 TWh/a). However, the simulations result in a reduction of only approximately 19% in hydropower availability during the demand peak in January comparing to the realised production in 2016 (2,235 MW), as dammed storages can be used to increase the discharges during this short period. However, the realised hydropower production during the peak in 2016 fell 315 MW short of the estimated availability, which is reasonable considering the moderate price level during the peak. Comparing with the estimated hydropower availability during the peak, the simulated availability during the drought is approximately 29% lower.

Figure 10 depicts the weekly average hydropower production with hydrology of 1941–1942 and 2015–2016. The values from 1940s are based on the hydrological simulations by the Finnish Environment Institute and the values from 2010s are based on realised hourly values [36]. However, it should be noted that hydropower production during 2015–2016 was notably above long-term average of approximately 13 TWh/a [68].

![Figure 10. Weekly average hydropower production in Finland with the hydrological conditions of 1941–1942 and 2015–2016 and the hydropower capacity of 2016.](image)

Thus, the impact of the Finnish drought on generation adequacy is much less severe (approximately 420 MW) than any of the stress factors analysed in Section 4.1.1 (technical faults in Olkiluoto power plants and in transmission...
lines between Finland and Sweden), and the system would therefore have had no problems with supplying the demand peak in 2016 or in 2020 in any of the scenarios in Publication III, Basic, Policy and Alternative. This is mostly due to the ability to use storage reservoirs during a short peak demand period. In 2030, the scenarios Basic and Policy could withstand the Finnish drought also without any measures of intervention. However, the Alternative scenario has a deficit of 590 MW already during a drought affecting only Finland.

However, the result above applies only if the drought takes place merely in Finland and electricity import from the neighbouring countries is not constrained in any way. This would likely not be the case. Thus, the following section analyses the impacts of a Nordic drought on generation adequacy in Finland.

### 4.4.3 Implications of a drought in the Nordic region

In order to understand the indirect impacts of a severe drought on Finland, Finland’s connections to its neighbouring power systems are analysed next. As described in Section 2.2.2, Finland has cross-border transmission lines to Sweden, Russia and Estonia. Moreover, there is a transmission line between Finland and Norway, but it is not in commercial use. Finland’s net electricity import from Sweden (and indirectly from Norway) was over 15 TWh in 2016 [30]. The Swedish and Norwegian power markets are both larger than the Finnish market and they are both by far more reliant on hydropower than Finland. Production and consumption figures in the Swedish and Norwegian power markets in 2016 are depicted in Table 12. Average annual hydropower production in the 2000s has been approximately 68 TWh in Sweden and 127 TWh in Norway, although hydropower capacity in Norway has been growing gradually. However, variation in the inflow to the Norwegian hydropower system has been around 60 TWh in the past few decades [69]. Consequently, annual fluctuations in hydropower production affect generation adequacy much more in Sweden and Norway than in Finland.

**Table 12. Electricity production and demand in 2016 in Finland, Sweden and Norway [70].**

<table>
<thead>
<tr>
<th></th>
<th>Finland</th>
<th>Sweden</th>
<th>Norway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total installed power capacity [GW]</td>
<td>17.0</td>
<td>39.4</td>
<td>32.0</td>
</tr>
<tr>
<td>Installed hydropower capacity [GW]</td>
<td>3.2</td>
<td>16.2</td>
<td>30.8</td>
</tr>
<tr>
<td>Annual consumption [TWh]</td>
<td>85.1</td>
<td>139.8</td>
<td>133.2</td>
</tr>
<tr>
<td>Annual demand peak [GWh/h]</td>
<td>15.1</td>
<td>26.6</td>
<td>24.5</td>
</tr>
<tr>
<td>Annual production [TWh]</td>
<td>66.0</td>
<td>151.5</td>
<td>148.8</td>
</tr>
<tr>
<td>Annual hydropower production [TWh]</td>
<td>15.6</td>
<td>61.2</td>
<td>143.4</td>
</tr>
<tr>
<td>Share of total production</td>
<td>23.6%</td>
<td>40.4%</td>
<td>96.4%</td>
</tr>
</tbody>
</table>

*in the end of 2016.

During dry years, both Norway and Sweden become net importers of electricity, whereas e.g. in 2016, both countries’ net electricity exports were more than 10 TWh. Most recently, this occurred for both countries in 2006 and 2010. In both cases, this was due to a combination of drought and technical faults in Swedish nuclear reactors [71], [72]. Consequently, the lack of hydropower availability was largely compensated by increases in Finnish and Danish thermal power generation, which both have decreased notably since.
The modelled drought of 1939–1942 is significantly more severe and lengthier than the dry periods in recent years. It has been estimated that the inflows to Norway’s reservoirs (2005 system) were approximately 25% below average in 1941 and 12-16% below average in 1939 and 1940 [73]. Similar reduction in inflow can also be assumed for Sweden. While the significant reservoirs in the Nordics (around 85 TWh in Norway and 34 TWh in Sweden [72]) can be used to buffer the effect of decrease in inflow, the storage capacity is not enough for a three-year-long drought. Therefore, when electricity import from Sweden to Finland stops during relatively modest dry periods such as in 2006 and 2010, it is safe to assume that during an extreme drought like in 1939–1942, no electricity import from Sweden to Finland would be available during the demand peak.

The Russian government implemented a mechanism called capacity delivery agreement (CDA) in order to incentivise investment in electricity generation capacity starting from 2010. Approximately 40 GW of generation capacity has been launched by CDAs in 2010–2015, namely nuclear, hydro and thermal generation [74]. However, demand for electricity has not grown as forecasted prior to the financial crisis and the mechanism has therefore resulted in a surplus of power capacity in Russia. Production capacity in Western Russia, where the Finnish and Russian power systems are connected, surpasses the annual demand peak by almost 70% (12.6 GW vs. 7.5 GW) [75]. Moreover, Russia is less dependent on hydropower production than the Nordic countries, and approximately two thirds of electricity in Russia is produced with natural gas [74]. Therefore, it is reasonable to assume that electricity trade between Finland and Russia would not be restricted in case the severe drought affected also Western Russia, particularly when assuming an electricity price level reflecting an imminent generation inadequacy in Finland.

Estonia has a very modest hydropower capacity and is currently self-sufficient regarding generation capacity during peak demand. However, Estonia is a transit country of electricity: in 2015, Estonia’s net import from Finland was 5.0 TWh and net export to Latvia was 5.9 TWh, which is a significant flow of electricity comparing to Estonia’s own annual consumption of 7.4 TWh [76]. Latvia and Lithuania, on the other hand, have notable hydropower capacities, and a transmission line between Lithuania and Sweden, NordBalt, was commissioned in late 2015. Therefore, a severe drought in Sweden would also affect Finland indirectly via the availability of electricity import from the Baltic countries. Furthermore, more than 80% of electricity in Estonia is produced with oil shale and a majority of it in Narva Power Plants. Most of these plants were constructed between 1959–1973 and some of them will most probably be decommissioned by 2024 [76]. Therefore, the availability of thermal capacity and hence the self-sufficiency of electricity supply in Estonia in 2030 remains uncertain. Publication III assumes that no restrictions in electricity import from Estonia occur in the stress test in 2020, but that the decommissioning of thermal capacity in the 2020s reduces the available electricity import by 200 MW in 2030.
In addition to the planned new transmission lines between Finland and Sweden, there are numerous plans to increase transmission capacity inside the Nord Pool region and between Nord Pool and Central Europe [77]. Publication III assumes, however, that alleviating congestion inside Sweden and Norway or between the countries does not solve the lack of hydropower availability during a severe drought. Moreover, the publication assumes that the planned new transmission lines between Nord Pool region and Central Europe (and UK) will not notably ease the stresses related to generation adequacy during the peak demand in Finland by 2030. However, this is a complex issue with conflicting views among industry experts. On the one hand, the increasing interconnection capacity will increase the demand for the cheap and flexible Nordic hydropower production, and hence decrease its availability in Finland. On the other hand, the new transmission lines will make the Central European thermal power production more available to the Nordic countries during peak demand.

In 2020, a drought affecting also Sweden and Norway would already cause a deficit of 360 MW during the stress test described in Section 3.1.1 in the Basic and Policy scenarios and 925 MW in the Alternative scenario due to the reduced availability of electricity import. By 2030, the impacts of the drought in neighbouring countries have increased due to the increased cross-border transmission capacity between Finland and Sweden, resulting in deficits of 820 MW, 1,730 MW and 3,590 MW in the scenarios Basic, Policy and Alternative, respectively. The deficit in the scenarios Basic and Policy could technically be supplied with the available measures and strategic reserves described in Section 2.2.4, but the deficit of 3,590 MW in the Alternative scenario is alarming. Table 13 summarises the results of the energy system simulations in Publication III, and Figure 11 illustrates the electricity demand and supply during the peak demand day in the Policy scenario in 2030 during a Nordic drought.

**Table 13.** Available production and transmission capacity after supplying the demand during the demand peaks in 2020 and 2030 in different scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Available capacity during the demand peak in 2020</th>
<th>Available capacity during the demand peak in 2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic</td>
<td>2,790</td>
<td>3,730</td>
</tr>
<tr>
<td>Basic, Finnish drought</td>
<td>2,040</td>
<td>2,980</td>
</tr>
<tr>
<td>Basic, Nordic drought</td>
<td>-360</td>
<td>-820</td>
</tr>
<tr>
<td>Policy</td>
<td>2,790</td>
<td>2,820</td>
</tr>
<tr>
<td>Policy, Finnish drought</td>
<td>2,040</td>
<td>2,070</td>
</tr>
<tr>
<td>Policy, Nordic drought</td>
<td>-360</td>
<td>-1,730</td>
</tr>
<tr>
<td>Alternative</td>
<td>2,225</td>
<td>160</td>
</tr>
<tr>
<td>Alternative, Finnish drought</td>
<td>1,475</td>
<td>-590</td>
</tr>
<tr>
<td>Alternative, Nordic drought</td>
<td>-925</td>
<td>-3,590</td>
</tr>
</tbody>
</table>
With regard to the energy security impacts of climate change on the Finnish energy system, Veijalainen concluded in Publication III that simulated scenarios indicate that climate change could actually work in favour of generation adequacy by increasing the precipitation and discharges during the winter season and decreasing the occurrence of extremely low temperatures. However, climate change can also increase the intensity of the extremes in inter alia precipitation and temperatures.

### 4.5 Primary energy import dependence

Finland imported 64.0% of its primary energy in 2016 of which 63.0% originated in Russia. That is, 40.4% of the total primary energy in 2016 was of Russian origin. This has sparked debate in Finland on whether the low self-sufficiency in energy and the high dependence on one supplier are in fact threats to energy security or merely a sign of mutually beneficial trade relations. Publication VI aimed to address this concern. The vital energy system at hand are the energy flows that support critical social functions and the risks are related to the lack of sovereignty.

#### 4.5.1 Finland’s dependence on Russian energy until 2016

Finland has a long history of energy trade with Russia and the trade is practically one-directional: Finland lacks domestic fossil fuel reserves in comparison with
its substantial demand for energy, whereas Russia has significant export volumes. Table 14 presents the Finnish primary energy consumption in 2016 and import from Russia. Value of the Finnish primary energy import in 2016 amounted to 7,128 MEUR, of which 67.7% was related to trade with Russia [30].

Table 14. Primary energy sources in Finland and the share of Russian import in 2016 [30].

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Consumption [TWh/a]</th>
<th>Share</th>
<th>From Russia [TWh/a]</th>
<th>Share of total</th>
<th>Share of import</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass</td>
<td>99.5 ¹</td>
<td>26.3%</td>
<td>10.9 ²</td>
<td>11.0%</td>
<td>91.5%</td>
</tr>
<tr>
<td>Oil</td>
<td>88.1</td>
<td>23.3%</td>
<td>67.4 ³</td>
<td>76.5%</td>
<td>76.5%</td>
</tr>
<tr>
<td>Uranium</td>
<td>67.5</td>
<td>17.9%</td>
<td>26.6 ⁴</td>
<td>39.4%</td>
<td>39.4%</td>
</tr>
<tr>
<td>Coal and coke</td>
<td>35.3</td>
<td>9.3%</td>
<td>21.6</td>
<td>61.2%</td>
<td>61.2%</td>
</tr>
<tr>
<td>Natural gas</td>
<td>20.3</td>
<td>5.4%</td>
<td>20.3</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Net electricity import</td>
<td>19.0</td>
<td>5.0%</td>
<td>5.9</td>
<td>30.9%</td>
<td>30.9%</td>
</tr>
<tr>
<td>Hydropower</td>
<td>15.6</td>
<td>4.1%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Peat</td>
<td>15.6</td>
<td>4.1%</td>
<td>0.1</td>
<td>0.5%</td>
<td>52.5%</td>
</tr>
<tr>
<td>Recycled and waste energy</td>
<td>8.1</td>
<td>2.1%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Heat pumps</td>
<td>5.9</td>
<td>1.6%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wind and solar</td>
<td>3.1</td>
<td>0.8%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Other</td>
<td>0.3</td>
<td>0.1%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>378.2</td>
<td>100%</td>
<td>152.7</td>
<td>40.4%</td>
<td>63.0%</td>
</tr>
</tbody>
</table>

¹ Including all wood-based fuels, black liquor, biogas and other bioenergy.
² Natural resources institute of Finland [78].
³ Including crude oil, middle distillates, heavy fuel oil, LPG, methanol and other petroleum products.
⁴ Estimated figure, as some of the oil is refined in Finland and exported.
⁵ Based on fuel sources and production volumes of Finnish nuclear power producers in 2016. Due to relatively easy storability of uranium, consumption of uranium is a better indicator than the import in a single year.

As depicted in Table 14, the most notable energy sources from Russia are oil, uranium, coal, and natural gas, respectively. Of these fuels, natural gas is the most sensitive in terms of security of supply, as practically all the natural gas consumed in Finland still comes through a single pipeline from Russia. Moreover, unlike for other imported fuels, there are practically no natural gas storages in Finland. However, the role of natural gas in Finland has decreased during the past decade. The global markets for crude oil and coal, on the other hand, are liquid. Uranium is not traded as openly, but there is still a variety of suppliers globally. All the aforementioned three fuels (oil, coal and uranium) are relatively easy to transport and store. Furthermore, due to the obliged storages of imported fuels (reviewed in Section 2.2.4), disruptions in their supply would not cause acute shortages for end users of energy.

Electricity import from Russia has decreased significantly due to the developments described in Section 4.4.3. As can be seen from Figure 12, a majority of Finland’s net electricity import came from Russia until 2011 [30]. Since 2012, electricity has been imported from Russia mostly during peak demand periods, and the majority of import originated in Sweden. Furthermore, as described in Section 4.4.3, it is highly unlikely that electricity trade between Russia and Finland could be hindered due to lack of available capacity in western Russia.
Finland’s notable dependence on imported primary energy has so far not resulted in any security of supply threats to materialise. Moreover, through purely techno-economic analysis, Publication VI did not find any acute energy security threats related to the Finnish-Russian energy trade. Primary energy supply is of such importance that Finland stores enough critical energy fuels in order to avoid an immediate energy crisis in case of disturbances in the fuel supply. However, Sakari Höysniemi from University of Helsinki notes in Publication VI that energy relations and the concept of energy security go beyond the flow of fuels and electricity. He describes that the Finnish policy has traditionally focused on retaining good relations, but not everything is in Finland’s control. The energy sector has a vital role for the Russian economy and it is entrenched deep in Russia’s political strategy. Finnish companies are mostly cooperating with the state-owned Russian companies that have been the key targets of sanctions by e.g. the EU and US since the annexation of Crimea. As a response for the broadening sanctions, Russia could for instance establish stricter policy for foreign companies in energy sector. This could increase the political risk of Finnish companies with business in Russia.

### 4.5.2 Development of Finnish-Russian energy trade

As described in Section 2.2.5, the Finnish energy policy aims towards increased self-sufficiency in energy supply. Consequently, the use of imported oil and coal should decrease notably by 2030, and the use of natural gas has declined due to market-based reasons. Furthermore, the natural gas market is about to open via Balticconnector and LNG terminals. Russian uranium import, on the other hand, remains quite even in case the Hanhikivi 1 power plant is deployed.

In order to study the future development of Finnish-Russian energy trade, Publication VI analysed three different energy market scenarios until 2040: Market trends, Low carbon and High carbon. Each scenario results in a reduction in the use of fossil fuels in Finland and, consequently, also in energy
import from Russia. The share of Russian import in the Finnish primary energy mix by 2040 in the Market trends, Low carbon and High carbon scenarios is 16%, 13% and 32%, respectively, comparing to 40.4% in 2016. Table 15 shows the development of the import in the scenarios. The scenarios are elaborated more in Section 5 of Publication VI.

Table 15. Primary energy import from Russia in the Market trends, Low carbon and High carbon scenarios.

<table>
<thead>
<tr>
<th>Energy source [TWh]</th>
<th>2016</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2035</th>
<th>2040</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Market trends scenario</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td>67.4</td>
<td>67.4</td>
<td>65.0</td>
<td>50.0</td>
<td>33.7</td>
<td>28.0</td>
</tr>
<tr>
<td>Uranium</td>
<td>26.6</td>
<td>26.6</td>
<td>26.6</td>
<td>26.6</td>
<td>25.6</td>
<td>25.6</td>
</tr>
<tr>
<td>Coal and coke</td>
<td>21.8</td>
<td>21.8</td>
<td>20.0</td>
<td>16.0</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Natural gas</td>
<td>20.3</td>
<td>20.3</td>
<td>17.0</td>
<td>14.0</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Electricity</td>
<td>5.9</td>
<td>5.9</td>
<td>3.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Total</td>
<td>141.8</td>
<td>141.8</td>
<td>131.6</td>
<td>107.6</td>
<td>78.3</td>
<td>70.6</td>
</tr>
<tr>
<td><strong>Low carbon scenario</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td>67.4</td>
<td>62.0</td>
<td>47.0</td>
<td>30.0</td>
<td>24.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Uranium</td>
<td>26.6</td>
<td>26.6</td>
<td>26.6</td>
<td>25.6</td>
<td>25.6</td>
<td>25.6</td>
</tr>
<tr>
<td>Coal and coke</td>
<td>21.6</td>
<td>20.0</td>
<td>13.0</td>
<td>6.0</td>
<td>4.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Natural gas</td>
<td>20.3</td>
<td>17.0</td>
<td>12.0</td>
<td>8.0</td>
<td>7.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Electricity</td>
<td>5.9</td>
<td>3.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Total</td>
<td>141.8</td>
<td>128.6</td>
<td>99.6</td>
<td>70.6</td>
<td>61.6</td>
<td>55.6</td>
</tr>
<tr>
<td><strong>High carbon scenario</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td>67.4</td>
<td>68.0</td>
<td>65.0</td>
<td>64.0</td>
<td>63.0</td>
<td>62.0</td>
</tr>
<tr>
<td>Uranium</td>
<td>26.6</td>
<td>26.6</td>
<td>26.6</td>
<td>28.6</td>
<td>31.6</td>
<td>34.6</td>
</tr>
<tr>
<td>Coal and coke</td>
<td>21.6</td>
<td>20.0</td>
<td>18.0</td>
<td>16.0</td>
<td>14.0</td>
<td>13.0</td>
</tr>
<tr>
<td>Natural gas</td>
<td>20.3</td>
<td>17.0</td>
<td>15.0</td>
<td>15.5</td>
<td>16.0</td>
<td>16.5</td>
</tr>
<tr>
<td>Electricity</td>
<td>5.9</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Total</td>
<td>141.8</td>
<td>133.6</td>
<td>128.6</td>
<td>128.1</td>
<td>128.6</td>
<td>130.1</td>
</tr>
</tbody>
</table>
5. Discussion and Conclusions

5.1 Main findings of this dissertation

This dissertation aimed to identify the most relevant market-related energy security threats in the Finnish energy system currently and in the future (Q1) and to analyse the system’s resilience against these threats (Q2). The dissertation applied a framework that defines energy security as the low vulnerability of vital energy systems. The identified vulnerabilities in the publications were all connected to the supply of energy on a system level. The most relevant vulnerabilities found in this dissertation related to generation adequacy and import dependence, with the underlying pressure to decarbonise the energy system in the following decades. Particularly interesting phenomena under these topics were the role of CHP production in the future, interdependence between generation adequacy and hydrological situation in the Nordics, and Finland’s notable dependence on one primary energy supplier, Russia. The next sections summarise the findings of this dissertation on the aforementioned topics.

5.1.1 Generation adequacy

Publications I and II analysed generation adequacy in the Finnish energy system currently, and Publication III analysed the development of generation adequacy in Finland until 2030. The ongoing energy transition has resulted in decreasing thermal power capacity, which has traditionally been used for peak power production in Finland. Concurrently, the annual electricity demand peaks have grown and, consequently, a growing share of the demand peaks has been supplied with imported electricity. Despite the raised awareness, however, Publications I and II concluded that the Finnish energy system is currently well prepared against stressful market conditions. Furthermore, the system has a variety of fail-safe mechanisms, which are yet to be tested. The significant and growing dependence on imported electricity during demand peaks, on the other hand, is an issue beyond techno-economic optimisation. Energy market integration is a key target in EU energy policy and Finland’s neighbouring countries are currently capable of producing electricity with lower marginal costs. Against this background, the question is how much Finland is and should be willing to pay for maintaining uncompetitive excess capacity due to self-sufficiency and security reasons and why.
Publication III concluded that generation adequacy in Finland should improve by 2030 in the scenarios of the Finnish National Energy and Climate Strategy, mainly due to the two new nuclear power plants and the increasing transmission capacity between Finland and Sweden. However, two issues arose that warrant attention, which will be discussed next: the future role of CHP production in Finland and the impacts of a severe drought.

5.1.2 Future role of CHP production

Publication II identified a controversy between generation capacity investment prospects in Finland and the expected contribution of CHP production according to the Finnish Energy and Climate Strategy. Thus, Publications IV and V delved deeper into the subject, analysing the economics of biomass-based thermal production in Finland and the energy security impacts in case a notable reduction in Finnish CHP capacity takes place in the 2020s, respectively.

Publication IV concluded that if electricity market prices maintain the level of 2012–2017, retiring CHP plants will be replaced with heat only production. Thus, the evident thermal efficiency compared to separate heat and power production is not enough to validate the existence of non-industrial CHP production in the Finnish energy market, despite its historical importance in the system. However, contrary to the market expectations in 2016–2017, electricity wholesale prices in the summer of 2018 soared due to drought and high EUA and coal prices.

Publication V analysed the implications of a significant decrease in the Finnish CHP capacity. CHP plants are a source of reliable capacity, flexibility and inertia with contribution to self-sufficiency and generation adequacy. However, the publication concluded that there are currently no clear price signals indicating a scarcity of any of the aforementioned, and the two new nuclear power plants and new transmission lines should in fact more than compensate for a notable decrease in the Finnish CHP capacity. Moreover, as Finland aims to decarbonise its energy system, the most probable fuel for new CHP plants would hence be biomass. However, the amount of biomass needed to substitute the retiring CHP production based on coal and natural gas is dubious with regard to sustainability and climate change mitigation. One finding of the publication was that limiting the analysis to a national energy system leads to local optimisation: if decommissioning a CHP plant in Finland results in a corresponding increase in separate heat and power production with higher emissions in the wider European energy system, it is questionable to justify it with sustainability.

5.1.3 Resilience against a severe drought

The Nordic energy system is highly dependent on hydropower production and, thus, Publication III analysed the energy security impacts of a severe drought in the Finnish energy system. A drought similar to the one experienced in 1939–1942 in Finland would result in an annual hydropower production half of that in e.g. 2016. However, the drought would likely not cause generation
inadequacy during a demand peak in Finland due to the ability to use storage reservoirs during short peak demand periods.

Swedish and Norwegian energy systems, on the other hand, are much more reliant on hydropower production than Finland. Therefore, a similar drought occurring in the whole Nord Pool region simultaneously would result in severe indirect energy security impacts in Finland via reduced availability of electricity import. Finland has imported a significant amount of electricity from Sweden during peak demand periods during the past decade. However, the analysed drought lasted for more than three years and, therefore, the substantial hydro reservoirs in Norway and Sweden that are used to buffer shorter drought periods would have been depleted. Based on dry periods during the past years, Sweden could become a net importer of electricity from Finland during a more severe drought. This could cause severe stress related to generation adequacy in Finland and in the Nord Pool area.

5.1.4 Import dependence on Russian energy

Publication VI analysed the energy security issues related to Finland’s notable import dependence on Russian energy. So far, there have been no notable disturbances in the supply of energy from Russia. Moreover, Finland aims to reduce the use of imported fossil fuels and, therefore, the dependence is unlikely to worsen in the future. The Finnish energy system is prepared for disturbances in the supply of energy fuels and there is a variety of global suppliers of coal, oil and uranium. The most critical dependence is connected to the existing infrastructure, i.e. natural gas pipelines and cross-border transmission lines, but both the amount of imported electricity and natural gas from Russia have decreased notably during the 2010s. However, energy trade between the countries goes beyond the trade of electricity and energy fuels, and energy-related issues between the countries are discussed in high-level diplomatic meetings. One example of a politically charged project between Finland and Russia in the field of energy is the nuclear power plant under planning and construction, Hanhikivi 1. Therefore, despite the absence of disturbances in security of supply, there are possible risks and feedback loops that could affect Finland due to the challenges in forecasting societal, political and economic trends.

5.2 Discussion

Despite the high demand for energy combined with the apparent lack of domestic resources, this dissertation found no insurmountable energy security threats in the Finnish energy system. Finland has a highly diversified energy supply mix, reliable infrastructure, and high energy efficiency due to e.g. CHP production. The severe drought similar to that in 1939–1942 would have the most tangible implications for the Finnish energy system, most notably via the reduced availability of cheap electricity import from Sweden and indirectly from Norway. Estimating the occurrence of such a drought followed by a record-high demand peak period is challenging, however. Therefore, Publication III
analysed the issue as a black swan event, i.e. an event that is extreme in its nature and difficult to predict.

Forecasting trends in complex systems such as in the field of energy is difficult. Moreover, energy security is a highly complex topic with a variety controversial objectives and innate trade-offs. Despite the relatively short time span of this dissertation, several predictive outlooks in the publications were proved inaccurate shortly later on. Based on the developments in the Nordic electricity market and the market expectations in the derivatives market, a notable increase in electricity price level was seen improbable at least. Yet, summer 2018 brought along significantly higher spot prices throughout the Nord Pool area. However, it remains to be seen how the price level develops from now on. Another statement in Publications I and II was that the materialisation of simultaneous faults in two or three major power system components is an event of severely unlikely occurrence. Yet again, the two largest power plants in Finland had simultaneous forced outages in 18 July 2018, while an annual maintenance took place in a transmission line between Finland and Russia. Moreover, the production of yet another nuclear power plant in Finland had to be downscaled due to technical fault in the following day. It should be noted, however, that the system withstood the situation without significant measures of intervention, such as activating the peak load reserve or resorting to rolling blackouts.

One theme worth emphasising is the growing urgency related to climate change mitigation. Climate change is acknowledged as an underlying theme in national energy policies, but as years pass by, we seem to be no closer in solving the challenge. The impacts of climate change grow more tangible every year, yet the wilful blindness regarding the global need to act on it dissipates slowly. Despite the long-term perspective for the implications to materialise fully, climate change is the most urgent energy security threat to address globally in the next few decades. The scenarios developed in Publication VI inevitably vary in terms of how the Finnish-Russian energy trade develops, but the more significant differences are in their impact on the global climate. As the Market trends scenario is already dubious with regard to climate change mitigation and the plausible multiplicative effects caused by climate change, materialisation of the High carbon scenario could result in challenges far greater than the slower development of Finnish self-sufficiency in energy supply.

5.3 Strengths and weaknesses of this dissertation

As discussed in Section 1.3, the novelty and thus the strengths of this dissertation are in its focus on highly topical issues in the Finnish energy system and its strong connections on the Finnish infrastructure, legislation and energy policy. Research questions of the individual publications were formed based on dialogue with Finnish energy authorities and officials as a part of the Winland project, a thorough review of energy system related research in Finland, public discussion by industry experts and politicians, and by analysing the Finnish energy policy goals in comparison with the current economic and political
Discussion and Conclusions

trends. Some of the topics in this dissertation have previously been analysed by e.g. Finnish consultancy companies and Master’s thesis students. However, prior to this dissertation, there has been no peer-reviewed academic research that would have addressed the analysed issues – particularly not with the interdisciplinary approach applied in this dissertation. Many of the studied phenomena required analysis and methods from several disciplines. Understanding the development of generation adequacy required analysis of the physical energy system, market mechanism, legislation, and economics. Analysing the impacts of a severe drought required deep understanding of hydrology, climate, hydropower production, and the dynamics related to the connections to neighbouring energy systems. Furthermore, a deep understanding of the political relations between Finland and Russia was needed in addition to understanding the related energy infrastructure and energy markets in order to analyse Finland’s dependence on Russian energy.

Limitations of this dissertation are most strongly connected to the complexity of the research topic. It is very difficult to quantify whether the most relevant energy security risks have been addressed in an energy system – let alone to predict and to rank those in the future by their severity. The phenomena selected for analysis in this dissertation reflect the existing consensus on the most topical and likely threats in the Finnish energy system. However, the existing consensus is not proof of these threats actually being the most severe threats the system faces.

The applied energy security framework allows the dissection and categorisation of the energy system itself and its plausible vulnerabilities. However, in the absence of similar results from other countries, comparing the results of this dissertation with other national energy systems is difficult. Moreover, there are no reliable statistics of e.g. extreme weather phenomena or one country’s tendencies to use energy trade for political leverage – currently or in future scenarios. Therefore, even comparing the results of individual publications in this dissertation with each other is challenging. Several studies on resembling topics have been made on e.g. the impacts of a drought [67], [73] and dependence on Russian energy [79], [80], and they are elaborated in the corresponding publications. Neither of the abovementioned studies on drought indicates severe problems for the Nordic power market. Studies on the energy trade between EU and Russia, on the other hand, often concentrate on a single fuel, namely natural gas. These studies often recognise Finland’s dependence on Russian natural gas, but do not delve deeper into the role and substitutability of natural gas in the Finnish energy market. One limitation of this dissertation is that the analysis lacks stochasticity and concentrates on analysing discrete ceteris paribus scenarios instead. The applied energy system simulation tool, EnergyPLAN, also shares this limitation. Limitations of the EnergyPLAN tool are described in more detail in Section 3.1.3.
5.4 Recommendations for future research

There are several issues increasing the uncertainty in the Nordic energy system, inter alia the fate of Swedish nuclear power plants and what replaces the Narva power plants in Estonia in the 2020s. Another issue worth a more thorough scrutiny is the impacts of increasing transmission capacity between Nord Pool area and Central Europe (and UK) on storage reservoirs and hydropower availability in the Nordics. These require a modelling tool more suitable for multi-regional analysis and are subjects of future research.

All the publications in this dissertation analysed energy security risks related to the supply of energy in one way or another. However, regarding the balance between supply and demand, the latter is also worth studying. Households account for most of the electricity demand during winter demand peaks in Finland, but they currently lack sufficient economic incentives to decrease their consumption during a stressful market situation. Therefore, the contribution of demand-side flexibility, particularly in households via aggregators, to address generation inadequacy during annual demand peaks is an important subject of future research.

Another development in the energy market that warrants attention is the emergence of electric vehicles. Electric vehicles have the potential to increase flexibility in the electricity market, but without planning or economic incentives, they can also increase mismatch between supply and demand. Research on the development of the annual electricity demand profile in Finland with the inclusion of electric vehicles is therefore vital in understanding energy security related phenomena in the future.
References


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Appendices

Appendix A: Publication I
Jääskeläinen, Jaakko; Zakeri, Behnam; Syri, Sanna. Adequacy of Power Capacity during Winter Peaks in Finland. IEEE Xplore, 14th International Conference on the European Energy Market (EEM), Dresden, 6–9 June 2017. DOI: 10.1109/EEM.2017.7981883.

Appendix B: Publication II

Appendix C: Publication III

Appendix D: Publication IV

Appendix E: Publication V

Appendix F: Publication VI
Jääskeläinen, Jaakko; Höysniemi, Sakari; Syri, Sanna; Tynkkynen, Veli-Pekka. Finland’s Dependence on Russian Energy – Mutually Beneficial Trade Relations or an Energy Security Threat?. MDPI. Sustainability 2018, Volume 10 Issue 10, 3445. DOI: 10.3390/su10103445.