FACULTY OF TECHNOLOGY

Vision for 100% renewable Åland Islands

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ENVIRONMENTAL ENGINEERING
Master's Thesis
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UNIVERSITY OF OULU

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ABSTRACT
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Abstract

Energy systems throughout the world are undergoing a transition where renewable energy is substituting combustion of fossil fuels in power and heat production. The motive for the energy transition origins from climate goals that are set out to limit global warming well below two degrees from pre-industrial levels. The objective of the thesis is to study how an existing energy network and local characteristics can be utilized to transform an energy system to operate 100% on renewable energy. As future energy systems are expected to rely highly on variable renewable energy (VRE) generation, the thesis also intends to study which additional investments on unit and system level elements would increase flexibility in an energy system with high intermittency in power supply. The energy system of Åland Islands is studied as a case example, as different stakeholders are currently aiming to convert the island fully renewable by 2025. The thesis outlines the energy system of Åland Islands to comprise of the regional power grid and district heating network located in the capital Mariehamn.

Based on literature review, three energy system scenarios were built to represent three alternative energy transition pathways for Åland Islands to be implemented by 2025. An energy system modelling tool developed at VTT was utilized to define the cost-optimal configuration of thermal production units in relation to scenario-wise capacities of VRE generators, flexibility elements and power interconnectors. Modelling results were utilized to evaluate technical feasibility as well as economic and environmental impacts of the studied energy transition pathways. In addition, value of additional flexibility investments in demand and supply balancing was studied.

Due to local conditions, Åland is able to base its power supply greatly on intermittent wind energy by 2025. As a key finding of the thesis, strengthening the link between power grid and district heating network via a bio-CHP unit would increase profitability and self-sufficiency of an energy system with high reliance on variable power supply especially, when the CHP unit is integrated to a thermal energy storage (TES). Feasibility of bio-CHP as a flexibility element was found to be reliant of biomass availability and price, however, neither is considered as a constraining factor for bio-CHP applicability in Åland Islands. An additional investment on a centralized electric boiler was discovered to increase internal utilization of local VRE supply, however, resulting in lower profitability of bio-CHP investment as electric boiler was discovered to reduce full load operating hours and annual energy output of the CHP unit. The role of the applied stationary electrochemical batteries were found to be negligible on system-level VRE balancing while usability of stationary electrochemical batteries in short-term grid balancing were unabled to be studied due to the chosen temporal scale in the modelling tool.

By investing on local energy assets, Åland would be able to cut reliance of imported electricity to reinforce power self-sufficiency on the island. Environmental benefits would arise from discarded fossil carbon emissions from power and district heating sector and as a potential net exporter of renewable energy, Åland would be able to decrease utilization of fossil fuels in surrounding power areas as well. Although the renewable energy transition in Åland Islands is technically possible and brings out environmental benefits, the studied renewable energy transition pathways for Åland Islands were discovered to be economically unprofitable. The current market model on the island has to be shaped to support local renewable generation. An alternative would be to partly fund the renewable energy transition in Åland Islands by public financial support schemes.

Methodology applied in the thesis related to required input parameters for energy system modelling and methods to examine the modelling results can be employed to investigate potential renewable energy transition pathways in energy systems throughout the world. The modelling results related to Åland Islands can be applied to evaluate potential benefits of bio-CHP and TES in facilitating VRE integration in areas aiming to utilize district heating network to balance intermittent VRE supply. In addition, the results can be utilized to evaluate the applicability of electric boiler in increasing internal utilization of locally produced VRE supply. However, as the energy transition pathways studied in the thesis were designed in particular to Åland Islands, more detailed techno-economic analysis of existing energy system elements and local characteristics should be performed to the region where similar approach to renewable energy transition and VRE integration would be applied as in Åland Islands in this study.

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Tiivistelmä

Energiamurros on käynnissä ympäri maailmaa, kun vähähiiliset ja uusiutuvat energiamuodot korvaavat fossiilisten polttoaineiden käyttöä sähkön ja lämmön tuotannossa. Murroksen takana ovat ilmastotavoitteet, joiden tarkoituksena on hillitä maapallon lämpötilan nousu selvästi alle kahteen asteeseen esiteollisesta ajasta. Tämä diplomityön tarkoituksena on tutkia, kuinka täysin uusiutuvaan tuotantoon perustuva energiajärjestelmä voidaan toteuttaa alueellisen energiajärjestelmän olemassa olevia elementtejä ja paikallisen uusiutuvan energian mahdollisuuksia hyödyntäen. Koska vaihtelevan tuotannon, kuten tuuli- ja aurinkovoiman, oletetaan lisääntyvän sähköntuotannossa tulevaisuudessa, diplomityön tarkoituksena on myös tutkia, millä yksikkö- ja systeemitason investoinneilla energiajärjestelmän joustavuutta voidaan lisätä sähkön tuotannon ja kysynnän tasaamiseen energiajärjestelmässä, jossa sähköntuotannon vaihtelu on suurta. Ahvenanmaan energiajärjestelmää käytetään case-esimerkkinä, koska eri sidosryhmät pyrkivät muuntamaan Ahvenanmaan energiajärjestelmän täysin uusiutuvaksi vuoteen 2025 mennessä. Tässä työssä energiajärjestelmän tarkastelu rajataan kattamaan Ahvenanmaan sähköverkko ja pääkaupunki Maarianhaminassa sijaitseva kaukolämpöjärjestelmä.

Kirjallisuuskatsauksen perusteella Ahvenanmaalle rakennettiin kolme vaihtoehtoista vuoteen 2025 mennessä toteutettavaa energiaskenaariota. VTT:llä kehitettyä energiamallinnustyökalua hyödyntäen jokaiselle skenaariolle laskettiin kustannusoptimi, jossa polttoon perustuvien energiantuotantolaitosten kapasiteetti optimoitiin etukäteen määritettyjen vaihtelevan tuotannon, joustoelementtien ja siirtoyhteyksien kapasiteettien mukaan. Mallinnuksen tuloksia hyödynnettiin eri energiapolkujen teknisen toteutettavuuden tarkastelussa sekä energiamurroksen talous- ja ympäristövaikutusten arvioinnissa. Lisäksi joustoelementtien tuomaa lisäarvoa kysynnän ja tuotannon tasaamisessa arvioitiin.

Paikallisten olosuhteiden ansiosta tuulienergia voi kattaa suurimman osan Ahvenanmaan vuotuisesta sähkönkulutuksesta vuoteen 2025 mennessä. Diplomityön keskeisimpien tulosten mukaan paikallisen sähköverkon ja kaukolämpöverkon vuorovaikutuksen lisääminen bio-CHP investoinnin avulla kasvattaa korkean sähköntuotannon vaihtelun omaavan energiajärjestelmän kannattavuutta ja omavaraisuutta etenkin silloin, kun CHP on yhdistetty kaukolämpövarastoon. Bio-CHP:n soveltuvuus energiajärjestelmän joustoelementtinä todettiin olevan riippuvainen biomassan saatavuudesta ja hinnasta; kumpikaan tekijä ei kuitenkaan rajoita bio-CHP:n käyttömahdollisuuksia ja kannattavuutta Ahvenanmaalla. Lisäinvestointi keskitettyyn sähkökattilaan lisää paikallisen sähkön käyttöä energiajärjestelmässä, mutta vähentää CHP investoinnin kannattavuutta, sillä keskitetyn sähkökattilan huomattiin vähentävän bio-CHP:n täysiä ajotunteja ja vuotuista energiantuotantoa. Keskitetyn sähköakun hyödyt systeemitason joustossa todettiin mitättömiksi, kun taas sähköakun potentiaalia sähköverkon alle tunnin mittaisessa säädössä ei voitu tutkia mallinnukseen valitusta tunnin aika-askeleesta johtuen.

Investoimalla paikalliseen energiantuotantoon Ahvenanmaa kykenisi vähentämään riippuvuutta tuontisähköstä lisäämällä näin alueen energiaomavaraisuutta. Ympäristöhyödyt Ahvenanmaan energiamurroksesta ilmenevät hiilidioksidivapaasta sähkön- ja lämmöntuotannosta fossiilisten päästöjen suhteen. Potentiaalisena uusiutuvan energian nettoviejänä Ahvenanmaa kykenisi vähentämään fossiilisten polttoaineiden käyttöä myös ympäröivillä energia-alueilla. Vaikkakin energiajärjestelmän muutos todettiin Ahvenanmaalla teknisesti mahdolliseksi, ja vaikka uusiutuva energiajärjestelmä toisi mukanaan ympäristöhyötyjä, tutkitut energiaskenaariot todettiin nykytilanteessa taloudellisesti kannattamattomiksi. Jotta energiajärjestelmän muutos olisi myös taloudellisesti kannattava, nykyinen energiamarkkinamalli Ahvenanmaalla tulisi mukauttaa tukemaan paikallista uusiutuvan energian tuotantoa. Vaihtoehtoisesti Ahvenanmaan energiajärjestelmä voitaisiin osin rahoittaa julkiseen rahaan pohjautuvilla tukimekanismeilla.

Diplomityössä käytettyä metodologiaa energiajärjestelmän mallinnukseen vaadittaviin alkuarvoihin ja tulosten analysointiin liittyen voidaan hyödyntää myös muiden täysin uusiutuvaan energiantuotantoon tähtäävien energiajärjestelmien mallinnuksessa ja analysoinnissa. Ahvenanmaan uusiutuvan energiajärjestelmän mallinnustuloksia voidaan etenkin käyttää bio-CHP:n ja kaukolämpövaraston potentiaalisten hyötyjen arvioinnissa alueilla, joissa vaihtelevan tuotannon osuus sähköntuotannossa on suurta, ja joissa paikallista kaukolämpöverkkoa halutaan hyödyntää vaihtelevan sähköntuotannon tasaamiseen. Lisäksi diplomityön tuloksia voidaan hyödyntää keskitetyn sähkökattilan käytettävyyden arvioinnissa alueilla, joissa paikallisesti tuotetun sähkön osuutta omassa energiankulutuksessa halutaan kasvattaa. Koska kuitenkin diplomityössä analysoidut energiaskenaariot on suunniteltu täysin Ahvenanmaan uusiutuvan energiapotentiaalin ja olemassa olevan energiajärjestelmän ominaisuuksien mukaan, yksityiskohtaisempi teknis-taloudellinen energiajärjestelmäanalyysi tulisi tehdä alueelle, jossa vastaavaa lähestymistapaa energiajärjestelmän muutokseen ja uusiutuvan energian integrointiin halutaan soveltaa kuin Ahvenanmaahan sovellettiin tässä diplomityössä.

Muita tietoja

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Jyväskylä, 23.4.2019 Kirsikka Kiviranta

TABLE OF CONTENTS

LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

CO_2	carbon dioxide
CHP	combined heat and power
EES	electrical energy storage
EU	European Union
EV	electric vehicle
GHG	greenhouse gas
GHI	global horizontal irradiance
HOB	heat-only boiler
HVAC	high voltage alternating current
HVDC	high voltage direct current
$NaNiCl_2$	sodium nickel chloride
PV	photovoltaics
TES	thermal energy storage
VRE	variable renewable energy

Symbol

C	cost	[€]

Subscripts

dh	district heat
el	electricity
exp	power export
ETS	Emissions Trading System
fixed	fixed cost
fuel	fuel
i	unit
imp	power import
j	hour
k	transmission line

OPEX	operating cost
PMT	investment payment
ramp	ramping penalty
tar	renewable energy tariff
tax	fuel tax

1 INTRODUCTION

Global targets and national policies of climate change mitigation along with cost reductions in variable renewable energy (VRE) technologies are driving a transition from fossil-based energy systems to ones dominated by renewable energy throughout the world (IRENA, 2018c). A key element in the transition is the Paris Agreement on climate change, an universal action plan set out to limit global temperature rise at the current century well below 2°C from pre-industrial levels (UNFCCC, 2018). To meet the 2°C climate targets, the share of renewable energy in the global power supply has to more than triple from 25% in 2017 to 85% in 2050, and the role of VRE sources will reach significant importance, as wind and solar PV are estimated to cover nearly 60% of the annual power supply in 2050 (IRENA, 2018b).

The transition towards a low carbon energy system comes with challenges, as high shares of VRE supply result in higher deviations in the residual load (IRENA, 2018c). If dispatchable generators in the power system are not capable to operate with increased fluctuations in the supply side, drawbacks in VRE integration will occur (IRENA, 2018d). A rapid increase in VRE deployment has created major problems for instance in China, where 56.2 TWh of wind and solar generation was curtailed in 2016 (Zhou & Lu, 2017). Increasing the capability of a power system to operate with higher deviations in the net load can be achieved by harnessing flexibility from different parts of the energy sector (IRENA, 2018c). Increased flexibility improves the accommodation of VRE sources and enables to maximize the potential of VRE in decarbonizing the energy system (IRENA, 2018c).

The purpose of the thesis is to study how local characteristics and existing energy system elements can be harnessed to achieve an energy system based on 100% renewable energy. In addition, the thesis intends to evaluate additional unit and system level elements required to facilitate integration of high VRE supply to an energy system. Energy transition in Åland Islands is utilized as a case study, as the island is participating in an energy transition project with the aim to convert Åland into a pilot platform to demonstrate a society running entirely on renewable energy (Flexens Oy Ab, 2018). According to Jacobson et al. (2017), Åland is a favorable region to demonstrate a full-scale energy transition as local conditions and the current power supply mix support investments on high VRE generation, whereas local biomass resources on the island have the potential to be utilized as a balancing element in the power grid. In addition, the potential of coupling power grid and district heating network in Mariehamn can be harnessed to achieve additional flexibility for VRE integration. Jacobson et al. (2017) also state that an implemented renewable energy system demonstration in Åland Islands has the potential to act as a successful example of Finnish know-how in the global markets of energy transition. In this thesis, attention will especially be drawn on the role of district heating network in balancing an energy system with increased level of VRE supply.

The research questions of the thesis are:

1. What is the most feasible renewable energy transition pathway for Åland Islands that could be implemented by 2025? The study is based on the knowledge from existing renewable energy islands as well as the current state of the power and district heating sector and renewable energy potential in Åland Islands.

2. What are the economic and environmental impacts of the renewable energy transition in Åland Islands?

3. Which flexibility elements can improve integration of VRE sources by increasing economic value and power self-sufficiency of the renewable energy system in Åland Islands?

4. Is the pathway for renewable energy transition in Åland Islands globally adaptable?

Theoretical part of the thesis consists of three main themes. In Chapter 2, a technical evaluation of renewable energy transitions in three islands with different local conditions is carried out to study similarities and differences in the unit level elements utilized to achieve a renewable energy system. In Chapter 3, local energy targets and previous work related to energy transition potential in Åland Islands are presented. Furthermore, the characteristics of the current power and district heating network along with the existing renewable energy potential are featured to assess potential measures to be utilized in the energy transition of the island. In Chapter 4, the challenge of high-share VRE integration is introduced, and the potential assets to increase power system flexibility in Åland Islands are studied.

The goal of the experimental part is to evaluate implementation potential of three energy system scenarios built for Åland Islands based on the theoretical evaluation of the existing energy system, local renewable energy resources and potential flexibility elements in Åland Islands. In Chapter 5, a simulation tool utilized to determine the cost-optimal configuration of different energy system scenarios with varying capacities related to power and heat generation, storage technologies and power transmission capacities is introduced. Parameters of the assessed energy system scenarios are defined in the same chapter.

In Chapter 6, results obtained from the simulation tool are presented to evaluate the technical requirements as well as the economic and environmental impacts of the studied energy system scenarios. Moreover, the value of flexibility elements in the energy transition are evaluated and potential constraints of biomass availability and price are considered. In Chapter 7, outcomes of the simulation results are discussed and the global replicability potential of the results are analyzed. In Chapter 8, conclusions of the energy transition potential in Åland Islands are presented.

THEORETICAL PART

2 RENEWABLE ENERGY ISLANDS

Island energy systems provide an interesting basis for high-share VRE integration studies due to several reasons. Firstly, power generation in majority of small islands with less than 100 000 inhabitants is primarily supplied by imported fossil fuels although islands are often abundant in VRE resources such as wind and solar (Blechinger et al., 2016). A transition to a power system running on domestic renewables would not only enable to reduce greenhouse gas (GHG) emissions but also to boost local economy on the island by creating jobs and by reducing dependency and costs related to imported fractions of fossil fuels (IRENA, 2018d). Secondly, the structure of island energy systems is often more simple in comparison to larger systems in mainland (Child et. al, 2017). By demonstrating energy systems on a smaller scale, islands provide a feasible platform to test and evaluate emerging technologies to integrate renewable energy sources to the energy system (Cross et al., 2017). Technically feasible examples of island energy systems with high VRE generation can act as blueprints for energy transition on larger, continental areas (Blechinger et al., 2016) accelerating the deployment of renewable technologies.

Technical characteristics of existing renewable island energy systems are evaluated to study similarities and differences of energy transitions in islands with different local conditions. Three islands, Samsø (Denmark), Tilos (Greece) and El Hierro (Canary Islands, Spain) with the geographical locations presented in Figure 1 are examined.

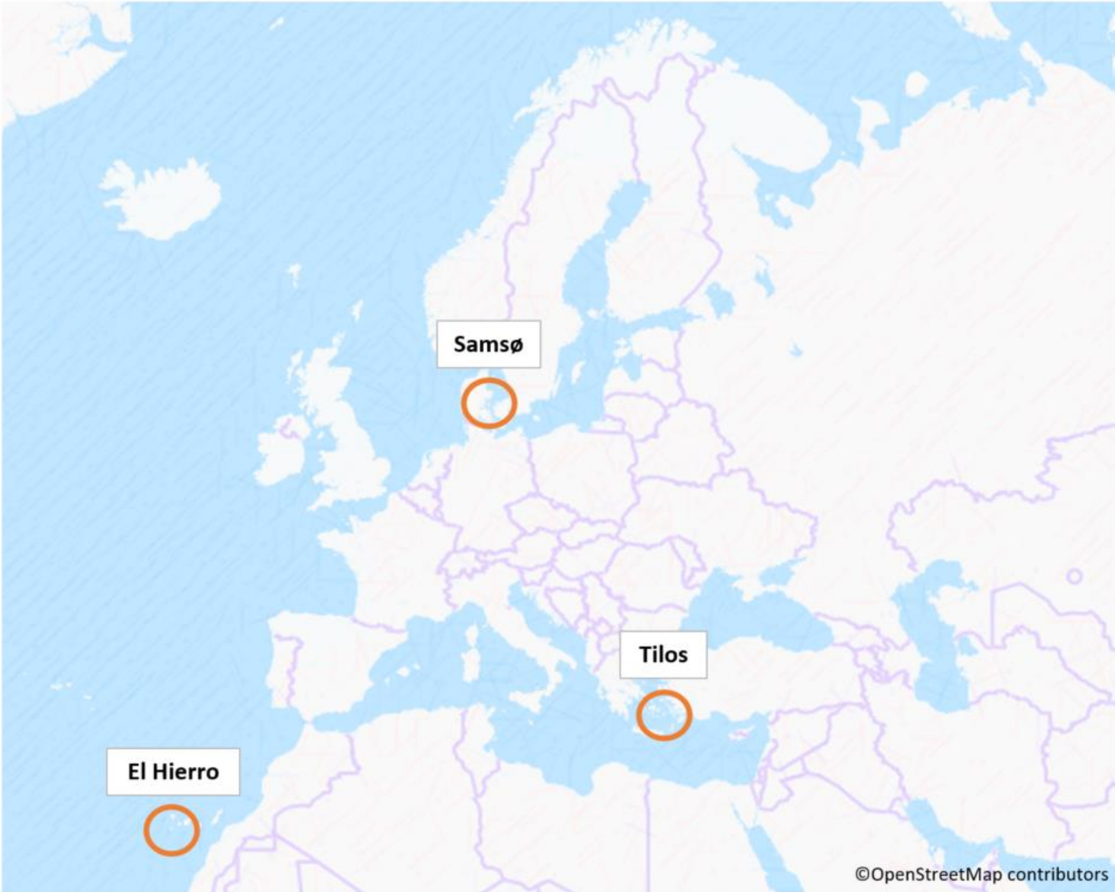

Figure 1. Geographical location of Samsø (Denmark), Tilos (Greece) and El Hierro (Canary Islands, Spain).

Samsø and Tilos have an interconnection with an external power system, serving as a backup power reserve, whereas the energy system of El Hierro is entirely isolated, without any opportunity for power exchange. All the islands have utilized mature technologies in the energy transitions, with wind power acting as the primary renewable energy supply source in all of the studied islands. Heating sector has received attention in the renewable transition on the island of Samsø due to colder climate conditions and hence higher heating demand in relation to the other two islands with warmer climates. Although the target in all the evaluated islands has been to cover domestic power demand entirely by locally produced renewable energy, none of the islands has been able to achieve the goal in practice yet.

2.1 Samsø

Samsø is a Danish island with 3 700 inhabitants, located next to the main peninsula of Denmark. The island of Samsø has been able to replace large parts of its fossil-fueled energy system with renewables in less than one decade (Sperling, 2017). The transition began in 1997, when the island won a competition announced by the Danish Ministry of Environment and Energy (Jørgensen et al., 2007). The island was chosen to become a demonstration site for Denmark to prove that increasing the share of renewables in the energy mix is possible up to an entirely renewable level. The existing wind and solar potential on the island are presented in Figure 2.

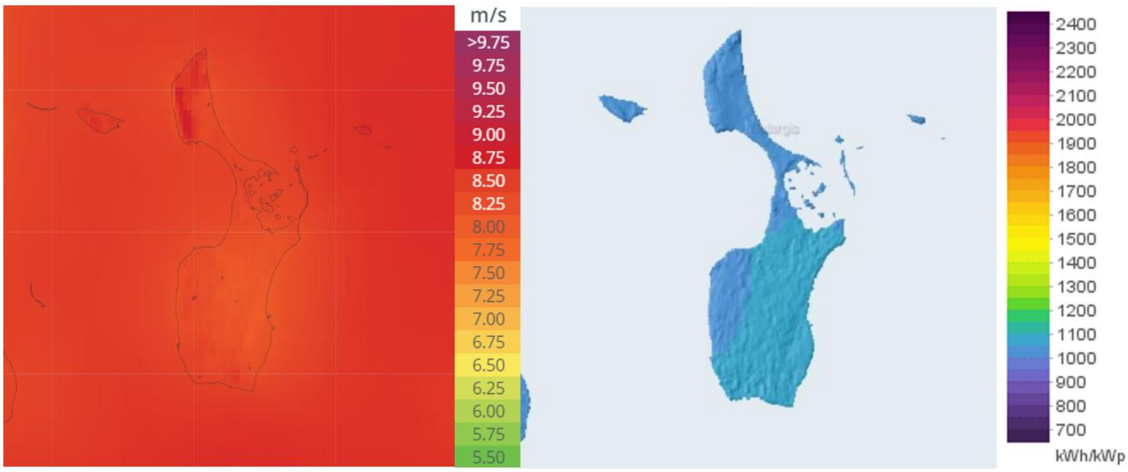

Figure 2. Wind (left) and solar (right) potential in the island of Samsø, Denmark. Wind data obtained from the Global Wind Atlas 2.0, owned and operated by the The World Bank Group and DTU (2018), solar data obtained from the Global Solar Atlas, owned by The World Bank Group (2019) and provided by Solargis.

Before Samsø transformed into an island operating on renewable energy, majority of the island's electricity supply was imported from Denmark. In 1997, the annual electricity consumption of the island (29 GWh) was estimated to be covered by a local wind power capacity of 11 MW. Eleven 1 MW wind turbines were built to three different areas on the island in 2000. An additional offshore wind capacity of 23 MW was commissioned in 2003, to compensate carbon emissions from fossil fuel usage in the transportation sector. Wind turbines on the island are owned by the community as they are possessed by local cooperatives, individuals, municipalities and other local stakeholders (Parkkari, 2018b). Local residents either directly or indirectly own 90% of the turbines. The ownership structure boosts local economy, as majority of the money paid for electricity does not leave the island. Primary owners of the power production units get income of the produced electricity, while the costs related to imported electricity and fuels decrease. (Jørgensen et al., 2007)

The amount of generated surplus electricity is significant in Samsø due to the overdimensioned wind power capacity. Samsø is connected to Denmark with undersea cables, in which electricity transmission is possible in both directions (Jantzen, Kristensen, & Haunstrup, 2018). The cable is mainly utilized to export excess electricity from the island to the mainland. In 2013, the island exported approximately 70% of the generated electricity to Denmark, which corresponds to the fact that most of the generated electricity is not integrated to the local energy system (Mathiesen et al., 2015).

In 2015, the annual power demand in Samsø was 25.5 GWh. In addition to power supplied by wind, also solar PV and imported electricity from Denmark account for small shares of the electricity supply on the island. As of 2015, the installed capacity for solar PV was 1.3 MW with an estimated contribution of 3.1 GWh and 12% to the annual electricity consumption, whereas the amount of imported electricity was estimated to be 1.5 GWh, accounting for 6% of the annual power demand. Electricity is imported to Samsø during low hours of solar and wind generation, since no backup units for electricity production exist on the island (Mathiesen et al., 2015). Imported electricity is in most cases generated with Danish CHP plants, which utilize coal, biomass and natural gas (Danish Energy Agency, 2016) as a fuel. Therefore, it cannot be guaranteed that the imported electricity is only from renewable sources. (European Commission, 2018b)

As reported by Parkkari (2018b), imported electricity creates challenges for the scalability of Samsø's energy system. Due to the small size of the island, backup power as in form of imported electricity is always available from Denmark. If the reference area were similar approach for energy transition as in the island of Samsø was much greater with higher electricity demand, the amount of available imported electricity from surrounding power areas might not be enough to meet the variance caused by intermittent power generation. However, if the surface of the reference area is large enough, it is possible that there is always an area with VRE supply, which could provide power balancing for the areas lacking renewable production at the current moment.

Four separate district heating networks exist in Samsø, of which three were established in the early 2000s, after Samsø was chosen to become the renewable energy demonstration site (Jørgensen et al., 2007). Three of the networks are heated by burning straw. One district heating plant produces 80% of its heat by burning wood chips and the remaining 20% of the heat is derived from a 2 500 m^2 solar heating system. The share of district heat accounted for 37% of the heat demand on the island in 2013, and the individual buildings outside the district heating networks are heated by oil and biomass boilers, in addition to heat pumps, electric heating and solar thermal units (Mathiesen et al., 2015).

2.2 Tilos

A small Greek island Tilos, located in the Aegean Sea, is a part of an ongoing EU funded project, where the aim is to turn Tilos into the first Mediterranean island to be powered entirely by renewable energy (European Commission, 2018a). The island has 530 inhabitants; however, the population can even triple at summer time due to tourist arrivals. The annual electricity consumption is approximately 3.2 GWh, with peak demand at 1 MW. Power has traditionally been entirely supplied from the neighboring island Kos through an undersea transmission cable. The imported electricity origins from a fossil-fueled power production unit. Dependency of imported electricity has resulted in frequent blackouts, especially during summer time, although Tilos has a 1.4 MW backup diesel generator for emergency situations. Due to mild weather conditions, both space heating and cooling needs of the island are largely supplied by power-based air conditioning. (Notton et al., 2017)

The island of Tilos has good wind and solar potential as seen from Figure 3. To achieve security in power supply and to the maximize the share of renewable and local power generation on the island, a hybrid wind and solar system for power generation including a battery storage has been designed (Notton et al., 2017) and implemented in 2017 (Voulgari, 2018). The hybrid system consists of a 800 kW wind turbine with the estimated annual power output of 2.1 GWh (TILOS, 2019c) in addition to a 160 kW solar PV park, with annual estimated yield of 265 MWh (TILOS, 2019b). The output of solar PV increases at summer time to correspond well with the increased power consumption of the tourist season (TILOS, 2019b). The battery storage system comprises of two 400 kW and 1.44 MWh sodium nickel chloride ($NaNiCl_2$) batteries, which are able to store excess electricity generated during VRE generation peaks, to be supplied to the local grid on hours of high demand (TILOS, 2019a). The battery system does not only enable to maximize internal utilization of local VRE supply, but it also provides ancillary services and contributes to grid management by enabling power exports from the island at times of high excess VRE generation (TILOS, 2019a). The hybrid system can cover 70% of the local power consumption on stand-alone operation, however, the goal is to achieve 100% electricity autonomy in the upcoming years (European Commission, 2018a).

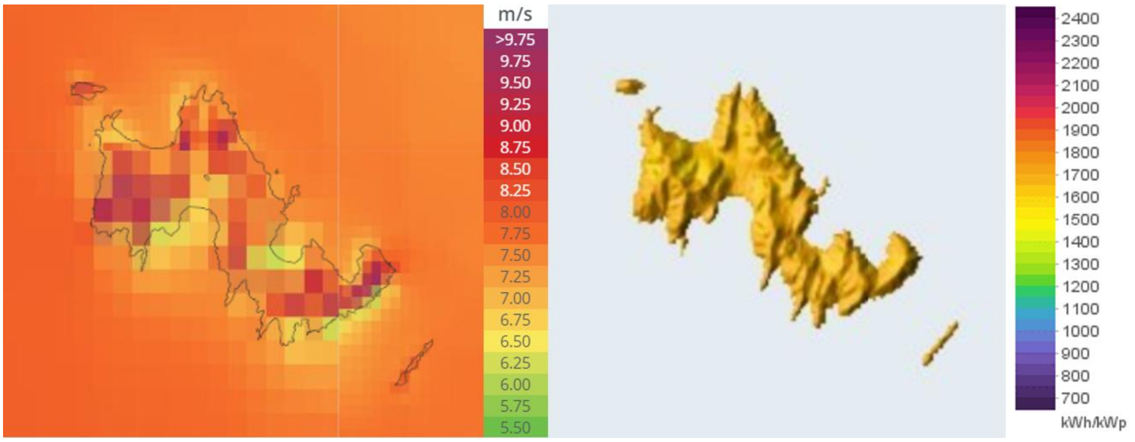

Figure 3. Wind (left) and solar (right) potential in the island of Tilos, Greece. Wind data obtained from the Global Wind Atlas 2.0, owned and operated by The World Bank Group and DTU (2018), solar data obtained from the Global Solar Atlas, owned by The World Bank Group (2019) and provided by Solargis.

Demand side management supports both VRE penetration and grid frequency and voltage control on the island. For instance, power demand of decentralized electrical water heaters can be remotely managed to support exploitation of surplus or deficit in VRE supply. In addition, load monitoring takes place for instance at local homes, where power load of fridge or air conditioning can be regulated for frequency and voltage control and for short-term grid balancing purposes. (Notton et al., 2017)

2.3 El Hierro

The island of El Hierro, located in the Canary Islands archipelago, is also aiming towards a power system supplied by 100% renewable energy (Hallam & Contreras, 2015). As for 2017, the island had roughly 10 600 inhabitants and the annual power demand was 43.6 GWh (Garcia Latorre et al., 2019). Diesel engines have traditionally covered the power demand on the island, with the existing capacity of 14.9 MW (Garcia Latorre et al., 2019). The island has been dependent of imported fossil fuels, as interconnectors for power exchange with other islands in the archipelago are technically and economically infeasible, because the island is surrounded by very deep water due to its volcanic origin (Cross et al., 2017).

El Hierro has high wind and solar potential as seen in Figure 4. The island has taken advantage of its great wind conditions and topography in developing a renewable solution to substitute dependency of fossil-based power generation (Hallam & Contreras, 2015). A hybrid wind and hydro system was taken into continuous use in 2016 to generate domestic renewable electricity and to act a source of dispatchable power source at times when needed. The dispatchable power supply element is a hydropower facility, where surplus wind supply is utilized to pump water to an upper water reservoir located 698 meters above the lower basin, to which the water is fed back through a hydropower plant at times of low wind. The wind park consists of five wind turbines with the total power output of 11.5 MW, whereas the hydropower plant has the output of 11.3 MW, with 6 MW pumping capacity. The existing diesel generators were supposed to provide backup power in exceptional situations, when power from the hybrid system is not available. (Garcia Latorre et al., 2019)

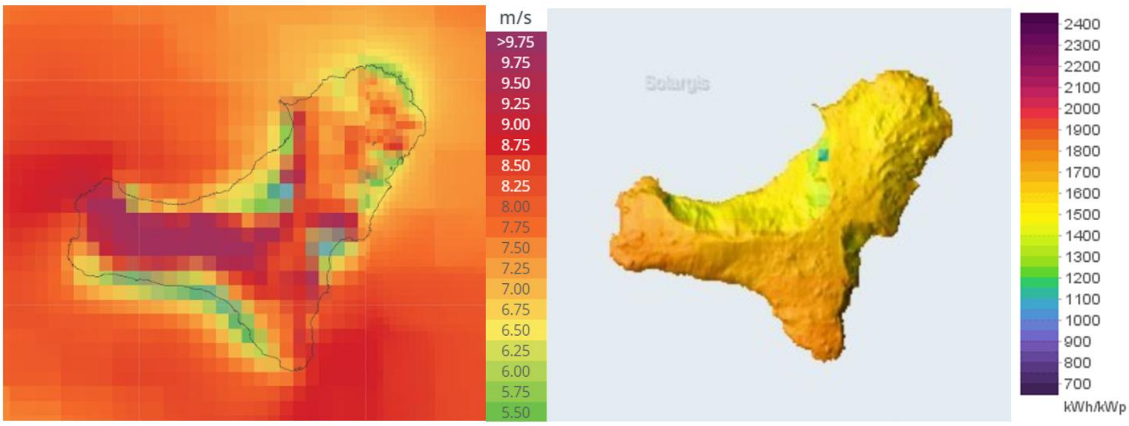

Figure 4. Wind (left) and solar (right) potential in the island of El Hierro, Canary Islands, Spain. Wind data obtained from the Global Wind Atlas 2.0, owned and operated by The World Bank Group and DTU (2018), solar data obtained from the Global Solar Atlas, owned The World Bank Group (2019) and provided by Solargis.

The intention of the wind and hydro hybrid system was to cover 70% of the annual power demand on the island and the aim was to reach the share of 100% by combining the facility with solar PVs and solar thermal collectors in the upcoming years (Hallam & Contreras, 2015). However, the hybrid facility has not reached its goal. In 2016 and 2017, the hybrid power plant has covered 40.6% and 46.3% of the annual power demand, respectively, while diesel generators have produced the remaining share (Garcia Latorre et al., 2019). According to Frydrychowicz-Jastrzębska (2018), the low output of the hydro facility is a result of a too small capacity of the upper water reservoir in relation to the installed wind capacity, preventing a smooth integration of the two elements. The mismatch has resulted in curtailment of wind power for grid balancing purposes, and increased the utilization of diesel generators from what was assumed. However, some occasions have emerged, where the hybrid system has been able to supply 100% of the local power demand. For instance, the island was entirely powered by renewable energy in the beginning of 2018 for 18 consecutive days (Frydrychowicz-Jastrzębska, 2018).

3 ENERGY SYSTEM OF ÅLAND ISLANDS

Åland Islands is an autonomous region of Finland, located in the Gulf of Bothnia on the Baltic Sea as seen in Figure 5. Åland is a group of over 6 700 islands, of which 65 are populated by the 29 500 inhabitants (ÅSUB, 2018) living in the area (Ministry for Foreign Affairs, 2013). Nearly 40% of the population live in the capital Mariehamn, which is the only town in the region (Ministry for Foreign Affairs, 2013). The remaining population live either in the smaller municipalities of the main island (53%) or in the archipelago district (7%) (ÅSUB, 2018). Åland is often referred as a small-scale representation of Finland, as the island has all the elements of a functioning society and its population, gross domestic product (GDP), land area, energy demand and forest use account for 0.5% of the national values (Jacobson et al., 2017; Ministry of Economic Affairs and Employment, 2017; Parkkari, 2018a).

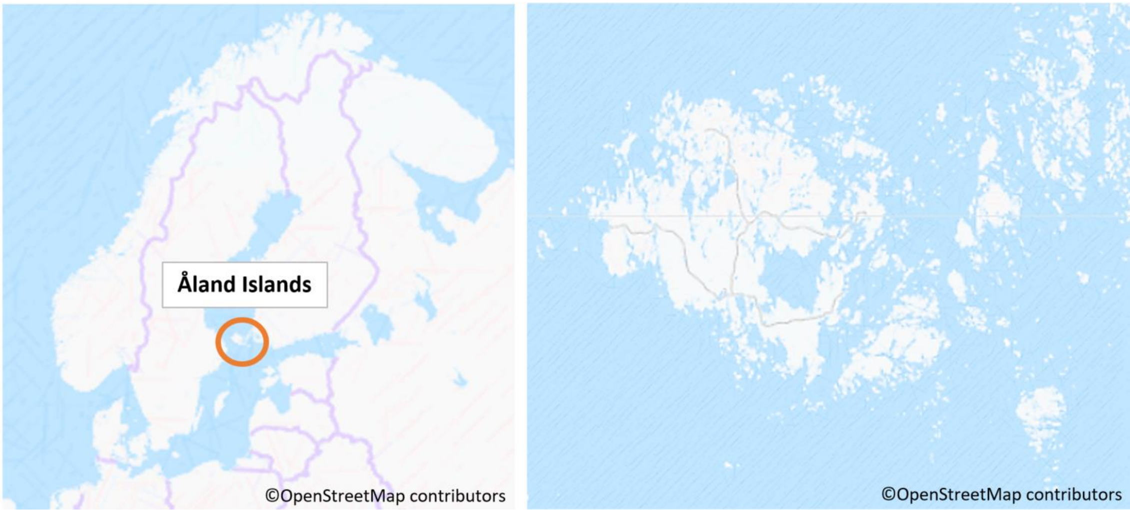

Figure 5. Geographical location of Åland Islands, Finland (left) and map of Åland Islands (right).

The energy system of Åland Islands has received special attention in the recent years. The Government of Åland has set an energy and climate strategy for 2030 to reduce greenhouse gas emissions and to boost production and utilization of local renewable energy on the island (Government of Åland, 2017a). The strategy is set in response to the Paris Agreement, which was ratified by the Government of Åland in 2016. The goals of the energy and climate strategy are to reduce carbon dioxide (CO_2) emissions below 60% from 2005 levels (260 000 tons of CO_2), cover 60% of local energy consumption by renewable energy and cover 60% of the local electricity supply by domestic and renewable sources. The targets of the strategy should be achieved by 2030.

Åland's energy actors and government are involved to a FLEXe Demo project coordinated by CLIC Innovation (Ålands landskapsregering, 2018). The aim of the FLEXe Demo is to use Åland Islands as a testbed to demonstrate a 100% renewable energy system, which bases its energy production on domestic resources (Parkkari, 2018a). CLIC Innovation, local companies and the Government of Åland have established a company Flexens in 2018, to implement the renewable energy system based on the FLEXe Demo concept and to commercialize the know-how of the renewable energy system (Flexens Oy Ab, 2018). The implementation of the energy system demo is aimed to be achieved by 2025, as if the implementation is postponed until the due date of the regional energy targets of Åland in 2030, the system might no longer be unique and its know-how might no longer have as high value to be commercialized (Parkkari, 2018a).

In addition to the ongoing FLEXe project related to the energy transition of Åland Islands, studies have been carried out assessing the potential of energy transition in Åland Islands from different perspectives. A study by Leichthammer (2016) has represented an outlook of different grid optimization methods with an ability to be utilized in the renewable energy network of the island. Child et al. (2017) has evaluated that an entirely renewable energy system including power, heat and transportation sectors is possible in Åland Islands by 2030, when plug-in electric vehicles are widely adopted to balance intermittent VRE generation. The role of electric vehicles in balancing the future power network of Åland Islands in 2030 is further analyzed in Child (2018). The study concludes that high participation of plug-in electric vehicles can act as a buffer between demand and VRE supply, reducing the required capacity of VRE sources and other electricity storage methods such as power-to-gas technologies in the renewable energy system. In this study, the evaluation of transportation sector in VRE balancing is excluded, as the energy system boundaries are set to include the regional power grid of Åland Islands and the district heating network located in the capital Mariehamn.

The latest study related to the energy transition of Åland Islands was published in March 2019 by Pääkkönen & Joronen. The study utilized the energy system of Åland Islands with increased VRE supply as a case platform to study feasibility of a bio-fueled CHP as a source of energy system flexibility. The study evaluated impacts of different technical and economical parameters to the unit-level operation and profitability of bio-CHP in VRE balancing. The study concluded that a bio-CHP can be a profitable source of flexibility in an energy system with high VRE supply, when availability of low-cost fuel and sufficient income from generated heat can be secured. For further research Pääkkönen & Joronen (2019) suggested to evaluate the impacts of thermal energy storage to the profitability of CHP in VRE balancing, which will be done in this study. In addition, system-level profitability of bio-CHP and TES as well as the benefits of electric boiler and electrochemical battery in VRE balancing will be evaluated in this thesis.

According to the renewable energy island assessment in Chapter 2, technical solutions of increasing the share of local renewables in Åland Islands can be expected to parallel most with the technologies utilized in the energy transition of Samsø, although the differences between population and annual power demand are high. Renewable energy potential in regards of wind speed and solar irradiation along with mean temperature in Samsø resemble most with the values of Åland Islands as seen in Table 1. In addition, Samsø is the only island with Åland Islands utilizing district heating in the heat sector, although the power grid and district heating network are not integrated in Samsø.

Table 1. Comparison of the main parameters characterizing Åland Islands and studied renewable energy islands Samsø, Tilos and El Hierro.

Parameter	**Unit**	**Åland Islands**	**Samsø**	**Tilos**	**El Hierro**
Population		29 500	3 700	530	10 600
Electricity demand	GWh	310.6	25.5	3.2	43.6
Interconnection		x	x	x	
District heating		x	x		
Land area	km^2	1553.5	114	64	270
Mean temperature	°C	6.7	9.3	20	21.1
Average wind speed[1]	m/s	8.6	8.6	10.1	12.3
Solar irradiation[2]	kWh/m^2	1100	1250	>2100	>2100

[1]Data from 10% windiest areas (The World Bank Group and DTU, 2018)
[2]Estimated based on European Commission (2017b)

In this thesis, attention will be especially drawn on the role of district heating network and bio-CHP in balancing an energy system with increased level of VRE supply. Therefore, energy system boundaries in the thesis are set to include power grid and district heating network excluding heat demand of individual buildings and energy demand related to transportation. The existing power grid and district heating network as well as the renewable energy potential in Åland Islands are evaluated in the following subchapters to give out a detailed outlook the current state and potential of renewable energy transition on the island.

3.1 Electricity

In 2017, a new record was set to the annual electricity consumption in Åland as 310.6 GWh of electricity was consumed on the island with the hourly consumption peak at 65.8 MW (Kraftnät Åland Ab, 2018). Total electricity supply reached 316.6 GWh, when exported electricity of 5.5 GWh is considered as well (Kraftnät Åland Ab, 2018). Household sector was the major consumer of electricity in 2017, with the annual demand at 125.4 GWh, followed by service and public sector with consumptions of 57 GWh and 46 GWh, respectively (ÅSUB, 2018). Seasonal deviation in electricity consumption is distinct as power consumption is notably higher during winter in comparison to the summer months as seen from Figure 6.

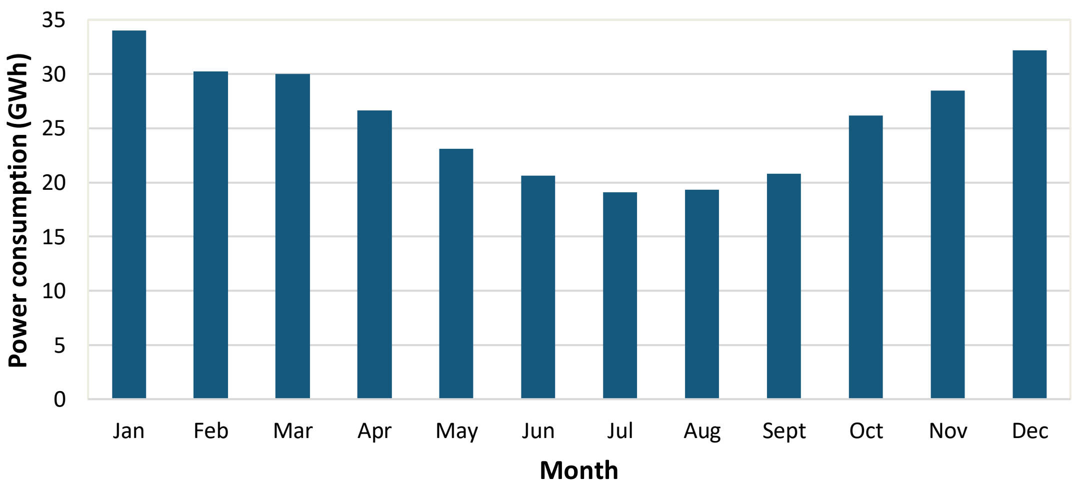

Figure 6. Monthly electricity consumption in 2017 in Åland Islands (Allwinds Ab, 2018).

Electricity supply mix in Åland Islands is not diverse, as imported electricity and local wind production have covered majority annual power supply in Åland Islands during the past decade as seen in Figure 7. Electricity supply relies heavily on imported electricity from Sweden, as its share from annual power consumption has been on average 78% since 2010. Finland also exports electricity to Åland, but in much smaller scale. Åland's electricity transmission grid is connected to Sweden and Finland with three transmission lines. Åland's transmission system operator, Kraftnät Åland AB, owns and operates the electricity transmission network and the interconnections with both of the mainlands (Kraftnät Åland Ab, 2018). Sweden is the main electricity importer to Åland due to its closer geographic location from the island (Pöyry, 2016). According to Pöyry, electricity is transferred from Sweden to Åland through an 80 MW undersea high voltage (110 kV) alternating current (HVAC) connection cable. Finland has two transmission connections to Åland Islands. The lower voltage (45 kV) cable from Kustavi is mainly utilized to provide electricity for the archipelago between the main island and Finland. The transmission cable is limited to 10 MW. In 2017, power transmission from Kustavi was 14.4 GWh, accounting for slightly over 4.5% of the total electricity supply (Kraftnät Åland Ab, 2018). The latest interconnection “ÅL-link” was commissioned in 2015 between Naantali and Åland to increase the energy security of the island (Raunio, 2016). Electricity transmission begins immediately through the 100 MW high voltage direct current (HVDC) cable, if outages with the power supply from Sweden occur. According to Kraftnät Åland Ab (2018), electricity transmission via ÅL-link was 2.3 GWh in 2017, corresponding to only 0.7% of the annual power supply.

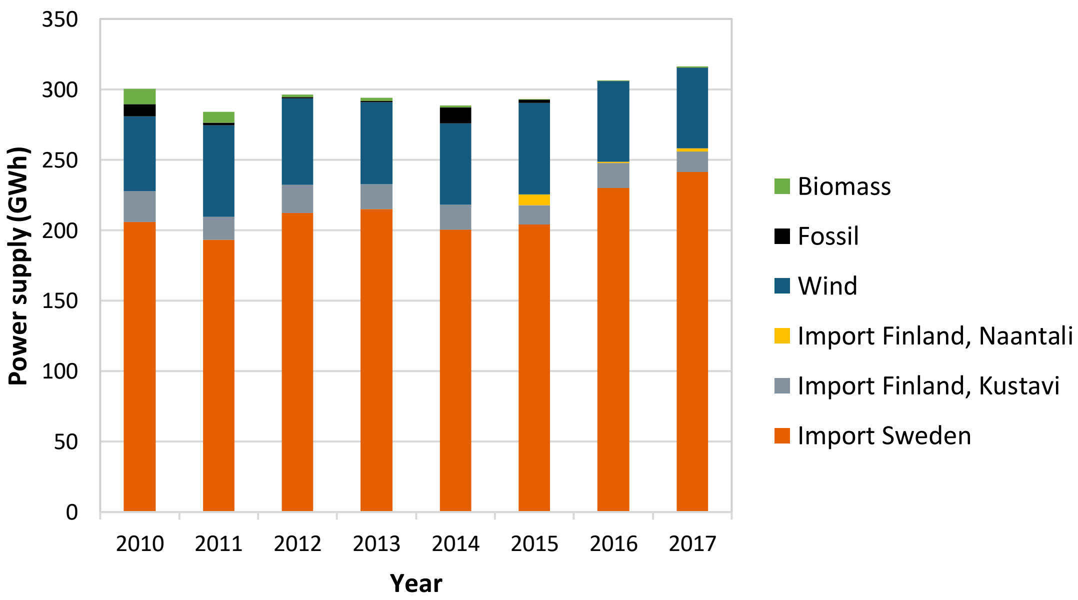

Figure 7. Electricity supply in Åland Islands 2010-2017 (Kraftnät Åland, 2011-2018).

Wind is currently the most utilized local electricity source in Åland Islands as its share in total electricity supply was about 57.5 GWh and 18% in 2017 (Kraftnät Åland Ab, 2018). Unlike the global trend where installed wind capacity has increased steadily over the past ten years (GWEC, 2018), installed wind power capacity in Åland has remained stable since 2007 (Allwinds Ab, 2018e). Current capacity consists of nineteen wind turbines, with the total rated power output at 21.3 MW (Allwinds Ab, 2018c). All of the wind turbines are managed and maintained by Allwinds AB, a company established by three largest wind turbine owners in Åland Islands: Leovind AB, Ålands Vindenergi Andelslag and Ålands Vindkraft AB (Allwinds Ab, 2018c).

Utilization of fossil fuels and biomass in electricity production has been very low in Åland Islands due to low spot prices in Nord Pool's day-ahead power market (Mariehamns Energi Ab, 2018 & Ålands landskapsregering, 2017). In 2017, fossil fuels contributed 0.02% to the total electricity supply by producing 71 MWh of electricity (Kraftnät Åland Ab, 2018) in which test runs of two diesel CHP units produced almost half of the electricity (Mariehamns Energi Ab, 2018). Therefore, the actual need for electricity from fossil carbon emitting sources was lower than produced. Kraftnät Åland Ab's gas turbine for reserve power produced 30 MWh of electricity in 2017 (Kraftnät Åland Ab, 2018). Bio-CHP plant owned by Mariehamns Bioenergi Ab produced 493 MWh of electricity from pellets in 2017, accounting for 0.15% of the annual supply (Mariehamns Energi Ab, 2018).

3.2 Heat

According to the trade association of Finnish energy industry sector Finnish Energy (2018d), heat production in Mariehamn's district heating network was 119.4 GWh in 2017. Monthly heat supply in the network in 2017 is presented in Figure 8. After excluding network losses and metering errors from the supply, total district heat delivery to the end-users was 105.9 GWh. Mariehamns Energi Ab is the district heating operator in Mariehamn region with the network in total of 73.9 kilometers (Mariehamns Energi Ab, 2018). The company has old production units of its own, but majority of heat is bought from Mariehamns Bioenergi Ab (Finnish Energy, 2018b). Heat production units of both companies are listed in Table 2. In addition to heat, CHP units also produce electricity, but the quantities have been very small in recent years due to uneconomic conditions as discussed in the previous section.

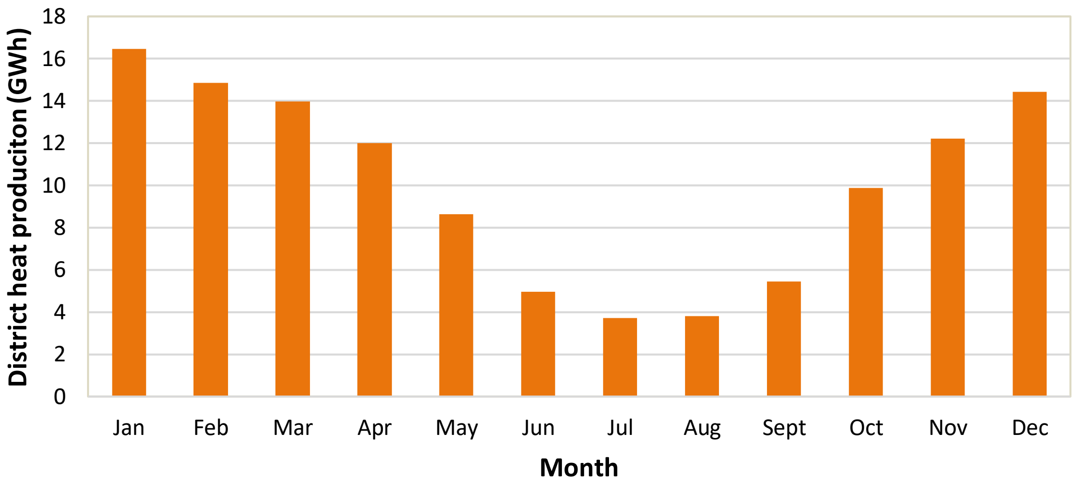

Figure 8. Monthly heat production in Mariehamn's district heating network in 2017 (Mariehamns Energi Ab, 2018).

According to Mariehamns Energi Ab (2018) renewable fuels produced 102.7 GWh and 86% of district heat in 2017, from which Mariehamns Bioenergi Ab covered 99%. Transportable heating units, used as a back-up reserve, produced the remaining percent from pellets during cold periods in January. Renewable fuels used are mainly residues from wood industry, obtained from a local forest industry company Ålands Skogsindustrier Ab (Ålands Skogsindustrier Ab, 2018). These residues include forest residues such as branches and tops as well as industrial residues such as bark and sawdust. Figure 9 presents the shares of different fuels utilized in the production of district heat in Mariehamn's district heating network (Finnish Energy, 2018b). Heavy oil fuel is the main conventional fuel utilized.

Table 2. Heat production units in the district heating network of Mariehamn (Finnish Energy, 2018b).

Company	Production unit	Heat output (MW_{th})	Power output (MW_e)	Main fuel	Year of installation
Mariehamns Energi Ab	CHP	24	8	Heavy fuel oil	1980
Mariehamns Energi Ab	CHP	13.3	15.8	Heavy fuel oil	1990
Mariehamns Bioenergi Ab	Bio heat-only boiler	5	-	Forest fuel	1995
Mariehamns Bioenergi Ab	Bio-CHP	11	2.1	Forest fuel	2007
Mariehamns Energi Ab	8 transportable heating units	45.8	-	Light fuel oil, forest fuel	

In addition to the district heating network located in Mariehamn, also smaller, local heating networks exist on the island. A local forest industry company Ålands Skogsindustrier Ab owns a bio heating plant in Godby, where the company utilizes its own residues to produce district heat mainly to the local heating network in Godby region, but also to its own operation facilities (Ålands Skogsindustrier Ab, 2018). In addition, a local heating network exists in Jomala, where heat is supplied from a heat-only boiler (HOB) fueled by residues from the local forest industry company (Ålands Skogsindustrier Ab, 2018). Occasionally heat is supplied to the local network of Jomala from a biogas plant, where bio-based by-products from local milk processing plant are converted to heat to be primarily utilized in dairy processes of the company (Ålandsmejeritet, 2018). Also several small heat boilers exist in the countryside such as in Lemland, Sund, Stalvik and Eckerö (Government of Åland, 2017b). These boilers can be fueled with wood chips and pellets. However, the district heating statistics related to Åland Islands, obtained from Finnish Energy include only the statistics related to Mariehamn's district heating network. It is estimated that the heat produced in the local networks outside Mariehamn represent approximately 5% of the district heat in produced in Mariehamn's district heating network (Government of Åland, 2017b).

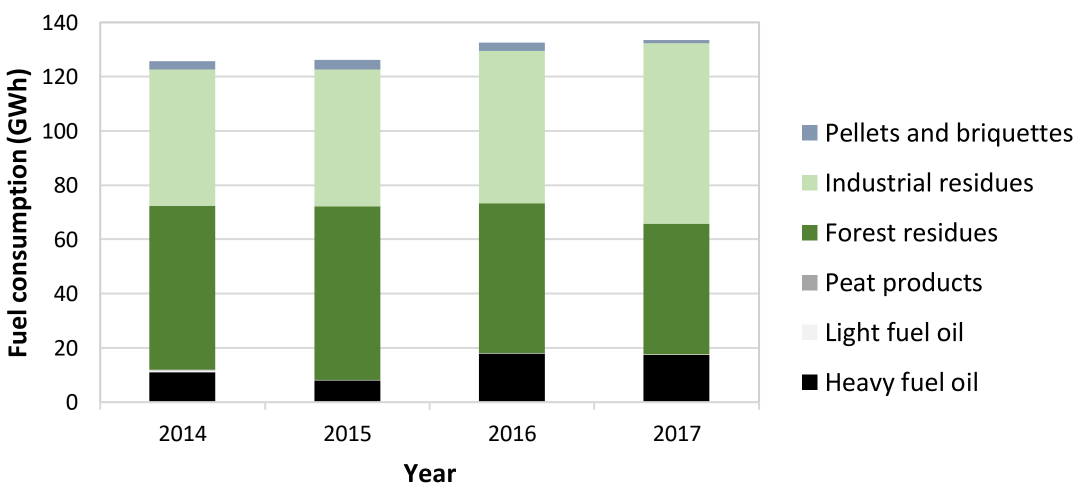

Figure 9. Consumed fuel energy in district heat production in Mariehamn (Finnish Energy, 2018b).

In accordance to Finnish Energy (2018b), 10 608 and 91% of population in Mariehamn lived in houses heated by district heat in 2017. Local heat, electricity, oil, gas, peat, coke and geothermal heat are heating sources utilized in the buildings of the island that are not connected to the district heating network of the capital. However, no public data exist regarding the total annual heat demand of Åland Islands.

3.3 Renewable energy potential

Åland's energy and climate strategy for 2030 defines wind, solar and biomass as the most potential local renewable energy sources for Åland Islands (Government of Åland, 2017a). Potential of the mentioned energy sources in Åland Islands are assessed to evaluate whether local resources are sufficient to increase the level energy independence on the island.

3.3.1 Wind

Åland is a wind-rich island with a large wind power potential due to its location as seen from Figure 10. Åland already receives approximately 20% of its annual electricity supply from local wind power production (Kraftnät Åland Ab, 2018) and therefore wind power is the most obvious source for renewable bulk electricity on the island. Child et al. (2017) estimated that the theoretical maximum potential for installed onshore and offshore wind capacity in Åland Islands is 522 MW and 4700 MW, respectively. These values are acquired by multiplying land and territorial sea areas of Åland with a land area availability value of 4% and capacity factors of 8.4 MW/km^2 and 10 MW/km^2 for onshore and offshore wind turbines. As the theoretical potentials for wind are very high in the region, the nominal capacity of wind is not constrained by wind availability. Other factors such as economics and legislation create the actual constraints restricting the investments.

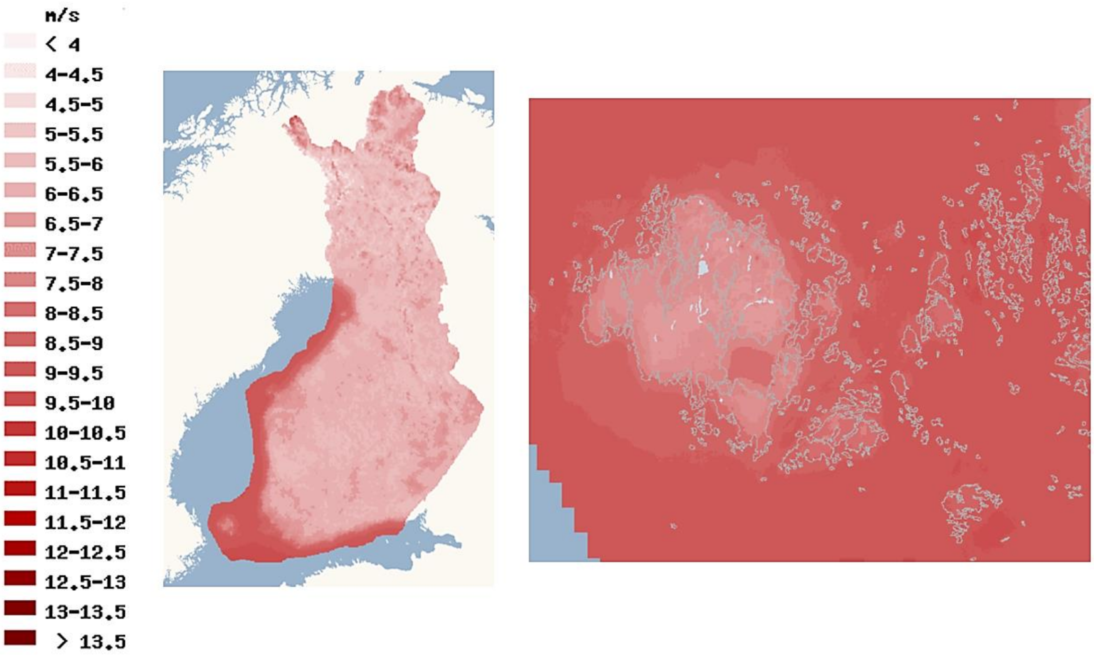

Figure 10. Wind velocity in Finland and Åland at 100 meters (Finnish Meteorological Institute, 2018b).

Currently nineteen wind turbines operate in Åland Islands, of which six 2.3 MW semi-offshore turbines installed in 2007 produce most of the generated electricity as seen from Figure 11 (Allwinds Ab, 2018b & Allwinds Ab, 2018c). In this thesis, semi-offshore wind turbines are defined in accordance to Child et al. (2017) as wind turbines located on the small islets of the scattered archipelago in the open sea. As a result, wind conditions resemble values of offshore turbines whereas the construction costs are more similar to onshore wind turbines.

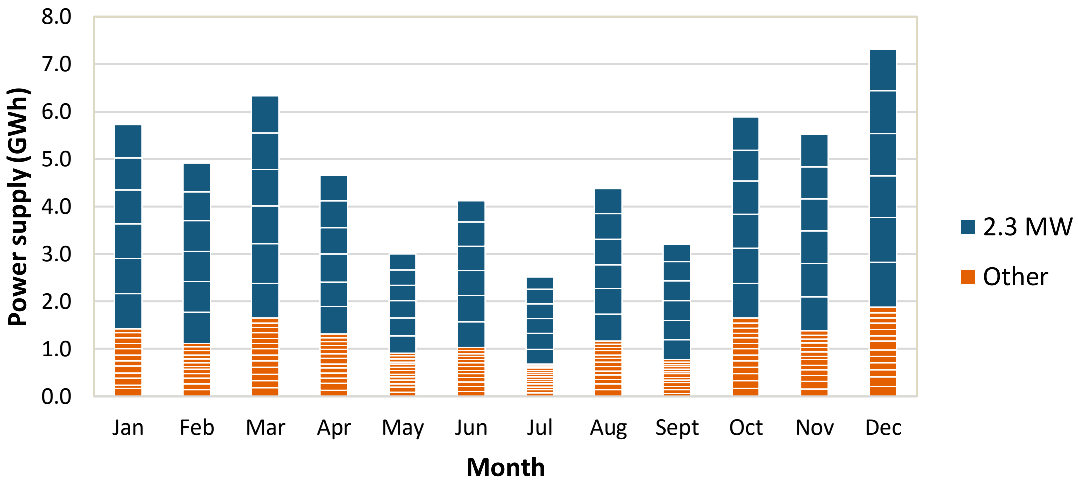

Figure 11. Wind power production by turbine in 2017 in Åland (Allwinds Ab, 2018c).

A detailed list of the operating wind turbines in Åland Islands including power output of each turbine, annual production volumes in 2017, installation years and models of the turbines is presented in Table 3. As the operation life of a wind turbine is 20-25 years (Finnish Wind Power Association, 2018), the older wind turbines will soon reach their end-of-life state. Replacing old onshore turbines with more productive ones could increase the wind power capacity in Åland. However, constraints regarding the size of a wind turbine on a certain location due to adverse effects such as increased shadow flickering, can restrict the size of the substitutive turbines (Jacobson et al., 2017).

Table 3. Summary of installed wind turbines in Åland Islands according to annual production volumes in 2017 (Allwinds Ab 2018a, Allwinds Ab, 2018b & Government of Åland, 2017a).

Name	**Power output (MW)**	**Production in 2017 (MWh)**	**Year of installation**	**Model**
Trefanten	2.3	7 346	2007	Enercon E-70
Donatus	2.3	7 304	2007	Enercon E-70
Konrad	2.3	7 160	2007	Enercon E-70
Anna	2.3	7 044	2007	Enercon E-70
Wendla	2.3	6 914	2007	Enercon E-70
Leo	2.3	6 843	2007	Enercon E-70
Oskar	0.66	1 611	2005	Vestas V47
Amalthea	0.6	1 314	2003	Enercon E-44
Astrea	0.6	1 311	2003	Enercon E-44
Albert	0.6	1 378	1999	Enercon E-44
Svea	0.6	1 201	1999	Enercon E-40
Fursten	0.5	1 066	1998	Enercon E-40
Gideon	0.5	995	1998	Enercon E-40
Altai	0.5	948	1998	Enercon E-40
Fredrika	0.6	1 086	1997	Vestas V44
Mika	0.5	1 078	1997	Enercon E-40
Freja	0.6	1 027	1997	Vestas V44
Fortuna	0.6	1 019	1997	Vestas V44
Frans	0.6	928	1997	Vestas V44
Total	21.26	57 573		

In addition on replacing old turbines with more efficient units, wind power capacity can also increase if the planned wind turbine projects currently on hold due to unprofitable economic conditions are realized (Government of Åland, 2017a). Most of the turbines related to the projects on hold are planned to be semi-offshore turbines such as the

2.3 MW turbines already existing in Åland (Allwinds Ab, 2018d & Allwinds Ab, 2018e). Locations of the existing turbines and planned wind turbine projects are displayed in Figure 12. Project Långstenarna is a common title for three projects Långnabba 1 & 2 and Stenarna located in the western part of Åland. The plan of the project is to install ten 3 MW onshore turbines and six 2-2.5 MW semi-offshore turbines with the total capacity of 42-45 MW to the areas displayed in the figure. The planned capacity for project Rödskär is 18 MW. The latest electricity transmission cable to Finland enables to install high wind power capacity to the eastern archipelago of Åland. Project Östra skärgården has the target to install 3 MW wind turbines with the total capacity of 100 MW to the islets in the eastern archipelago. In total, the capacity of the upcoming projects is expected to reach 160-163 MW. (Allwinds Ab, 2018d & Allwinds Ab, 2018e)

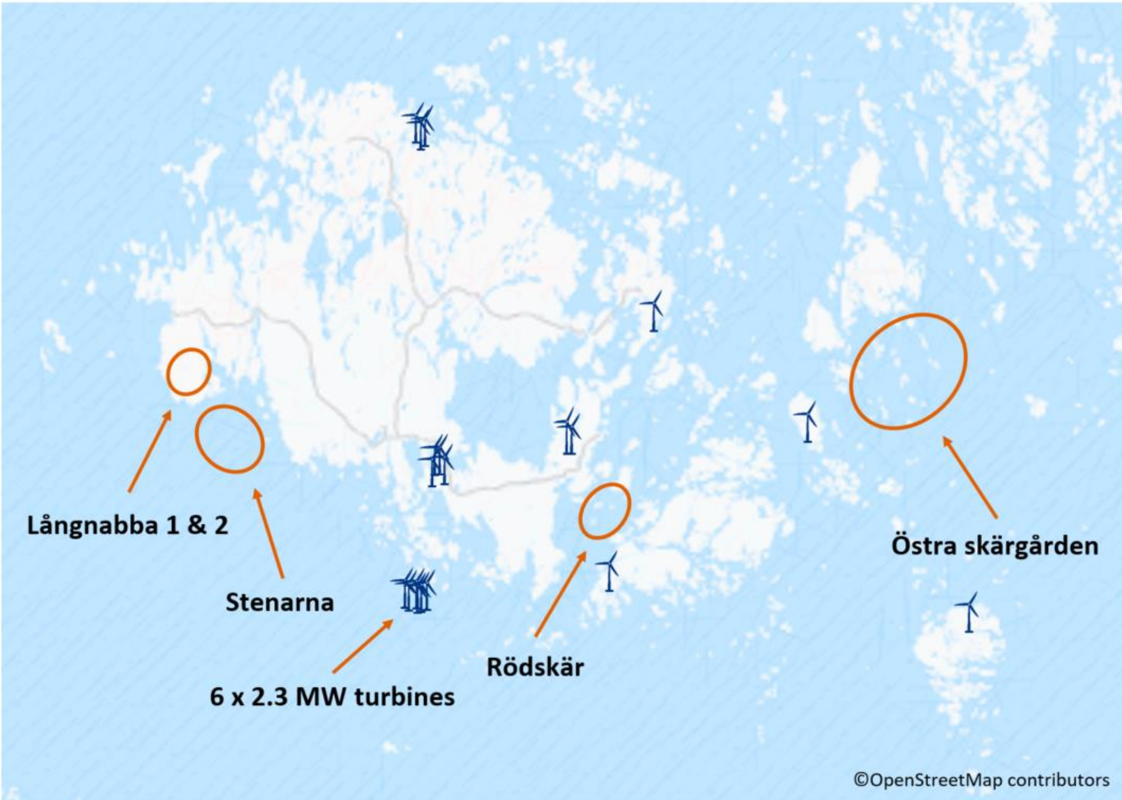

Figure 12. Current wind turbines and planned wind turbine projects in Åland Islands (Allwinds Ab, 2018b & Allwinds Ab, 2018e).

The annual power output of project Östra skärgården is estimated to be 300 GWh, which is almost equal to the current electricity consumption in Åland Islands (Allwinds Ab, 2018d). If all the projects on hold are realized, the total annual yield of local wind power could be higher than the island's current annual electricity demand. However, due to the intermittency of wind, Åland is not able to rely only on one supply source of electricity, even if the highest planned and assumed wind power capacity would be installed. Other local renewable energy sources or storage technologies are required to secure the supply of electricity during low hours and seasons of wind.

3.3.2 Solar

Solar power is described as an untapped energy source in Åland Islands (Government of Åland, 2017a). Biggest technical challenges on implementing solar energy in the region relate to the daily and seasonal variability of available solar energy, of which latter is highlighted in Nordic latitudes (Hakkarainen et al. 2015). Monthly electricity output for a grid connected and south-oriented 1 kW_p rooftop crystalline silicon PV system installed in Mariehamn with a performance ratio of 0.75 and a fixed angle at 44° is displayed in Figure 13 to emphasize the seasonal variance in the solar power output in the region. The values in the graph are derived from a Photovoltaic Geographical Information System (PVGIS) tool managed by European Commission (2017a), which calculates monthly performance of a solar PV system for a selected location.

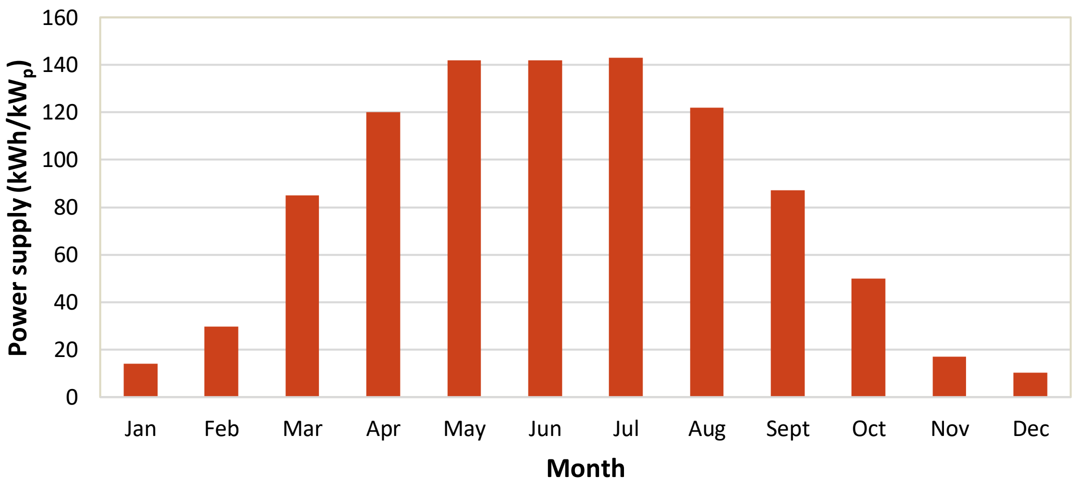

Figure 13. Monthly energy output of a south-oriented 1 kW_p photovoltaic system with fixed angle at 44° located in the capital Mariehamn (European Commission, 2017a).

As reported by the Government of Åland (2017a), solar energy should be utilized only as a complementary energy source in Åland Islands, as the production rates are low during winter, when power demand is on its highest. As seen from Figure 14, global irradiation values in Åland Islands (>1100 kWh/m^2) are good in relation to Finland

(900-1100 kWh/m^2) and the global irradiation values in Åland Islands are similar to the values in northern Germany (1200 kWh/m^2).

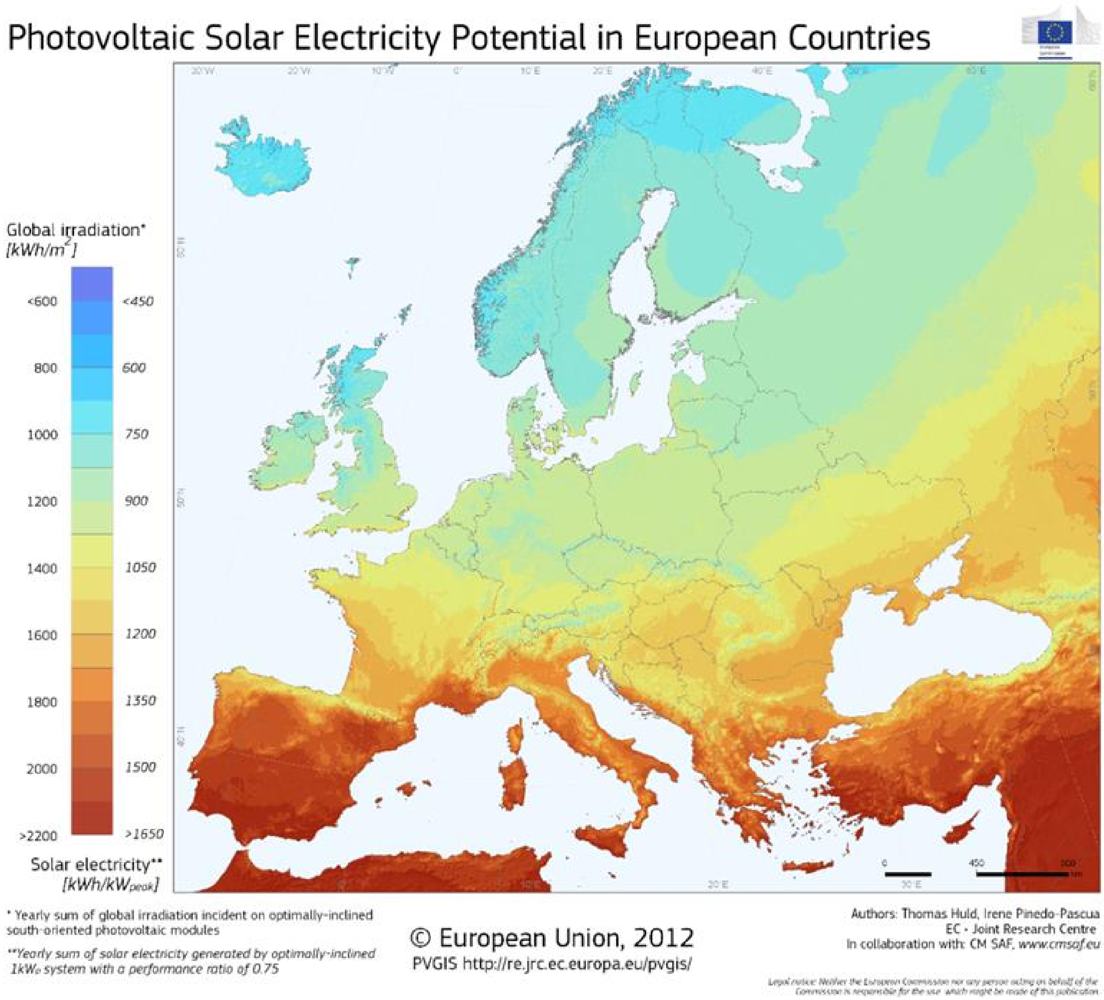

Figure 14. Photovoltaic solar electricity potential in Europe (European Commission, 2017a).

Only few buildings in Åland Islands are currently equipped with solar PV systems (Government of Åland, 2017a). Jacobson et al. (2017) estimated that the average size of an installed rooftop PV system in Åland is currently 7 kW$_p$. Since no public data is available from current solar electricity production on the island, output of the existing solar PV capacity is too small to be noticed on a system level approach. According to the energy and climate strategy of Åland Islands (Government of Åland, 2017a), the target power output of solar PV in 2030 is 17 MW or 5% of the annual electricity consumption.

3.3.3 Biomass

Ability to utilize biomass in the energy system does not necessarily require local biomass resources as if no local biomass resources are available, biomass can be imported to CHP plants and to other thermal energy production units (Jacobson et al., 2017). However, in relation to energy self-sufficiency, local biomass is the foremost option. The Government of Åland has published a forestry program (Government of Åland, 2017b) where Åland's forest-based biomass potential for energy use has been assessed based on forestry values derived from Natural Resources Institute Finland. The estimated values are based on most technically and economically sustainable annual harvesting volumes until 2042. According to the program, total available annual forest-based biomass potential in Åland Islands is 160-170 000 solid cubic meters (m_s^3), which consist of 70 000 m_s^3 energy wood from thinning operations, 50-60 000 m_s^3 from forest residues and 40 000 m_s^3 from stumps. In addition to the energy-wood potential directly from forests, industrial residues such as bark and sawdust of 30 000 m_s^3 can also be annually utilized in energy production. Total fuel energy potential related to forest-based biomass in Åland is almost 400 GWh as evaluated in Table 4, which is over three times the current forest-based fuel usage (120 GWh in 2017; Finnish Energy, 2018b) in district heat and CHP production on the island.

Table 4. Theoretical energy potential of forest-based biomass in Åland Islands.

Source	**Theoretical availability[1] (m_s^3)**	**Bulk energy density[2] (MWh/m^3)**	**Solid energy density[3] (MWh/m_s^3)**	**Potential energy content (MWh)**
Thinning wood	70 000	0.7-0.9	1.75-2.25	122 500-157 500
Forest residues	55 000	0.7-0.9	1.75-2.25	96 250-123 750
Stumps	40 000	0.7-1.2	1.75-3	70 000-120 000
Industrial residues	30 000	0.45-0.9	1.125-2.25	33 750-67 500
Total	195 000			322 500-468 750
			Average	395 625

[1]Derived from Government of Åland (2017b)

[2]Bulk energy density as received (E_{ar}), deviation resulting from variance in the moisture content. Industrial residues include sawdust and bark. (Alakangas et al., 2016)

[3]Based on bulk-to-solid ratio 0.4 (Alakangas et al., 2016)

Direct combustion and anaerobic digestion to biogas are examples of waste-to-energy processes, which enable to recover energy from municipal solid waste (Pimiä et al., 2014). According to Child et al. (2016), annual municipal solid waste potential in Åland Islands is 32.500 tons. However, currently municipal solid waste generated in Åland Islands is shipped to Sweden for waste incineration, as local waste combustion for energy purposes is considered uneconomic. Therefore, energy potential from waste combustion is excluded from the thesis. A study by Allerborg et al. (2015) has evaluated biogas production potential in Åland Islands. According to the study, the annual amount of locally available feedstock for biogas production is approximately 35.000 tons. The feedstock consists of manure, animal-based residues, mixed food waste, garden waste and sorted bio-waste from the residential sector. The study estimates the amount of biogas produced from the available feedstock to be 3.27 million m^3_n annually, with a methane concentration at 63%. With the estimated biogas yield and a biogas heating value of 4-6 kWh/m^3_n (Alakangas et al., 2016), the available yearly fuel potential from biogas is estimated to be 13-20 GWh in Åland Islands.

4 ENERGY SYSTEM FLEXIBILITY

In traditional power systems with low shares of VRE generation, electricity demand has been the main source of variability, in addition to unexpected generator outages in the power supply side. In these systems, generators with the capability to operate at varying load such as gas turbines and hydropower plants along with pumped hydro storages, have been primary sources of electricity generation flexibility. As the share of VRE sources in the power generation mix gradually expands due to cost reductions in VRE technologies and national policies driven by global targets of climate change mitigation~~,~~ requirements for energy system flexibility increase as well. High penetration of VRE increases variability in the power supply side and hence challenges demand and supply balancing, as dispatchable generators are required to manage with higher variability and uncertainty in the residual load. Variability stands for the non-controllable nature of VRE supply, as power production from VRE sources is fluctuating and intermittent depending on weather conditions. Uncertainty refers to the inability to precisely forecast power output from VRE sources before the actual realization. (IRENA, 2018c)

The challenge of high VRE capacity is framed in Figure 15, where system-level impact of high variable generation on power balance on a three-week period is illustrated. As seen from the figure, intermittent generation of wind and solar does not couple with the power demand. Flexibility is required to avoid curtailment of excess VRE generation at supply peaks and increase adaptability of other power supply sources during periods of low VRE output.

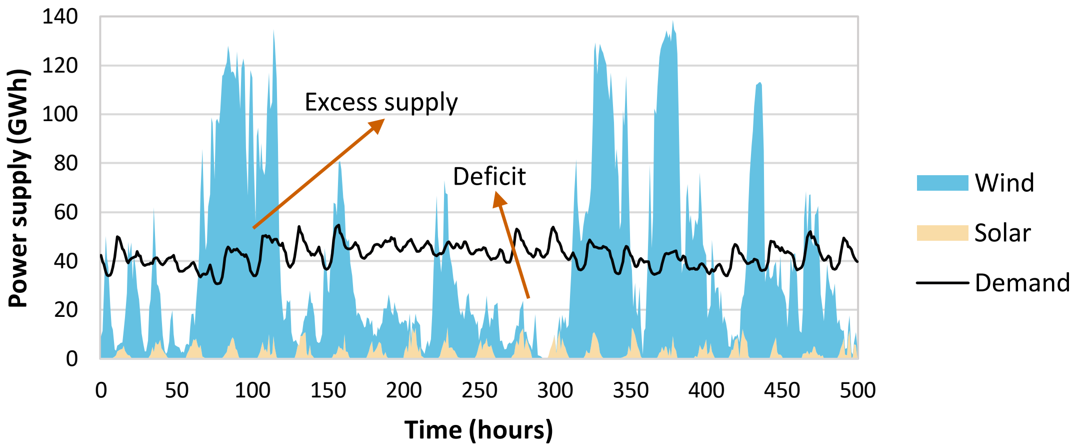

Figure 15. Flexibility issues on a three-week period in an energy system with high VRE penetration.

Integration of VRE sources and hence increased variability and uncertainty in power supply can decrease the profitability of the energy system in several means. If curtailment of high VRE generation cannot be avoided, utilization rate of VRE sources decrease, reducing the revenue gained from VRE investments (Bloess et al., 2018). By outstripping the feed-in of conventional baseload power units during periods of high VRE supply, increased VRE capacity reduces profitability of dispatchable thermal units. In addition, as residual load confronts more rapid changes, the utilization of units with fast ramping capabilities and higher marginal costs increase, as the economic and larger production units are not able to keep up with the sudden load changes. Investing on flexible units that have the capability to manage with high variability in the residual load adds extra costs in VRE integration as well. Apart from variability, forecast errors related to uncertainty in VRE supply can also increase total system costs by increasing short-term balancing requirements. (Kiviluoma, 2013)

The costs occurring at different parts of the power system due to increased VRE deployment are referred as system integration costs (Joos & Staffell, 2018). Cost-effective flexibility mechanisms can enable to mitigate costs related to increased variability and uncertainty resulting from increased VRE capacity. A study by Kondziella & Bruckner (2015) divided flexibility options to facilitate VRE integration into five categories presented in Table 5. In general, the study states that both demand and supply side elements in the energy system can participate in providing flexibility for VRE integration, storage technologies operating in both sides.

Table 5. Flexibility alternatives for VRE integration (adapted from Kondziella & Bruckner, 2015).

Flexibility alternative	**Definition**
Power-to-Power	Electrical energy storages
X-to-Power	Functional power storages such as bioenergy and demand response
Power-to-X	Power conversion for heat, gas or transportation fuel
Transmission	Power exchange (imports and exports)
Other	Flexible thermal units, curtailment

The aim of the following chapters is to provide an overview of potential energy system elements that could increase energy system flexibility cost-effectively in Åland Islands by 2025. Potential unit and system level flexibility elements in both power and heating sector are considered including district heating network, CHP, thermal energy storage (TES), electric boiler and electrical energy storage (EES). Although power-to-X technologies converting surplus VRE into energy carriers such as hydrogen, methane and ammonia are considered as an essential part of the global energy transition (Frontier Economics, 2018), only the potential of power-to-heat conversion in providing demand-side flexibility for VRE generation in Åland Islands is evaluated in the thesis. Other power-to-X technologies are excluded, as exploiting their full potential would require incorporating other sectors such as industry and transportation to the thesis, which currently considers only power sector and district heating network. For instance, in accordance to Schulze et al. (2017) power-to-gas conversion could be profitable in energy systems, where excess VRE is converted to hydrogen to be utilized in mobility sector, which is excluded from the energy system analysis in this study.

4.1 District heating

District heating networks comprise of energy supply sources, distribution network and end-users with heat demand (Olsthoorn et al., 2016). The purpose of a district heating network is to distribute heat generated in centralized production units into areas, where heat demand is high enough to promote the establishment of a district heating system (IRENA, 2018a). Heat is carried to end-users via pipes, transferred to heat exchangers, after which the cooled water is fed back to the heat production units (Kiviluoma et al., 2017). Heat can be supplied to the district heating network from various of sources, depending on the locally available resources (Olsthoorn et al., 2016).

Referring to Arasto et al. (2017), when available, heat derived from waste incineration and industrial processes are applied as the primary supply source of heat in the district heating network due to low costs. If neither source is available, baseload of heat is generally covered by a CHP plant, which generates both heat and electricity at high overall efficiency. The operation of CHP is complemented with heat-only boilers, which are utilized during cold periods in the winter, when the capacity CHP is not sufficient to cover the heat demand alone or in summer, when the operation of CHP might not be beneficial due to low heat and power demand (Pöyry, 2018a). As for 2017, 90% of the global heat supply from CHP and heat-only boilers in the district heating networks originated from fossil sources such as coal, natural gas and oil (Werner, 2017). In Finland, fossil fuels contributed 35% of the district heat supply in 2017 (Finnish Energy, 2018a).

Biomass combusted in thermal plants in addition heat from geothermal wells and solar collectors are global examples of renewable heat supply sources that have been deployed in district heating networks in recent decades to substitute fossil fuel usage in CHP and heat-only plants. Increased deployment of VRE sources in power sector creates potential to apply flexibility elements such as electric boilers, heat pumps and thermal energy storages to district heating networks as well. Strengthening the link between power and heating sectors beyond CHP plants results in bidirectional benefits for both power and district heating networks, as flexibility elements have the potential to facilitate integration of VRE sources to the power sector while accelerating decarbonization of heating sector at the same time. (Werner, 2017)

Flexibility potential of district heating network in facilitating VRE integration has been evaluated for instance by Kiviluoma & Meibom (2010). The study stated that district heating network provides greatest flexibility benefits for VRE integration, when the district heating network is connected to a CHP unit, thermal energy storages and electric boilers. Flexibility potential of these elements are individually assessed in the following subchapters. According to Kiviluoma et al. (2017), the potential of a district heating network in power system balancing should primarily be harnessed in areas where district heating networks already exist, as installing district heating networks to existing cities is difficult and expensive. In addition, IRENA (2018b) suggests that the existing flexibility potential of elements already existing in the energy system should be applied first, before investing into new flexibility components. As district heating network already exists in Åland Islands, its ability to increase system flexibility on the island should be evaluated.

4.1.1 CHP

Dispatchable power supply from bioenergy has been acknowledged as a potential source of flexibility in future energy systems with increased VRE supply (Arasto et al., 2017). Benefits of CHP generation are versatile in relation to separate heat and power production. According to Finnish Energy (2010), total overall efficiency in CHP generation can reach levels of over 90%, as heat generated in power production process is recovered and utilized in a district heating network or in industrial processes. To compare, separate power production in condensing power plants can reach efficiency of only 35-45% (Statistics Finland, 2013). According to Werner (2017), the ability to utilize CHP units in energy production has been an important driver for establishing district heating networks throughout the world, for the very reason that the thermal losses generated during power production in CHP units can be recovered in fulfilling heat demand elsewhere. In addition on avoiding heat losses, CHP production enables to reduce CO_2 emissions per produced kilowatt as well, due to higher fuel conversion efficiency in comparison to separate heat and power production processes (Finnish Energy, 2010).

Output of the CHP unit generally follows heat demand in the district heating network, whereas electricity is produced as a side-product creating inflexibility related to dispatchable power supply (Arasto et al., 2017). CHP units could increase power system flexibility in energy systems with increased variability in power supply, if they were able to alter their dispatchable power output more efficiently based on power price signals in the power market (Arasto et al., 2017). Currently, CHP units in combination to a district heating network can provide flexibility to the energy system in some extent. By covering heat load, smaller heat-only boilers can enable CHP to decouple its output from the heat demand, allowing some operational sensitivity related to electricity prices (Kiviluoma et al., 2017). In addition, district heating network can accumulate heat momentarily in a situation where CHP unit should increase its power output due to power grid requirements (Korpela et al., 2017). Furthermore, an opportunity to alter the production rate between heat and power generation exists in some CHP units, increasing operational opportunities of CHP production (Kiviluoma et al., 2017). In some occasions, power production of the unit can be entirely ceased by bypassing the turbines generating electricity (Pöyry, 2018a).

Although CHP has been acknowledged as a beneficial dispatchable power source in VRE balancing for instance in Rinne & Syri (2015) and Pääkkönen & Joronen (2019), increased penetration of VRE can pose multiple challenges for the operation of the CHP unit. Baseload units in both heat and power sector, including CHP, prefer to operate at high capacity, as the optimal generation efficiency drops when the output of the unit is reduced, resulting in increased generation costs at low loads (Arasto et al., 2017). According to Kiviluoma (2013), increased share of VRE production in the power sector can reduce efficiency of the baseload power units, as they need to reduce their output to avoid curtailment of surplus VRE supply. In addition, increased VRE capacity decreases operating hours of thermal power plants (Kiviluoma, 2013). Reductions in both operating hours and efficiency increase unit costs of the baseload plants resulting in decreased unit profitability. Furthermore, increased fluctuations in the residual load create more irregularity to the operation of thermal power production units. Irregularity results in increased amount start-ups and shut-downs in addition to increased requirements related to both ramping and partial and minimum load operations (Arasto et al., 2017). As altering the operational load of baseload plants is expensive and slow (Lund et al., 2015), generators with enhanced operational capabilities to cope with the intermittency in the energy output are required. In conventional energy systems, gas turbines and hydropower with fast start-up times and ramping responses are used to provide instant supply side flexibility (Lund et al., 2015). An alternative is to combine cost-effective flexibility elements, such as thermal energy storages and electric boilers with CHP unit to increase its potential in providing power system flexibility as already suggested by Kiviluoma & Meibom (2010).

In Åland Islands, the baseload of heat is currently supplied by heat-only boilers, as the turbine in the existing bio-CHP unit is by-passed due to economic constraints in thermal power production as discussed in section 3.1. As the thermal production units in Mariehamn's district heating network are rather old and partly ran by fossil fuels, the feasibility of a new bio-CHP investment should be studied. The bio-CHP unit would not only replace the old heat-only boilers and act as source of renewable heat generation, but the bio-CHP investment could also serve as a potential source of flexibility in power production, assuming the VRE capacity on the island will increase. As the profitability of CHP as a flexibility element is largely dependent of fuel prices (Pääkkönen & Joronen, 2019), the impacts of biomass price variance on the feasibility of CHP investment should also be investigated, if the investment on a bio-CHP was made.

4.1.2 Thermal energy storage

Centralized thermal energy storage (TES) connected to a district heating network accumulates thermal energy by heating a storage material from which heat is recovered when required (IEA-ETSAP & IRENA, 2013). Thermal energy storage levels out heat demand in district heating network by storing heat generated at off-peak hours and discharging it to the network during periods of higher heat demand (Pöyry, 2018a). Thermal energy storages in the district heating network are often either steel or concrete tanks or rock caveats located close to CHP units, where water is used as a storage medium (Pöyry, 2018a). Charging and discharging rates of TES can vary from hours to days (Alanen et al., 2003). Seasonal thermal energy storages exist as well, where heat is stored for months. For instance, a Finnish energy company Helen is planning to build a seasonal TES, where surface sea water heated by sun in the summer is stored in large rock caveat to be utilized in heating purposes during winter (Helen Oy, 2018).

A thermal energy storage enables to disconnect the operation of CHP from heat demand and therefore, TES enables to increase power generation from CHP at times when dispatchable power generation is needed in the grid. Increased operational opportunities of CHP reduce the need of condensing power plants often fueled by oil or coal. By substituting power generation from fossil fuels at lower fuel conversion efficiency, TES also contributes on increasing the overall efficiency of the energy system resulting in lower CO_2 emissions. (Rinne & Syri, 2015)

In addition on enabling CHP to maximize its power output more often based on grid requirements, thermal energy storage also allows CHP to shut down at times when the operation of the CHP unit is less profitable, such as during periods of high VRE supply and low power consumption (Kiviluoma & Meibom, 2010). CHP unit can stay shut for longer periods, if TES is charged by heat generated from excess electricity in power-to-heat conversion as discussed later. In addition on increasing operational flexibility of the CHP unit, thermal energy storage can also serve as a reserve source of heat during unexpected outages in heat supply (Alanen et al., 2003)

If Åland was to invest on a new bio-CHP unit for heat generation and VRE balancing purposes, a thermal energy storage would potentially increase operational flexibility of the CHP unit and hence enable more opportunities for dispatchable power generation during hours of low VRE supply. Both Rinne & Syri (2015) and Pääkkönen & Joronen (2019), from which latter studied the profitability of bio-CHP in VRE balancing in Åland Islands as discussed in section 3, agreed that if a CHP unit was applied to an energy system for VRE balancing purposes, the impacts of TES in increasing operational flexibility of CHP should be evaluated. As the capital Mariehamn has an available thermal energy storage capacity of 350 MWh (Pääkkönen & Joronen, 2019), the potential benefits of TES should be studied if an investment on a CHP unit was made.

4.1.3 Electric boiler

Integration of VRE sources can be facilitated by power-to-heat technologies, which convert electricity into thermal energy. Centralized large-scale heat pumps and electric boilers connected to a district heating network are power-to-heat sources, which are able to provide demand side flexibility for the power grid (Yilmaz et al., 2018) by altering power consumption based on market signals. Heat pumps convert power to heat with higher efficiency in comparison to electric boilers, whereas investment costs of electric boilers are lower and hence less full operation hours are required to make the investment profitable (Yilmaz et al., 2018). Kiviluoma & Meibom (2010) found that heat pumps are not an important source of flexibility in a district heating network including a CHP unit, as both CHP and heat pump require large amount of full operating hours to become profitable. Therefore, they compete for the same operating time. As CHP plant is a potential future source of flexibility in the energy system of Åland Islands, further evaluation of power-to-heat technologies in providing flexibility will focus only on electric boilers. However, majority of the benefits provided by electric boilers apply to heat pumps as well.

Electric boilers utilize electricity to generate hot water or steam via electrical resistance coils or electrodes, which both can reach conversion efficiency up to 99% (Garcia et al., 2012). When integrated to a district heating network, electric boilers can provide multiple system level benefits in energy systems with high levels of VRE. By utilizing excess electricity as a fuel, electric boilers are able to reduce VRE curtailment at periods of high VRE supply, resulting in higher utilization rate of VRE technologies and increased profitability of VRE investments (Bloess et al., 2018). In addition, as the share of VRE supply increases in the power mix, periods of low or even negative power market prices are more likely to occur (Nielsen et al., 2016). Electric boilers are able to increase operational flexibility of thermal plants at these occasions. For instance, heat production via electric boiler enables to shut down CHP generation during low power prices (Kiviluoma & Meibom, 2010), when operation of CHP unit is less profitable. Due to zero start-up costs and ramping requirements, electric boilers are also able to participate in short-term grid balancing (Nielsen et al., 2016). The current use of electric boilers in district heating networks is mainly driven by the ability to provide ancillary services such as frequency control for the power grid (Danish Energy Agency, 2019)

By substituting heat generation from thermal plants, electric boilers reduce fuel usage in heating sector, which can be economically beneficial in regions where low-cost and renewable fuel for thermal heat production is not available (Pöyry, 2018b). If electric boiler reduces heat generation from fossil sources, it contributes to decrease CO_2 emissions as well, accelerating decarbonization of the heating sector (Bloess et al., 2018) In Finland, an important constraint for power-to-heat conversion from surplus VRE generation has been high taxation related to electricity used by energy companies. Energy companies have to pay energy tax from the higher taxation category, resulting in additional costs of 22.5 €/MWh of electricity utilized for heat conversion (Pöyry, 2018a).

From technical perspective, the seasonal pattern of wind supply would fit in well with heat demand in Åland Islands, as both wind supply and heat demand are high during winter and reduce as approaching summer. Therefore, electric boiler could have great potential in increasing internal utilization of locally produced electricity and reducing VRE curtailment during transmission congestions between Åland and the neighboring power areas. Electric boilers could also contribute on providing ancillary services for the power grid.

4.2 Electrical energy storage

As the share of VRE generation grows in the energy mix, the importance of electrical energy storages (EES) in balancing intermittent VRE generation and providing ancillary services, such as frequency and voltage control for power grid increase (IRENA, 2017). In 2017, pumped hydro storage accounted for 176 GW and 96% of the installed EES capacity in the world (IRENA, 2017) making it evidently the most commercialized electricity storage technology. Pumped hydro storage takes advantage of the energy potential difference between upper and lower water reservoir of a hydropower plant, as surplus electricity is utilized to pump water to the upper reservoir to be converted back to electricity in the hydropower plant during hours with high power demand (Suberu et al., 2014). Flat topography (The World Bank Group and DTU, 2018) and absence of hydropower constraints implementation of pumped hydro storage in Åland Islands.

Cost reductions accelerate the deployment of stationary electricity storages in energy systems with increased levels of VRE generation. Electrochemical battery technology is one of the most growing form of electricity storage, as growth in the installed global power capacity has been exponential between 1996 and 2016, although the total power capacity of electrochemical batteries reached only 1.9 GW in 2017. Lithium-ion batteries are the most utilized electrochemical storage technology, and as for 2017, lithium-ion batteries covered 1.12 GW and 59% of the global installed electrochemical battery power capacity. Contrary to other electrochemical storage devices, cost reduction potential of lithium-ion batteries is especially highlighted due to its supreme role in electric vehicles. As the deployment of EVs is expected to expand, the increasing production capacities related to lithium-ion batteries utilized in electric vehicles will create opportunities to reduce the costs related to stationary lithium-ion batteries as well. (IRENA, 2017)

Electrochemical batteries convert electricity into chemical form, which can be stored and converted back to electricity during discharging processes (Suberu et al., 2014). Adaptability and scalability of electrochemical batteries is wide, as individual electrochemical cells can be combined in different series and parallel combinations to achieve the desired power capacity output. Electrochemical batteries have multiple beneficial characteristics such as fast response time and discharging durations up to several hours, which promote their usage in grid-scale applications in energy systems with high VRE penetration. (Argyrou et al., 2018)

Fast response time enables electrochemical batteries to participate in frequency and voltage control in addition on increasing power quality in the grid (Argyrou et al., 2018). Fast response time i.e. the ability to shift rapidly to discharging stage drives the commissioning of by far biggest stationary battery in Nordic countries. With the purpose of promoting integration of VRE technologies to the power grid, Fortum aims to install a

5 MW and 6.2 MWh stationary battery to Sweden in 2019, to enhance the speed and accuracy of grid balancing services provided by a hydropower plant (Fortum, 2018). The battery is charged with hydropower and discharged at times when frequency control is needed (Laatikainen, 2018a). The investment is made in continuum of a successful demonstration project in Järvenpää, Finland, where Fortum installed a 2 MW and 1 MWh lithium-ion stationary battery to provide second and minute level frequency control for the Finnish power grid (Fortum, 2017).

As the power and capacity of the electrochemical battery can be scaled, electrochemical batteries are able to reach discharging times up to several hours, which allow batteries to engage in peak shaving and load leveling (Argyrou et al., 2018). Batteries can store excess VRE and rescheduled power generation supplied at off-peak hours and deliver the stored electricity during hours with high consumption. Lithium-ion battery system is utilized for peak demand management for instance in Southern California, where a 20 MW and 80 MWh stationary electrochemical battery reduces dependency of peak power plants running on natural gas (Lambert, 2017). Currently the largest global utility battery is the 100 MW and 129 MWh Hornsdale Power Reserve located in South Australia, which facilitates integration of VRE sources by charging surplus wind power at times when power demand is low while participating in frequency control as well (Hornsdale Power Reserve, 2018).

Storage technologies operating at different response and discharging rates are needed in Åland Islands to address the increased volatility in the power grid caused by the expected increase in the VRE supply. A stationary electrochemical battery storage could provide dispatchable power supply to balance intermittent VRE generation by peak shaving and load leveling in addition on providing short-term stability and balancing services such as frequency and voltage control for the power grid. As VRE supply is expected to increase in Åland Islands, the potential benefits of a stationary electrochemical battery should be evaluated for the future energy system of Åland Islands.

EXPERIMENTAL PART

5 SIMULATIONS

The objective of the simulations is to evaluate the most cost-optimal configuration of thermal production units in relation to VRE sources and certain flexibility elements in three different energy system scenarios built for Åland Islands. The simulation results are utilized to evaluate which energy production units and flexibility elements are most feasible and sustainable on making the energy system of Åland Islands renewable by 2025. The simulations aim to answer the following questions from the perspective of Åland Islands to support the research questions introduced in section 1:

- Would the renewable energy system of Åland Islands be viable without imported electricity?
- What is the system level impact of high VRE capacity?
- What are the economic and environmental impacts of a renewable energy system?
- Which flexibility elements can improve integration of VRE sources and bring additional value for the renewable energy system?
- What are the impacts of biomass availability and price on the dynamics and profitability of the studied renewable energy system scenarios?

5.1 Simulation tool

An energy system modelling tool utilizing methodology applied in several energy system analysis tools such as in Balmorel (Balmorel, 2019) and EnergyPLAN (EnergyPlan, 2019) has been developed at VTT and applied in the thesis. The modelling tool enables to define the cost-optimal dispatchable energy generation portfolio to adapt to the changes in VRE capacity by optimizing the hourly dispatch schedule of the applied energy system elements for a given period. The optimization problem is created with Pyomo written in Python and solved by using commercial IBM ILOG CPLEX solver. The tool is not available under open source conditions. In the thesis, the modelling tool is utilized to define the cost-optimal configuration of dispatchable power and heat production units in different energy system scenarios with fixed capacities of VRE technologies, energy storages and transmission capabilities, to satisfy the hourly demand in both power and district heating network. The optimization period in the model is set to be one year, which is divided into hourly time steps. The reference year is 2025, as it is assumed, that the realization of the renewable energy system is finalized in Åland Islands by that time.

In the model, the capacity of existing conventional and renewable energy production units and the capacities of new VRE investments in Åland Islands remain constant with no opportunity for capacity optimization. Fixed capacity investments are also made for energy storage units; however, the model is able to define the storage capacity required for cost-optimal system operation, which can be below the invested capacity. Similar methodology is also applied for power transmission, as although the maximum boundaries for hourly electricity import and export are set, the optimized power exchange maximum can be below the given rated capacity.

Each analyzed scenario represents a collection of potential dispatchable power and heat generation units with a manually controlled capacity range, to which an investment can be made. The model optimizes hourly dispatch of the potential dispatchable power and heat production units and defines their cost-optimal capacity from the set capacity range. Hourly dispatch in the simulation tool is based on system cost minimization and therefore, the most cost-effective technologies are dispatched first. Investment on a new dispatchable unit with a certain capacity is made, if the unit is required to fulfill power or heat load and/or the unit is able to reduce annual system costs and hence facilitate the integration of VRE technologies to the energy system of Åland Islands.

The objective function (1) to define the cost-optimal solution of the given parameters is divided into four lines to outline the source of income or cost in *n* units, 8760 time steps and *m* transmission lines as follows:

$$\max_{c \in \mathrm{R}} \left(\begin{array}{c} \sum_{i=0}^{n} \sum_{j=0}^{8760} C_{\mathrm{dh,i,j}} + C_{\mathrm{el,i,j}} + C_{\mathrm{tar,i,j}} \\ - \sum_{i=0}^{n} \sum_{j=0}^{8760} \mathrm{C}_{\mathrm{fuel,i,j}} + C_{\mathrm{ETS,i,j}} + C_{\mathrm{tax,i,j}} + C_{\mathrm{OPEX,i,j}} + C_{\mathrm{ramp,i,j}} \\ - \sum_{i=0}^{n} C_{\mathrm{OPEX,fixed,i}} + C_{\mathrm{PMT,i}} \\ - \sum_{k=0}^{m} \sum_{j=0}^{8760} (C_{\mathrm{imp,k,j}} - C_{\mathrm{exp,j,k}}) \end{array} \right) , \tag{1}$$

where Line 1 = Income for each applicable unit (i) on a given hour (j) from sold district heat C_{dh}, sold electricity C_{el} and renewable energy tariff C_{tar}.

Line 2 = Cost for each applicable unit (i) on a given hour (j) from fuel cost C_{fuel}, emission allowance cost C_{ETS}, fuel tax C_{tax}, additional operating cost C_{OPEX} and ramping penalty C_{ramp}.

Line 3 = Cost for each applicable unit (i) from annual fixed operation costs $C_{\mathrm{OPEX,fixed}}$, including both new and existing units and annual investment payments C_{PMT} of new units.

Line 4 = Cost and income from power imports C_{imp}, and exports C_{exp}, on a given hour (j) for each transmission line (k).

Fixed investments of VRE and storage technologies are not included in the objective function, however, they are added to the total system costs.

Certain hard constraints are applied in both unit and system level to outline the system boundaries for optimization. For instance, the units are forced to operate within the defined load limits. Power demand of the system must be covered at every hour from local power supply sources including storage, or from imported electricity. Supplied district heat from heat generation units and storage must be equal to the district heat demand at all times. In addition, load of each energy supply source must always be below the set maximum capacity rate. Certain soft constraints are applied as well. For instance, large thermal production units are penalized for rapid load changes. In addition, electricity imports are penalized to favor local power generation. However, in the economic assessment, the penalty from imported electricity is deducted.

5.2 Scenario descriptions

Energy system analysis for Åland Islands is performed for the year 2025. Electricity and district heat demand are expected to grow according to the trends of the past decade. Annual consumption values as well as future projections related to annual demand and sale of electricity and district heat in Åland Islands are presented in Figure 16. According to the latest annual report of Åland's transmission system operator (Kraftnät Åland Ab, 2018), total electricity consumption on the island has increased on average 1.5% annually during the previous ten years. Applying the yearly growth rate of 1.5%, total electricity consumption in Åland Islands is evaluated to reach 350 GWh_e in 2025. Equally to electricity, sale of district heat in Mariehamn's district heating network has also increased on average 1.5% annually during the last decade, when losses are excluded from the supply (Finnish Energy, 2018c). Following the annual growth rate of 1.5%, the sale of district heat is set at 119 GWh_{th} in 2025. Heat loss is added to the estimated sales volume to determine the overall heat demand in the district heating network in 2025. As for 2017, heat loss accounted for 10.9% of the heat supply in the district heating network of Mariehamn (Mariehamns Energi Ab, 2018). Applying the same percentage of heat loss results in total district heat demand of 132 GWh_{th}, which is the total heat demand applied in the simulations.

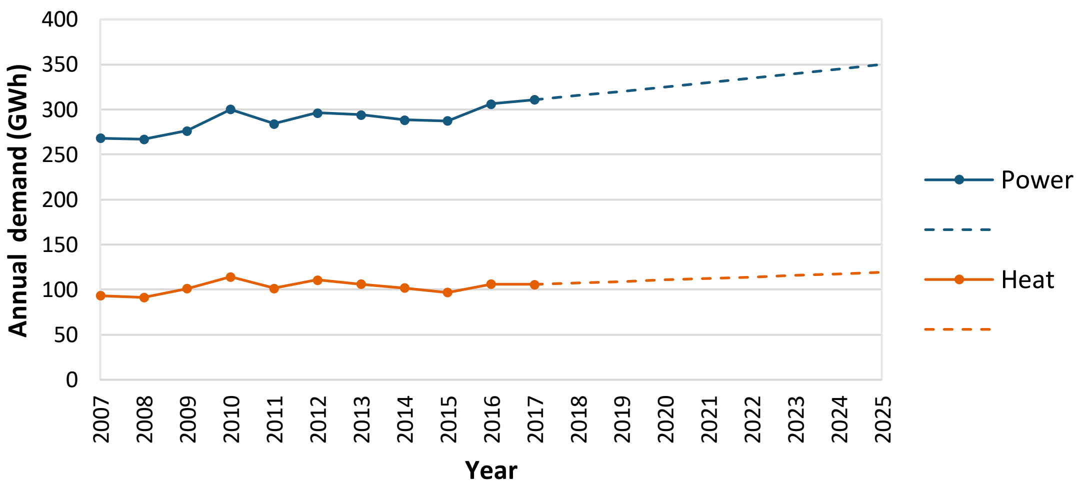

Figure 16. Electricity consumption and sale of district heat in Ålands Islands 2007-2025 (Kraftnät Åland Ab, 2018).

As hourly power and district heat consumption profiles in Åland Islands and Mariehamn are not publicly available, hourly load curves are manually quantified for simulation purposes. National hourly electricity consumption curve from Finland obtained from Fingrid (2018) is scaled to resemble hourly electricity load of Åland Islands. Ratio between monthly electricity consumption in Åland (Allwinds Ab, 2018c) and Finland is determined, and the received values are multiplied with the related hourly consumption values from Finland. Load consumption curve for the district heating network in Mariehamn is determined by utilizing temperature data from Mariehamn (Finnish Meteorological Institute, 2018a) and monthly district heat production volumes from

Mariehamns Energi Ab (2018). As all the acquired data is based on values from 2017, the resulting hourly load curves are scaled to feature the previously determined annual power and heat supply volumes in 2025.

Hourly production profiles of wind and solar PV origin from weather data based on values from 2017. Hourly wind speeds are acquired from Finnish Meteorological Institute (2018). Wind speed data is not in most cases available from the exact location where the wind turbines are planned to be installed or where they exist at the moment. Therefore, wind data from the closest observation station with the similar coastal or inland conditions are utilized. The gaps in the data are filled with an average value of the preceding and following measurement.

Hourly wind speed data is converted into electrical output by utilizing pre-calculated power curves derived from wind turbine supplier Enercon (Enercon GmbH, 2018a-c). Table 6 determines which turbines and hence power curves are utilized for the existing turbines and the upcoming projects based on Allwinds Ab (2018e). Power curve of Enercon E-44 turbine is utilized for the existing turbines with rated power output below 2.3 MW, although the actual turbine models vary as seen in Table 3. As wind speeds are measured from the altitude of the observation station, the wind speed data is corrected to the right hub height of 55 (E-44), 65 (E-70) and 99 (E-101) meters by utilizing wind power law. The resulting hourly output data for the existing turbines is scaled based on the realized monthly production values in 2017 derived from Allwinds Ab (2018c).

Table 6. Existing wind power fleet and assumptions of the turbines in the upcoming projects based on Allwinds Ab (2018e).

	Quantity	**Model**	**Rated power (MW)**	**Installed capacity (MW)**
Existing large turbines	6	E-70	2.3	13.8
Existing small turbines	13	E-44	0.9	7.5[1]
Långnabba 1 & 2	10	E-101	3.05	30.5
Stenarna	6	E-70	2.3	13.8
Rödskär	6	E-101	3.05	18.3
Östra skärgården	34	E-101	3.05	103.7
Total				187.6

[1]Actual existing capacity in accordance to Allwinds Ab (2018b) & Government of Åland (2017a)

Estimated hourly power output of solar PV in Åland Islands is determined based on hourly global horizontal irradiation (GHI) values derived from Finnish Meteorological

Institute (2018). Solar PV output is calculated for a combined solar PV capacity of 15 MW_p, consisting of commercial 300 W_p poly crystalline silicon PV panels with 1.63 m^2 surface area and 18.4 % module efficiency (RECOM, 2018). Performance ratio is set at 0.75. It is assumed that all panels are south-oriented and optimally tilted at 44º in accordance to optimized slope values from European Commission (2017a).

Regarding the existing thermal power plants, the two CHP units fueled by heavy oil and owned by Mariehamns Energi Ab are expected to be decommissioned by 2025 as the units are old and ran by fossil fuels. Therefore, the units are excluded from the analyzed scenarios. Bio-CHP unit owned by Mariehamns Bioenergi Ab has rated power capacity of only 2 MW_e, which is not enough for grid balancing purposes. The unit is converted to a heat-only boiler (HOB 11) with thermal output of 11 MW_{th} to enhance its heat generation efficiency, resulting is estimated efficiency at 80%. The existing heat-only boiler (HOB 5) with thermal output of 5 MW_{th} is applied to the energy systems as well. The fuel conversion efficiency of HOB 5 is expected to be 88%. Annual available energy potential from local forest-based biomass is limited to 395.6 GWh as defined in section 3.3.3. Price for local forest-based biomass is set at 24 €/MWh, in accordance to the average price of forest chips in Finnish electricity and heat production during the last ten years (Statistics Finland, 2018b).

Market price for district heat is set at 80 €/MWh in accordance to the average price of district heat in Finland in 2017 (Finnish Energy, 2018c). Hourly market prices for electricity are obtained from Nordpool (2018). The hourly market prices of SE3 bidding area in 2017 are utilized as to simplify the optimization model, power transmission lines from Åland Islands are aggregated to one line, where all power exchange with the neighboring power areas occur. Curtailment of VRE supply is prohibited, and all excess electricity not capable to be utilized within the local system are exported. However, curtailment can be expected to occur, if surrounding power areas are not able to receive the exportable electricity. No subsidies for renewable generation are included in simulations. In addition, no emission allowance costs or fuel taxes are applied, as none of the thermal production units applied in the future energy system scenarios operate with fossil fuels. Economic input parameters for utilized technologies and CO_2 emission coefficient values for different fuel fractions applied in the simulations are presented in Table 7 and Table 8.

Table 7. Economic parameters for Åland Islands in 2025.

Technology	Capex (€/kW$_e$)	Fixed opex (% of capex)	Reference
Wind onshore	1000	2.5	Child et al. (2017)
Wind semi-offshore	1200	3[1]	Child et al. (2017)
Solar PV[2]	700	1	Child et al. (2017)
Bio-CHP	2400	4	VTT estimate
Bio HOB	370[3]	0.8	Ikäheimo et al. (2018)
Biogas turbine	1200	1	Danish Energy Agency (2019)
TES	3	0.7	Child et al. (2017)
Electric boiler	65	1.6	Danish Energy Agency (2019)
Stationary lithium-ion battery	200[4]	2.5	Ikäheimo et al. (2018)

[1]Own elaboration based Child et al. (2017)

[2]Residential solar PV system

[3]€/kW$_{th}$

[4]€/kWh

Table 8. CO_2 emission factor for fuel fractions utilized in Åland in 2017 and 2025 (Statistics Finland, 2018a).

Fuel	CO_2 emission factor (t/TJ)	CO_2 emission factor[1] (kgCO_2/MWh)
Forest-based biomass	109.6	395
Biogas	56.1	202
Heavy fuel oil	79.2	285
Light fuel oil	73.5	265
Peat	97	349

[1]Own calculation based on 1 MWh = 0.0036 TJ

5.2.1 Scenario 1

Starting capacities for Åland's energy generation mix in 2025 are listed in Table 9. Wind acts as a major power production technology as its capacity is increased to 85 MW$_e$, which is approximately the current wind capacity combined with the upcoming projects of Långnabba 1 & 2, Stenarna and Rödskär introduced in Table 6 in section 5.2. Solar PV provides an additional contribution to VRE generation, however in much smaller scale. Solar PV capacity is set to 15 MW$_e$, which is estimated to produce 4% of the annual power consumption in 2025, when utilizing monthly production curves derived from European Commission (2017a). The output is in good relation to the strategy set by the Government of Åland, where solar power is targeted to produce 5% of the annual electricity consumption by 2030 (The Government of Åland, 2017a). Achieving total solar PV output of 15 MW_e requires 50 000 pieces of 300 W_p panels. As the amount of detached residential buildings in Åland Islands is 9 850 (ÅSUB, 2018) and by assuming that each installed residential solar PV system equals to 7 kW_p, over 20% of the residential buildings in Åland Islands would be equipped with solar PV systems in 2025.

Table 9. Energy production units for Scenario 1.

Production units	**Power output (MW_e)**	**Thermal output (MW_{th})**
Wind onshore	37	-
Wind semi-offshore	48	-
Solar	15	-
Bio-CHP	15	18.75
HOB 11 (old CHP)	-	11
HOB 5	-	5
Total	115	34.75

Existing peaking plant portfolio to cover variability of wind and solar generation is currently quite narrow in Åland Islands as discussed in section 3.1. As the two CHP units running on fossil fuels are assumed to be no longer in use for energy production purposes in 2025, and as the bio-CHP unit with 2 MW_e power output is converted to a heat-only boiler, the energy system is allowed to invest on a new CHP unit to act as a source of dispatchable power supply. The size of the plant is limited to 37.5 MW_{fuel} with electrical efficiency at 40% and thermal efficiency at 50%, resulting in maximum outputs of 15 MW_e in electricity and 18.75 MW_{th} in heat. Note that the given capacity for CHP is not necessarily the most optimal capacity for the generator. Simulations will determine the optimal size of the CHP plant.

Locally produced biogas is allowed to be utilized in covering power demand peaks. With Åland's annual estimated biogas yield of 3.2 million m^3_n (Allerborg et al., 2015) and average biogas heating value of 5 kWh/m^3_n (Alakangas et al., 2016) the amount of fuel assumed to be derived from biogas annually is 16 GWh, resulting in a continuous fuel production of 1.8 MW/h. A storage tank of 300 MWh is able to store the biogas production of one week. Biogas storage is applied to the system in addition to a gas turbine with maximum capacity of 20 MW_e and efficiency at 35% to convert the stored biogas into electricity.

A centralized thermal energy storage (TES) of 350 MWh with a maximum rate-of-change at 35 MW_{th} is coupled with the new bio-CHP unit to store excess heat to provide flexibility for the operation of the CHP unit. The capacity of TES is set in accordance to the currently available heat storage capacity in Mariehamn (350 MWh) as discussed in section 4.1.2. In addition, a centralized electric boiler with maximum rated power of 5 MW_e and efficiency at 95% is added to the district heating system to convert excess VRE supply to heat to be utilized in the district heating network. Furthermore, a stationary electrochemical battery of 5 MW_e and 5 MWh is applied to balance hourly variation in intermittent electricity generation. The electrochemical battery can be charged with surplus of any power production unit, including imported electricity. Electricity imports and exports from neighboring power areas are restricted by the current capacity of the Swedish interconnector, and therefore, the maximum hourly power exchange in both ways is limited to 80 MW. A summary of the flexibility elements utilized in Scenario 1 is presented in Table 10.

Table 10. Flexibility elements in Scenario 1.

Parameter	**Nominal power (MW)**	**Capacity (MWh)**
Thermal energy storage (TES)	35	350
Electric boiler	4.8	-
Electrochemical battery	5	5
Biogas tank	-	300
Biogas turbine	7	-
Power import	80	-
Power export	80	-

5.2.2 Scenario 2

The second scenario examines how increasing the installed wind capacity affects the operation of the energy system. Power derived from wind is significantly increased as installed wind capacity is set to 185 MW_e. This includes the current fleet and all upcoming projects introduced in Table 6 in section 5.2. Installed solar capacity remains at 15 MW_e. As wind power output is expected to highly exceed Åland’s electricity demand, investment for a new CHP unit is prohibited. Instead, the model is allowed to invest on a heat-only boiler running on renewables with maximum capacity of 20 MW_{th} with a thermal efficiency at 90%, to ensure the security of heat supply in the district heating network. Capacities of energy production units for Scenario 2 are presented in Table 11.

Table 11. Energy production units for Scenario 2.

Production units	Power output (MW_e)	Thermal output (MW_{th})
Wind onshore	37	-
Wind semi-offshore	148	-
Solar	15	-
HOB 11 (old CHP)	-	11
HOB 5	-	5
New HOB	-	18
Total	200	34

Due to the high volume of wind, requirements for storage and export capacity increase when compared to Scenario 1, if curtailment is aimed to be avoided as seen from Figure 17. Residual load curves in the figure represent the hourly load after wind and solar PV production with the given capacities from Table 9 and Table 11 are deducted from the power demand in 2025. Negative values indicate that the power supply from VRE sources exceed the power demand. Generated surplus power needs to be stored or exported to neighboring power areas, or else it will be curtailed.

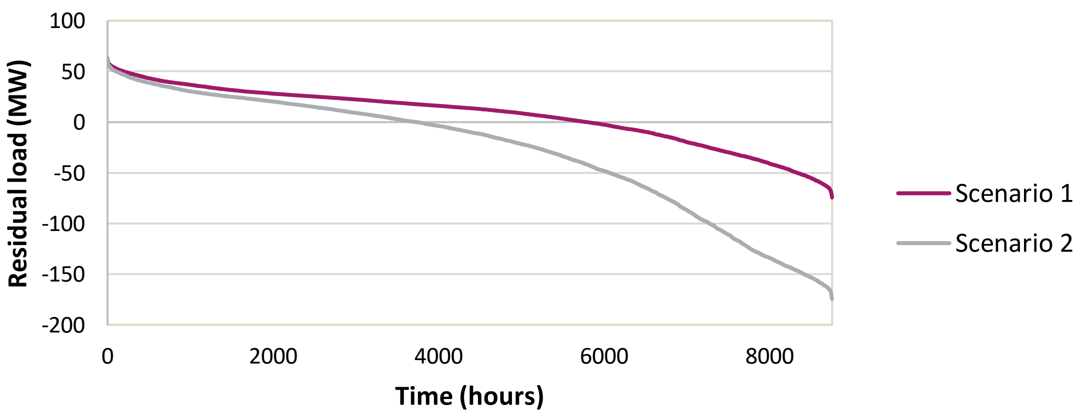

Figure 17. Residual load curve of Scenario 1 and Scenario 2 with solar capacity of 15 MW_e and wind capacities of 85 MW_e and 185 MW_e, respectively.

To minimize curtailment, hourly export maximum is increased to 180 MW_e, which includes the Swedish interconnector of 80 MW_e and the new 100 MW_e transmission cable between Åland and Finland. However, the interconnector is still simulated at one aggregated transmission line. As seen from Figure 17, the yearly peak demand does not reduce despite the variable generation capacity is increased. Therefore, the allowed maximum feed-in capacity for imports remains at 80 MW_e as in Scenario 1.

The rated power of electrochemical battery is increased to 20 MW_e with similar storage capacity to provide more opportunities to balance increased intermittency in VRE generation. Rated power of the electric boiler is doubled to 10 MW_e with efficiency remaining at 95%, to provide more flexibility in both power and heating sector. As the annual availability of biogas in Åland Islands is constrained, the capacities of biogas-related elements remain constant. Flexibility elements utilized in Scenario 2 are summarized in Table 12.

Table 12. Flexibility elements in Scenario 2.

Parameter	Nominal power (MW)	Capacity (MWh)
Thermal energy storage (TES)	35	350
Electric boiler	9.5	-
Electrochemical battery	20	20
Biogas tank	-	300
Biogas turbine	7	-
Power import	80	-
Power export	180	-

5.2.3 Scenario 3

Main goal of Scenario 3 is to achieve a highly self-sufficient energy system in relation to electricity and heat, meaning that the energy supply would only origin from local renewable resources. However, power imports are allowed in extreme cases, as achieving full independency in relation to power supply is not considered feasible as discussed below.

In order to define the amount of storage capacity required to achieve an entirely self-sufficient energy system with no power imports in Åland Islands, biggest deficit gap between generation and demand is evaluated. Unit capacity sizes from Table 13 are applied to the modelling tool in order to maximize dispatchable power generation in combination to a high VRE volume. Negative hourly load balances with higher demand in relation to local generation are evaluated by subtracting hourly VRE and CHP outputs from the power demand data of 2025. As seen from Table 13, the applied wind capacity is similar to Scenario 2, whereas other production unit capacities are parallel to Scenario 1. It is assumed that CHP operates on maximum capacity within the limits of the residual load.

Table 13. Energy production units for Scenario 3.

Production units	**Power output (MW_e)**	**Thermal output (MW_{th})**
Wind onshore	37	-
Wind semi-offshore	148	-
Solar	15	-
Bio-CHP	15	18.75
HOB 11 (old CHP)	-	11
HOB 5	-	5
Total	215	34.75

The largest detected balance gap between power supply and demand is 1.84 GWh_e, which represents the amount of storage capacity needed to maintain annual grid balance, if power supply in Åland was to rely only on local renewable resources in 2025. Maximum hourly peak deficit reaches 48 MW_e, determining the maximum hourly discharge rate required from the storage system. Assuming that the balance gap in Åland Islands was to be covered with electrochemical batteries, the power capacity of the electrochemical battery required for an entirely self-sufficient operation would be 48 MW_e and 1.84 GWh_e, which is considered as unreasonable. For reference, according to Renewable Energy Agency (2017) the global capacity estimate for installed stationary electrochemical battery storage reached 11 GWh in 2017. The installed stationary electrochemical battery storage capacity in United States was 867 MWh at the end of 2017 (U.S Energy Information Administration (EIA), 2018) and hence the required storage capacity in Åland Islands in 2025 would require electrochemical battery capacity twice as large as the capacity in United States.

Figure 18 represents the demand and supply curves of the highest negative balance gap detected when the production units presented in Table 13 are applied in the energy system of Åland Islands. As can be noted, increasing the capacity of VRE sources would not contribute enough to reduce storage requirements, as the hours with the highest supply deficit are low in wind speed and solar irradiation. Doubling the capacities of CHP, wind and solar would not reduce the storage requirements to a feasible level (575 MWh), not to mention the potential economic feasibility issues related to of doubling the production capacity for peaking purposes.

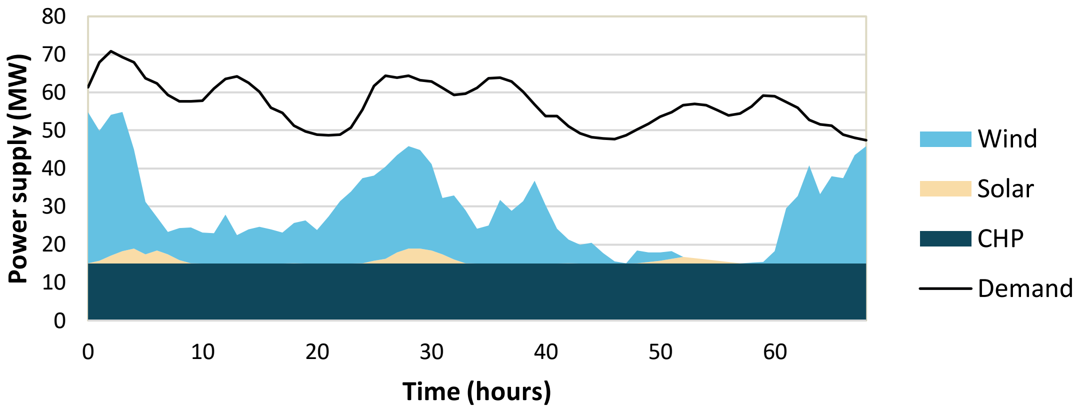

Figure 18. A three-day deficit gap in February determined for production unit capacities presented in Table 13.

As capacity requirements for an entirely self-sufficient power system are considered to be infeasible in terms of economics and unit capacities, Scenario 3 is evaluating an energy system aiming to reach high level self-sufficiency instead of full power independency. Flexibility elements from Table 14 are added to the energy production mix determined in Table 13. Flexibility elements applied in the third scenario are same in terms of nominal power and capacity as the flexibility elements applied in Scenario 2.

Table 14. Flexibility elements in Scenario 3.

Parameter	Nominal power (MW)	Capacity (MWh)
Thermal energy storage (TES)	35	350
Electric boiler	9.5	-
Electrochemical battery	20	20
Biogas tank	-	300
Biogas turbine	7	-
Power import	80	-
Power export	180	-

6 RESULTS

Simulation results are analyzed to study differences between the three energy system scenarios with different approach to transfer the power grid and district heating network of Åland Islands fully renewable by 2025. System-level role of energy production units is studied by analyzing annual unit-specific power and heat production. Economic and environmental impacts are evaluated by analyzing cost structures and emissions of the energy system scenarios. Integration potential of flexibility elements is studied based on unit and system level impacts of TES, electric boiler and a stationary electrochemical battery. System-level impacts of biomass availability and price variance are evaluated to guide applicability potential of the different renewable energy transition pathways in regions with different local characteristics.

6.1 Energy production

Cost-optimal capacities regarding the investible dispatchable power and heat generation units for Scenarios 1-3 are presented in Table 15, when techno-economic assumptions given in the scenario descriptions are applied. Capacities of VRE generators, flexibility elements and interconnectors of each scenario are also displayed in the table.

Table 15. Cost-optimal component capacities for Scenarios 1-3.

	Unit	**Scenario 1**	**Scenario 2**	**Scenario 3**
Wind	MW_e	85	185	185
Solar	MW_e	15	15	15
CHP	MW_e /MW_{th}	15/18.75	-	15/18.75
HOB 11	MW_{th}	11	11	11
HOB 5	MW_{th}	5	5	5
New HOB	MW_{th}	-	14.4	-
Biogas turbine	MW_e	3.5	3.8	3.9
Thermal energy storage (TES)	MW_{th}	18.1	-	17.3
Electric boiler	MW_{th}	4.8	9.5	9.5
Electrochemical battery	MW_e	5	20	20
Power import	MW_e	50.3	80	65.4
Power export	MW_e	57.8	166.7	157.2

In most cases, the maximum outputs of TES and power imports and exports are below the given fixed capacities, as the system does not require their full volume for cost-optimal operation. Hourly power imports reach the given maximum capacity only in Scenario 2, as the scenario has the lowest dispatchable power generation capacity. According to the results, investing on the manually controlled maximum capacity of CHP is the cost-optimal solution when the investment is allowed to be made, as cost penalty for imported electricity induces the system to favor self-consumption over power imports.

6.1.1 Electricity

Total electricity supply increases in all future scenarios when compared to annual power supply in 2017 as seen from Figure 19. Wind has an important role in power generation in all future scenarios, as it accounts for 54%, 84% and 81% of annual power supply in Scenarios 1-3, respectively. Despite high local power supply, imported electricity cannot be entirely excluded in any of the scenarios, although the amount of annual imports reduce significantly in relation to 2017. In 2017, imported electricity accounted for 82% of the annual power supply, whereas in Scenarios 1-3, the share of imports in annual power supply is reduced to 19%, 13% and 5%, respectively. Shares of power production units in percentages in relation to annual supply volumes are displayed in Figure 20.

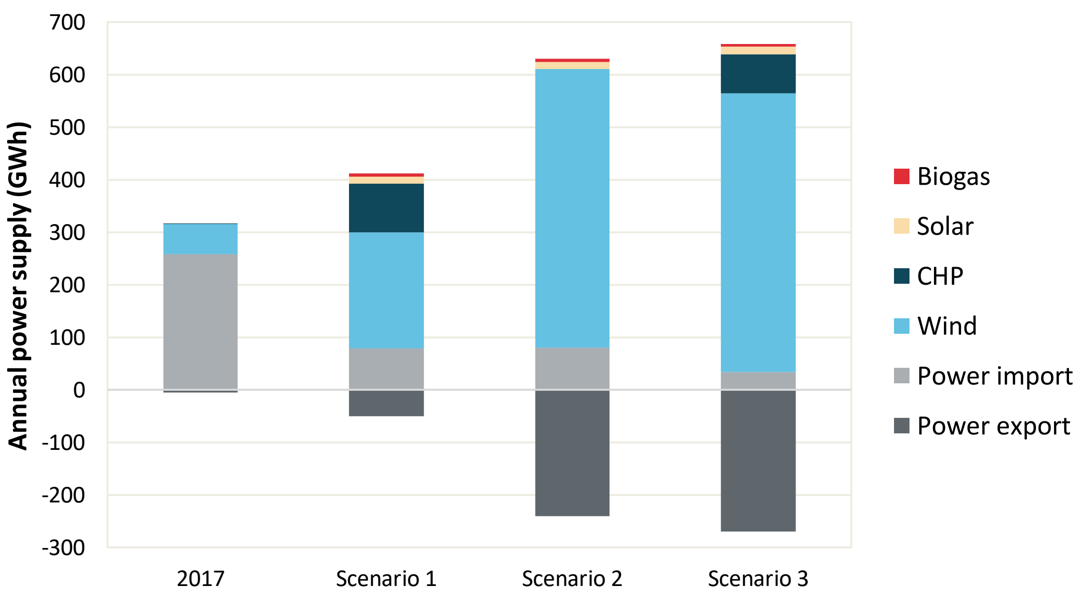

Figure 19. Total electricity production in 2017 and in Scenarios 1-3.

Annual power output of CHP is considerably lower than the annual wind power output in Scenarios 1 and 3. However, CHP has an important role in power system balancing as it covers deviations between VRE supply and power demand. The amount of imported electricity is somewhat equal between Scenarios 1 and 2 (79.1 GWh vs 79.5 GWh) despite the local power supply in the latter scenario is significantly higher due to high wind turbine capacity. As the result, dispatchable power generation from CHP is able to reduce overall electricity supply without reducing the level of self-sufficiency in power sector and is therefore a profitable investment, if overall power exchange is aimed to be reduced.

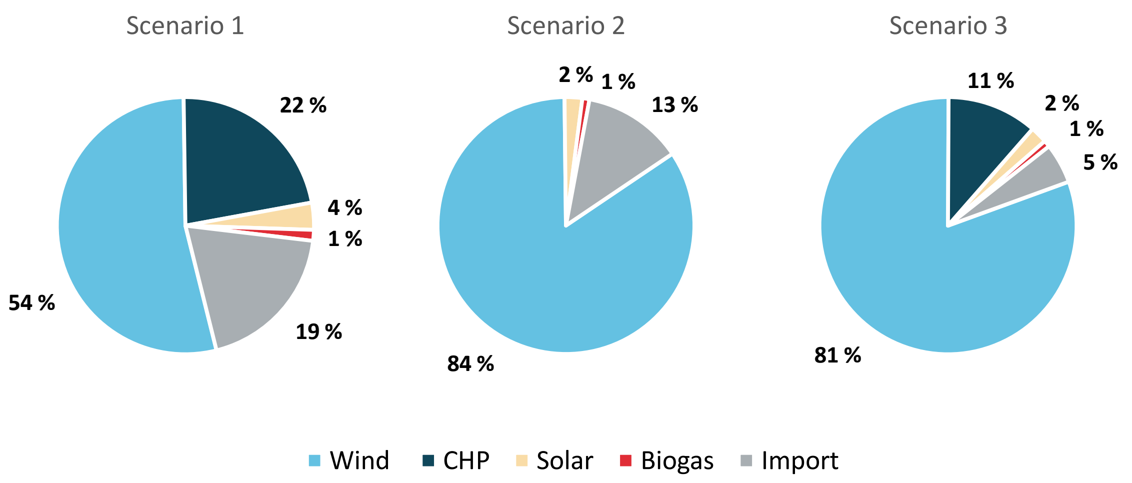

Figure 20. Share of power production elements in annual supply in Scenarios 1-3.

While decreasing annual power supply with having only a negligible impact on the annual volume of imported electricity, CHP unit also enables to decrease annual power imports and increase power self-sufficiency on the island. The amount of imported electricity is lower in Scenario 3 (33.2 GWh) when compared to Scenario 2 (79.5 GWh), although the only difference is that the opportunity to invest on a 20 MW_{fuel} heat-only boiler is replaced with an opportunity to invest on a 37.5 MW_{fuel} CHP unit when moving from Scenario 2 to Scenario 3. The optimal capacity of CHP on which the investment should be made depends from the system economics and from the level of power self-sufficiency the island is aiming to achieve.

Increasing the capacity of CHP reduces annual amount of imported electricity resulting in increased power self-sufficiency in Åland Islands. For instance, if the capacity of CHP was increased from 37.5 MW_{fuel} to 60 MW_{fuel}, annual imports would reduce by 16.8 GWh and 12.3 GWh in Scenario 1 and 3, respectively. However, additional CHP capacity does not contribute to reduce annual power imports linearly as seen in Figure 21. Therefore, full self-sufficiency cannot be achieved by increasing the capacity of CHP, as power output from CHP will eventually be restricted by the heat demand in the district heating network or by domestic biomass availability, if only local fuel is aimed to be used. Furthermore, as the capacity of the CHP unit increases, full load operation hours of the unit decrease resulting in lower capacity factor of the unit. Eventually the reduction in the capacity factor of CHP begins to reduce the annual economic benefits of the unit. Figure 22 shows annual system net profit in Scenarios 1 and 3 in relation to the capacity of CHP. From the system point of view, the most optimal capacity for CHP is 32.5 MW_{fuel} in Scenario 1 and 25 MW_{fuel} in Scenario 3. Therefore, the CHP capacity applied in Scenarios 1 and 3 (37.5 MW_{fuel}) is not the economic optimum for neither scenario. Note that minimum capacities of 18 MW_{fuel} and 9 MW_{fuel} of CHP are required in Scenarios 1 and 3, respectively, to fulfill heat demand in the district heating network.

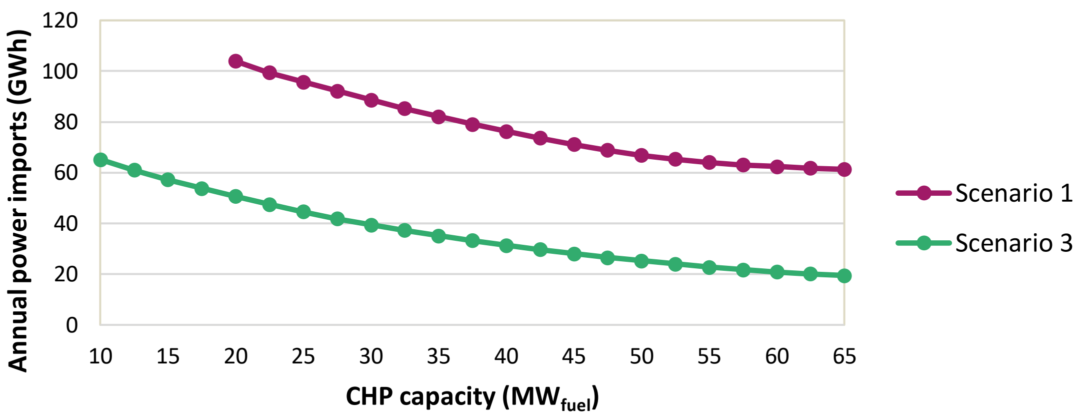

Figure 21. Annual power imports in relation to CHP capacity in Scenarios 1 and 3.

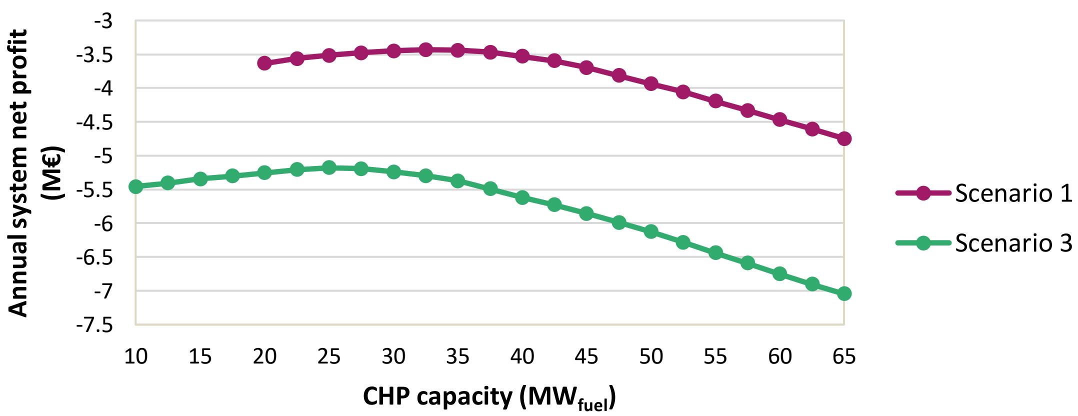

Figure 22. Annual system net profit in relation to CHP capacity in Scenarios 1 and 3.

System level contribution of solar PV and biogas is small when considering total annual power outputs of different power supply sources as seen in Figure 19 and Figure 20.

Additional solar PV capacity could increase the annual yield from solar PV and reduce annual imports. However, the model calculates solar PV output assuming that all panels are south-oriented with an optimal angle. The reality can be different, and hence increasing solar capacity does not necessarily contribute linearly to its annual output in the real world. Non-optimal conditions for solar power production would result in lower cost-effectiveness of solar PV investments. Low available feedstock volumes for biogas production limit annual power output from biogas. As the annual power output is almost negligible on a system level, more feasible option could be to utilize biogas in heat production with a better fuel conversion efficiency. Small-scale heat generation could take place near the sites where feedstock for biogas is produced, reducing the logistical demand of gathering and transporting different fractions of biomass to a centralized gasification plant.

Annual volumes of power exports increase as local power supply increases as seen in Figure 19. Exports are highest in Scenario 3, where the quantity of exported electricity reaches 270 GWh. As seen in Table 15, highest surplus peak of VRE peak is attained in Scenario 2, where the VRE peak reaches 166.7 MW_e. All the power export peaks seen in Table 15 are lower than the set export capacities in Åland Islands in 2025 (80 MW_e in Scenario 1 and 180 MW_e in Scenarios 2-3). Therefore, all the energy systems are able to export the highest VRE supply peak without curtailment, if no constraints regarding power exports exist with the neighboring power areas. However, if the capacity of wind was significantly increased from 185 MW_e, the VRE supply peak can be assumed to exceed the transmission capacity resulting in curtailment of surplus VRE. It should be noted that the modelled VRE outputs cover wind speed and solar irradiation data only from one year. To have a more precise analysis related to the sufficiency of power transmission capacity in Åland Islands in 2025, hourly wind speed and solar irradiation data from multiple years should be applied in the simulations.

6.1.2 Heat

Fossil fuels produced 14% of the annual district heat supply in 2017 (Mariehamns Energi Ab, 2018). As the thermal units in 2025 are allowed to utilize only forest-based biomass as a fuel, heat output from fossil fuels is entirely discarded in the 2025 scenarios. As seen in Figure 23, heat produced from CHP unit covers the base heating load in Scenarios 1 and 3. A new investment on a bio-fueled HOB with thermal output at 14.4 MW_{th}

(Table 15) covers the base heating load in Scenario 2. The existing heat-only boilers provide peaking capacity for periods with high heat demand in all scenarios. Annual output of HOB 5 outstrips the output of HOB 11 in all scenarios. The operation of HOB 5 is preferred as it has higher fuel conversion efficiency in comparison to HOB 11, which is converted from the old CHP unit.

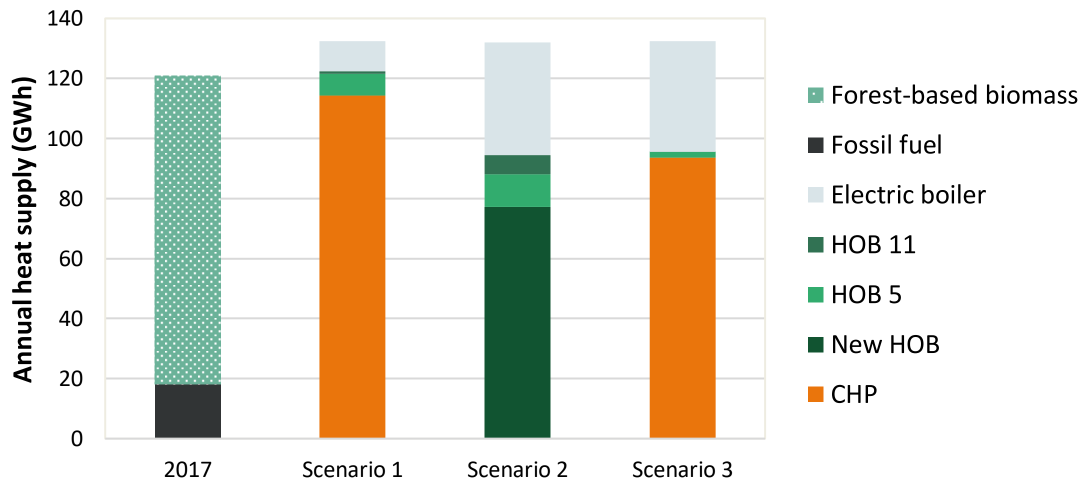

Figure 23. Annual heat supply in 2017 and in Scenarios 1-3. No unit-specific data for heat supply is available for the reference year 2017 and therefore, the heat supply data from 2017 is presented in accordance to combustion fuel.

Electric boiler possesses relatively high shares in the annual heat supply Scenarios 2 and 3 (28.5% and 27.8%, respectively). The amount of excess VRE supply is high in both scenarios due to high wind capacity. During VRE supply peaks, heat generation from excess fuel-free electricity is preferred instead of combusting more expensive biomass. It needs to be noted that the capacity of electric boiler is 5 MW_e in Scenario 1 and 10 MW_e in Scenarios 2 and 3. The impacts of maximum power rate of the electric boiler to the system dynamics are evaluated later.

6.1.3 Fuel consumption

Total annual fuel inputs for reference year 2017 and Scenarios 1-3 are presented in Figure 24. Highest forest-based biomass consumption takes place in Scenario 1 (238 GWh) where power generation from biomass compensates the lack of wind-based power production in comparison to other scenarios, where installed wind capacity is significantly higher.

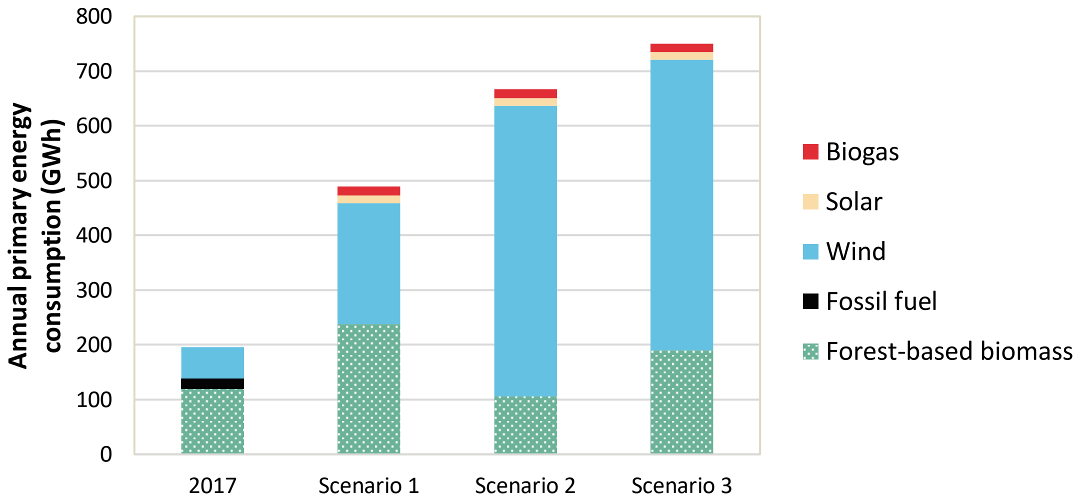

Figure 24. Annual fuel consumption in 2017 and in Scenarios 1-3. Imported electricity is excluded from the graph.

When compared to the reference year 2017, forest-based biomass utilization volume nearly doubles in Scenario 1. However, the utilization level of forest-based biomass does not reach its estimated maximum potential (396 GWh) in any of the future scenarios as the usage of forest-based biomass reaches only 60%, 27% and 48% of the annual available volume in Åland Islands in 2025 in Scenarios 1-3, respectively. Therefore, the availability of forest-based biomass is not a constraining factor for cost-optimal energy system operation in any of the energy system scenarios.

6.1.4 Self-sufficiency

System level sensitivity analysis is carried out to determine the most essential power production unit in terms of power self-sufficiency. The results of the sensitivity analysis enable to guide potential investment decisions, if the aim is to decrease Åland's dependency of power imports. The analysis is carried out by reducing and increasing the reference capacity of a new power generator asset by 20%. The results are presented in Figure 25 where *low capacity* defines the change in annual imports when the capacity of a power production unit is reduced by 20% from the reference investment capacity defined in sections 5.2.1-5.2.3, whereas in *high capacity* the capacity of the production unit is increased by 20% from the reference value.

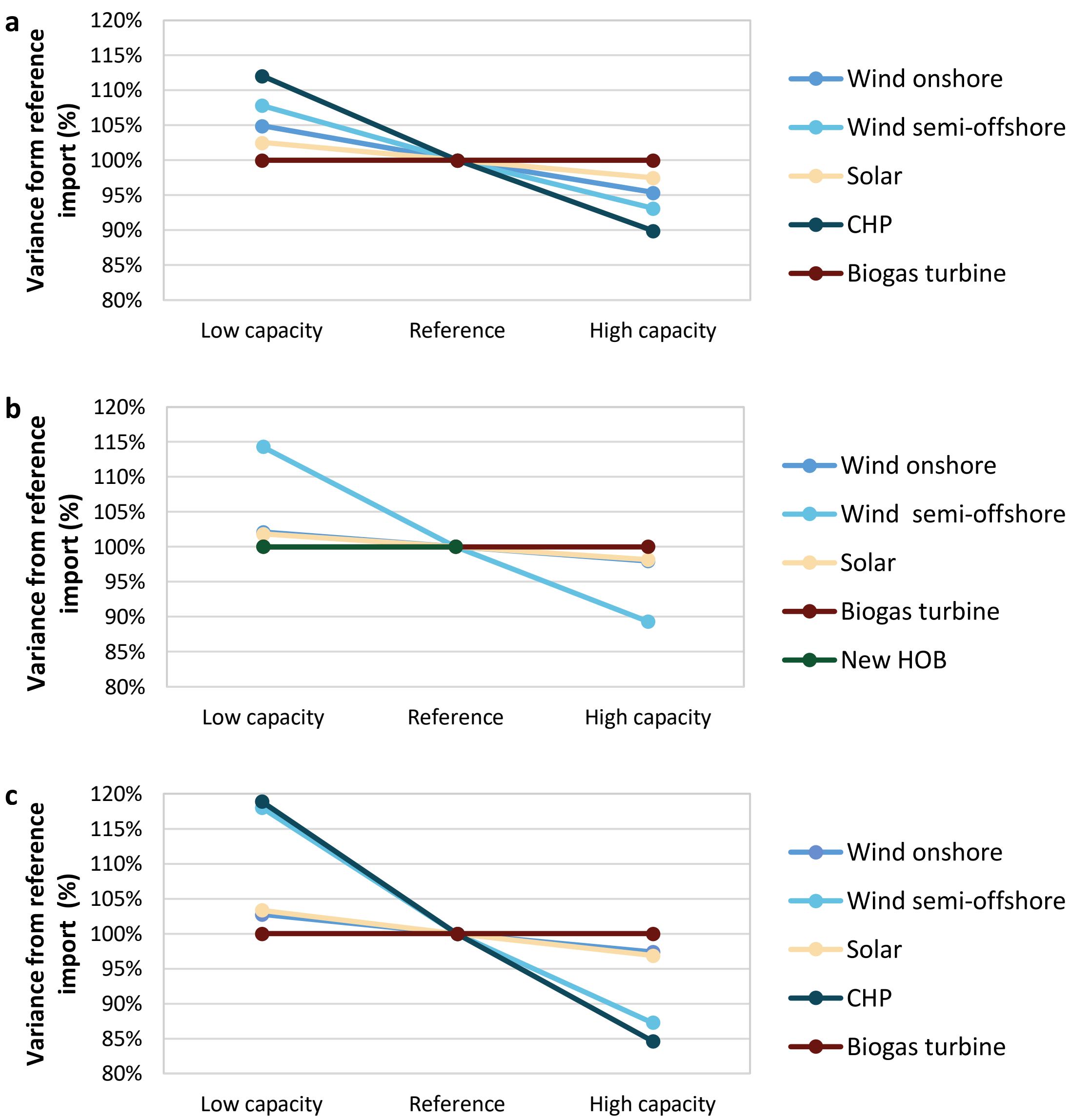

Figure 25. Sensitivity analysis on annual power imports when capacity of a new generation asset in reduced or increased by 20% in: a) Scenario 1; b) Scenario 2; c) Scenario 3.

Results in Figure 25 indicate that in Scenarios 1 and 3, change in the capacity of CHP unit has the greatest impacts on annual power imports. This is reasonable, as the dispatchable power generation from CHP is able to cover residual load during times when VRE supply is low, reducing the amount of imported electricity. Reducing the capacity of CHP unit abates its possibilities to cover power demand at periods of low VRE production, increasing the need for imported electricity. Investing on the given semi-offshore wind capacity is also important in maintaining the level of power self-sufficiency in the assessed scenarios. The impacts of semi-offshore wind in power self-sufficiency are highlighted in Scenarios 2 and 3, where its reference capacity is high.

The capacity of semi-offshore wind turbines has more critical role in maintaining power self-sufficiency in comparison to onshore turbines as the reference capacity is greater and therefore, the relative capacity change in the sensitivity analysis is higher. In addition, semi-offshore wind turbines are estimated to generate more power per installed megawatt due to more favorable wind conditions.

It should also be noticed that the original capacity of the CHP investment in Scenario 3 is considerably smaller when compared to the reference semi-offshore wind capacity, resulting in smaller relative change in the sensitivity analysis. Yet smaller capacity change in CHP unit in comparison to semi-offshore wind results in higher importance on power self-sufficiency, highlighting the role of CHP in increasing power independence on the island. Capacity change of solar PV has only small impacts on annual imports, explained by low original capacity and low annual power output. Changing the capacity of biogas turbine has no impacts on annual power imports due to its negligible share in the total power supply resulting from low feedstock availability.

6.2 Economic impact

Total overnight capital costs for Scenarios 1-3 are 123 M€, 223 M€ and 254 M€, respectively. Capital costs increase when more elements are added to the energy system. As Scenario 1 has the lowest additional installed energy production capacity, capital investment costs are also lowest. Scenario 3 has the highest capital costs due to greatest investments on new technologies, which on the other hand contribute to the highest level of power self-sufficiency. Majority of capital costs in all scenarios comprise of new wind turbine investments, as they account for 56%, 87% and 76% of capital costs in Scenarios 1-3, respectively.

When utilizing cost assumptions applied in the thesis, annual net profit of each energy system scenario is negative as seen in Figure 26. Annual net profit of each scenario includes annual net profit of each energy system element in addition to the costs and revenues related to annual power imports and exports. When considering thermal production units, annual net profit is determined by deducting annual operation, fuel and investment costs from the annual profit gained from generated energy. Annual net profit related to wind, solar and flexibility elements including TES, electric boiler and electrochemical battery consist only of annual investment payments and fixed operating costs, as income derived from these elements is embedded in annual import and export expenses. No subsidies nor taxes for energy production from any source are included to the annual net profit of the energy system scenarios.

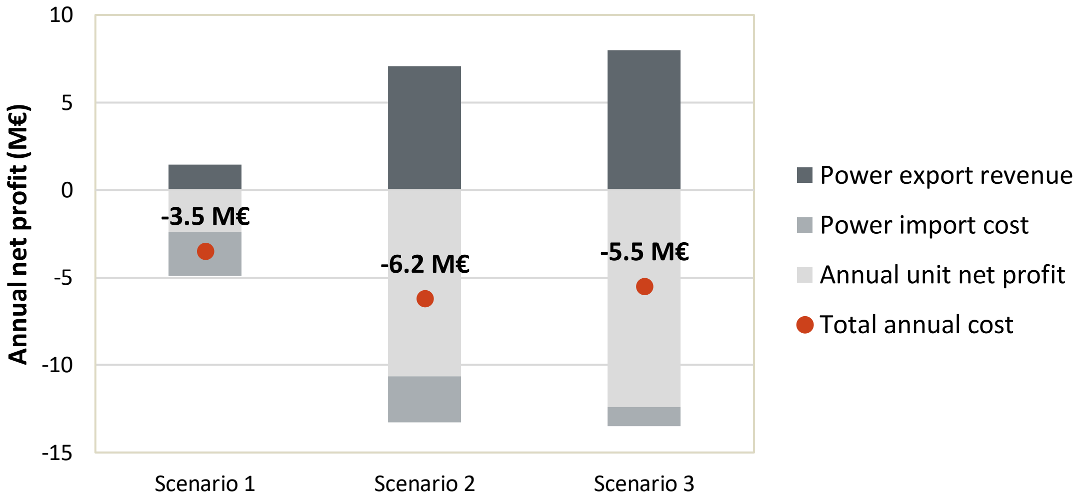

Figure 26. Breakdown of total annual net profit in Scenarios 1-3.

As seen from Figure 26, Scenario 1 is the most profitable energy system scenario as it has highest net profit, although the profit is net negative. Main contributor to the highest net profit in Scenario 1 is the lowest investment cost related to wind power. Due to the lowest wind capacity, revenues from power exports are also lowest in the first scenario, as less surplus power is generated in comparison to Scenarios 2 and 3. Scenario 3 has the lowest expenses related to imported electricity due to highest level of power self-sufficiency.

Annual net profits of the scenarios indicate that a CHP investment increases annual net profit the energy system. As discussed earlier, adding a CHP unit to the energy system is profitable investment when the aim is to reduce overall power transmission between Åland and the neighboring power areas. Although the volume of power imports is somewhat equal between Scenario 1 (79.1 GWh) and Scenario 2 (79.5 GWh), the economical difference is substantial. Annual net profit of Scenario 1 is 2.7 M€ higher when compared to annual net profit of Scenario 2. Therefore, investing on a CHP unit instead of high wind capacity is economically more feasible, as the CHP unit considerably increases annual net profit of an energy system in relation to high wind capacity. Moreover, as discussed before, CHP investment is also beneficial when the goal is to increase the degree of energy self-sufficiency. Volumes of power imports in Scenarios 2 and 3 are 79.5 GWh and 33.2 GWh, respectively. As the total annual net profit of

Scenario 3 is 0.7 M€ higher in comparison to Scenario 2, CHP investment does not only reduce dependency of imported electricity, but it also increases annual net profit of the energy system despite additional capital costs. This is because dispatchable power derived from CHP unit is able to substitute power imports purchased during hours with low VRE generation.

Multiple uncertainty factors can influence the economic viability of the scenarios. For instance, electricity price development in the upcoming years will have mid-term impacts to the annual net profit of the energy system scenarios. As seen from Figure 27, increased market spot prices of electricity in Nord Pool's day-ahead power market from 2017 (SE3) would benefit all scenarios. The breakeven point when the annual system net profit exceeds zero is reached, when spot prices in the common power markets are scaled up by 150% in Scenarios 1 and 2 and by 60% in Scenario 3.

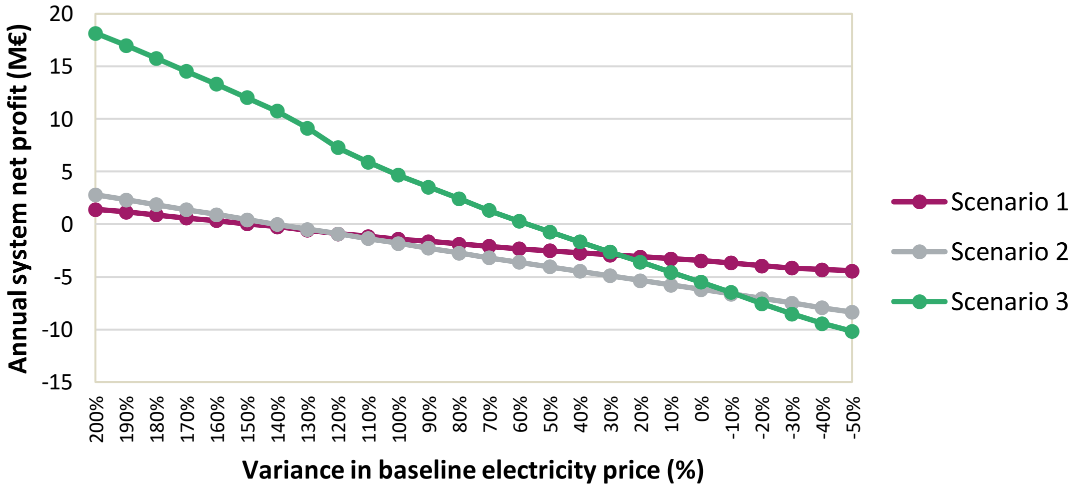

Figure 27. Annual system net profit in Scenarios 1-3 in relation to variance in baseline electricity price.

Benefits of increased spot prices are especially emphasized in Scenario 3, as in addition to the more distinct net revenue from power exchange, the economic benefits of CHP increase as well. In Scenario 1, increased power price would decrease net revenue from power exchange as the amount of power imports surpasses power export volumes. However, economic benefits from CHP increase along with power prices, which is why the net profit of Scenario 1 is also higher as the power prices in the common markets increase. On the contrary, as the power prices decrease, CHP investment becomes less profitable in Scenarios 1 and 3. In addition, the annual net profit from power exchange decreases in Scenarios 2 and 3. Therefore, reductions in the spot prices on the day-ahead power market would have negative economic impacts in all scenarios, although in Scenario 1, the net loss of power exchange decreases.

6.3 Environmental impact

Environmental impacts of the energy system scenarios are evaluated by assessing the scenario-wise carbon emissions. Figure 28 presents the amount of CO_2 emitted from domestic energy generation in Åland Islands in reference year 2017 and in Scenarios 1-3. As seen, total amount of CO_2 emissions from local energy generation increase in Scenarios 1 and 3, when compared to annual emissions in 2017. However, apart from the current state, none of the thermal units in the future scenarios operate with fossil fuels and therefore fossil-derived CO_2 emissions from local energy production are cut out by 2025.

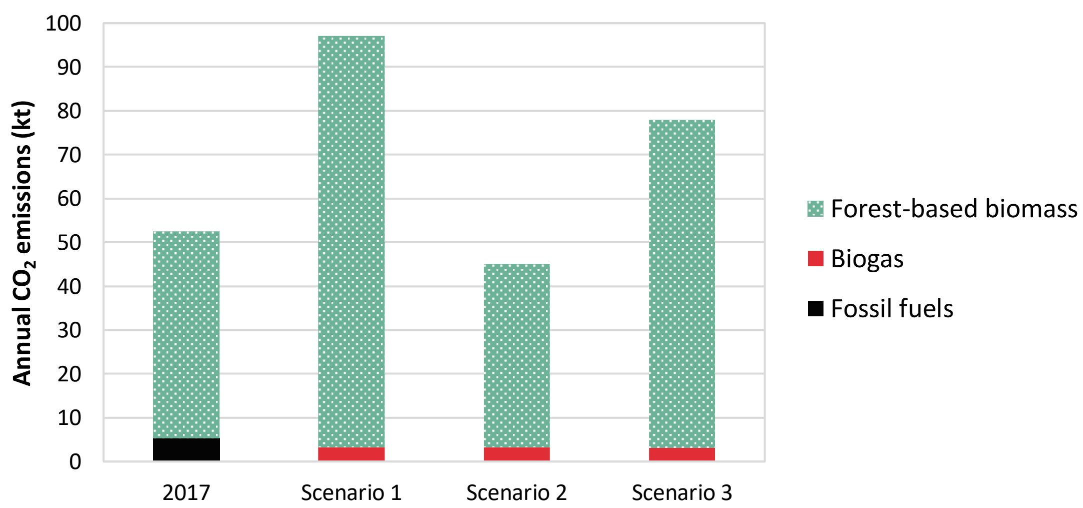

Figure 28. CO_2 emissions from local energy production in reference year 2017 and in Scenarios 1-3. CO_2 emissions from reference year are calculated based CO_2 emission factors from Statistics Finland (2018a) and on consumed fuel energy values in district heat and CHP production in Åland Islands in 2017 from Finnish Energy (2018b).

It should be noted that statistics in Figure 28 do not represent total carbon emissions of the energy supply in the reference year 2017 and of the 2025 scenarios. First, carbon emissions from imported electricity are excluded from the graph. Missing emissions from imported electricity show greatest importance in the reference scenario from 2017, where the amount of imported electricity reached 258 GWh. In Scenarios 1-3, the significance of missing emission values is smaller, as power import volumes are 79.1 GWh, 79.5 GWh and 33.2 GWh, respectively. However, since Sweden is the main electricity importer to Åland Islands, producing electricity mainly in hydro and nuclear plants (Svenska kraftnät, 2019), it can be assumed that the fossil CO_2 emissions related to imported electricity are relatively small. Second, the assessed CO_2 emissions represent only the emissions related to the core processes of the energy system, meaning that only the emissions emitted at the operation stage of the energy system are assessed. Life cycle emissions related to different supply chain stages of the technologies are not evaluated.

6.4 Value of flexibility

Sources of flexibility are added to the studied energy system scenarios to provide power demand and supply balancing for different time scales. In this chapter, system-level impacts of three flexibility elements including a thermal energy storage (TES), electric boiler and stationary electrochemical battery storage are evaluated. In addition, the impacts of TES on unit-level operation of the bio-CHP is studied.

6.4.1 Thermal energy storage

Thermal energy storage is expected to increase operational flexibility of the bio-CHP investment and therefore increase the feasibility of CHP in balancing intermittent VRE supply. In Scenarios 1 and 3, a 350 MWh TES is connected to the CHP unit. As seen from Figure 29, TES allows CHP to operate more often on maximum capacity instead of partial load. Full load operation hours of CHP increase from 2470 to 5400 (119%) and from 1360 to 3830 (182%) in Scenarios 1 and 3, respectively, when the unit is integrated to a 350 MWh TES in comparison to a situation with no TES integration. In addition, annual energy output of CHP increases by 16.4 MWh (7.7%) and 23.2 MWh (16.3%) in Scenarios 1 and 3, respectively, after a 350 MWh TES is combined with the unit. It should be noted that a TES of much smaller capacity than 350 MWh would also result in considerable operational benefits for the CHP unit. For instance, a 150 MWh TES would increase full load operation hours of the CHP unit by 100% and 134% and the annual energy output of CHP by 5.9% and 11.9% in Scenarios 1 and 3, respectively. Increasing the capacity of TES above 350 MWh has only marginal impacts on the operation of the CHP unit.

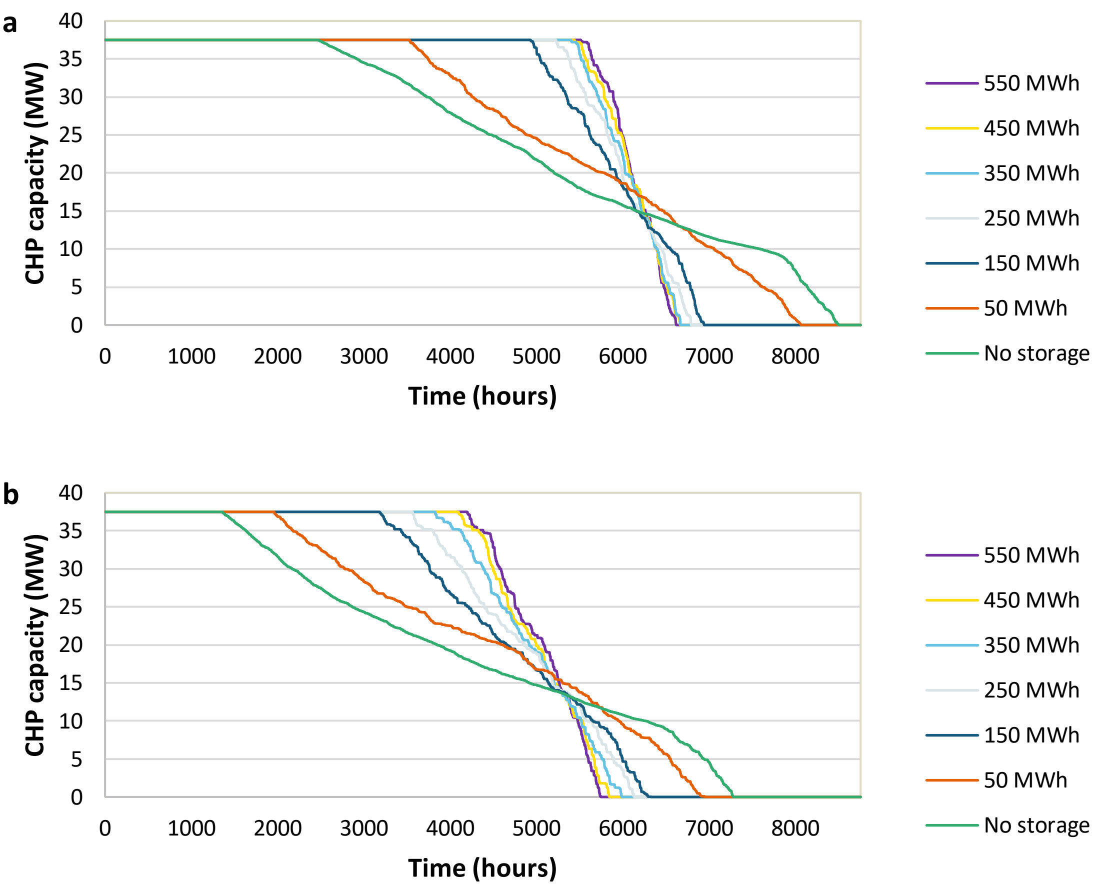

Figure 29. Impacts of TES to the operation of CHP in: a) Scenario 1; b) Scenario 3.

By increasing the annual output of CHP, TES increases the profitability of the CHP unit as seen in Figure 30. When a thermal energy storage of 350 MWh is integrated to the CHP unit, the annual net profit of CHP increases from 3.53M€ to 4.05M€ (14.8%) in Scenario 1 and from 2.10M€ to 2.90M€ (36.7%) in Scenario 3. As the relative increase in the annual net profit of CHP is higher in Scenario 3 when compared to Scenario 1, the role of TES in increasing the profitability of CHP is greater as the capacity of VRE increases.

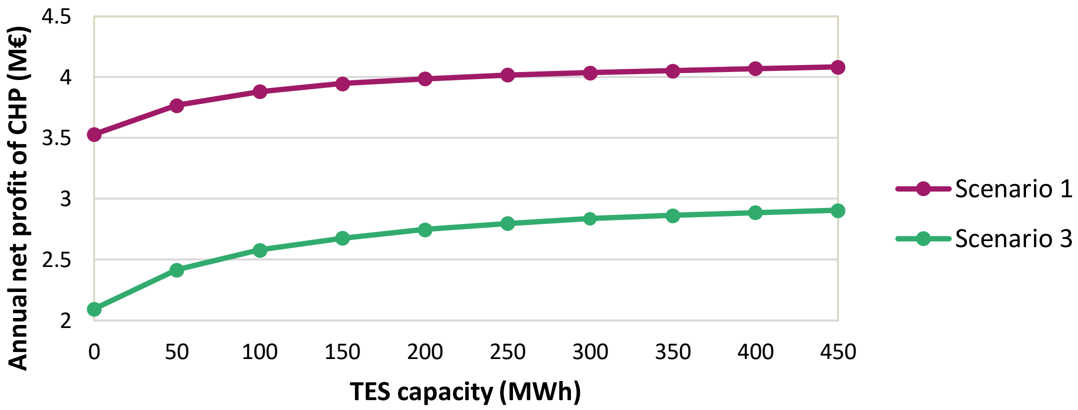

Figure 30. Annual net profit of CHP in Scenarios 1 and 3 in relation to TES capacity. Power rate of TES is 10% of the capacity.

In regards of system economics, combining CHP with TES is profitable as seen from Figure 31. TES of 350 MWh reduces annual system costs by 8.2% and 6.3% in Scenarios 1 and 3, respectively, when compared to a situation where TES is not included to the energy system. TES of smaller capacity would provide reductions in annual system costs as well. For instance, 150 MWh TES reduces annual system costs by 7.7% and 5.5% in Scenarios 1 and 3, respectively. Increasing TES capacity above 350 MWh does not provide financial system level benefits.

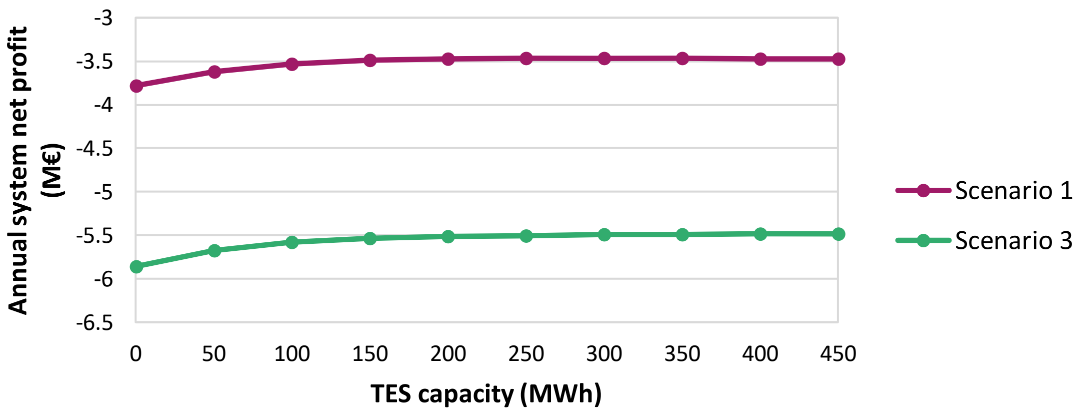

Figure 31. Annual system costs in Scenarios 1-3 in relation to TES capacity. Power rate of TES is 10% of capacity.

As the annual output of CHP increases when TES is integrated with the unit, the annual heat output of electric boiler and peaking heat-only boilers decrease as seen from Figure 32. Utilization of peaking capacity decreases, because TES is able to shift production of heat from hours of peak demand to off-peak hours. In the power sector, the level of self-sufficiency increases after a 350 MWh TES is combined with CHP unit, as the increased dispatchable power output from CHP reduces annual power imports by 8.2% and 19.8% in Scenarios 1 and 3, respectively.

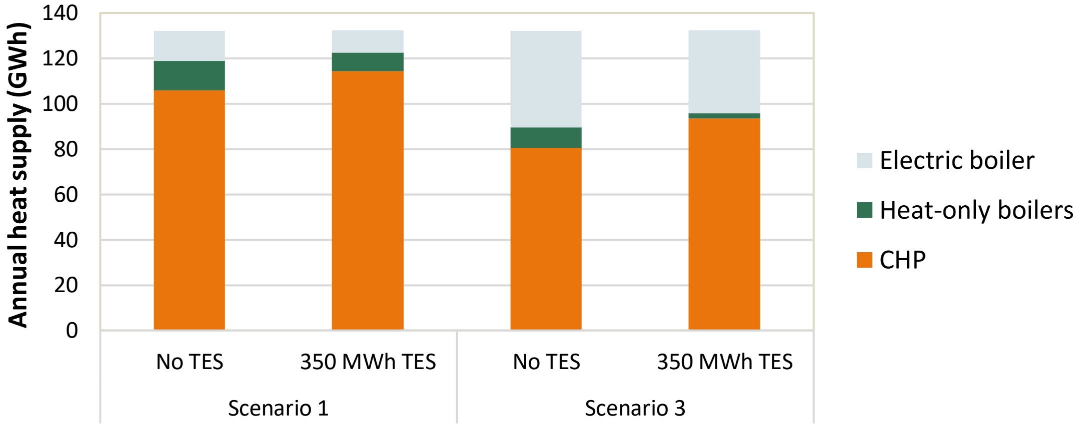

Figure 32. Annual heat supply in Scenarios 1 and 3 with and without a 350 MWh thermal energy storage.

Annual consumption of forest-based biomass increases as the increased energy output from CHP unit replaces heat converted from electricity. As annual fuel usage increases, annual CO_2 emissions from the energy system increase as well. In a conventional energy system, where peaking capacity is often fueled by fossil fuels, load leveling enabled by TES could contribute on reducing fossil CO_2 emissions emitted during peak load hours. In the scenarios built for Åland Islands, the increased level of CO_2 emissions is a trade-off between utilizing local renewable biomass resources in power and heat production instead of imported electricity.

6.4.2 Electric boiler

Electric boiler is applied to each energy system scenario to strengthen the link between power and heating sector by providing demand-side flexibility for VRE generation. According to the results, electric boilers convert excess electricity to heat and therefore increase internal utilization of locally produced electricity resulting in reduced annual power exports as seen in Figure 33.

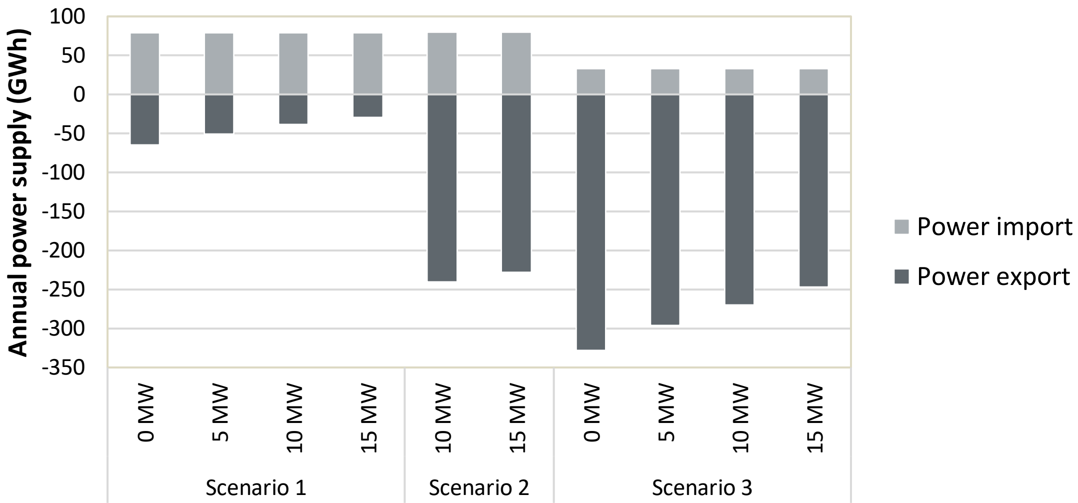

Figure 33. Annual supply of power import and export in Scenarios 1-3 in relation to electric boiler capacity.

As seen from Figure 34, adding an electric boiler and increasing its capacity reduces annual heat supply from thermal heat production units in all three scenarios. It needs to be noticed that a 10 MW electric boiler is a prerequisite for Scenario 2. If the capacity of the electric boiler was smaller, electricity produced at the highest VRE supply peak would be partly curtailed due to lack of transmission capacity.

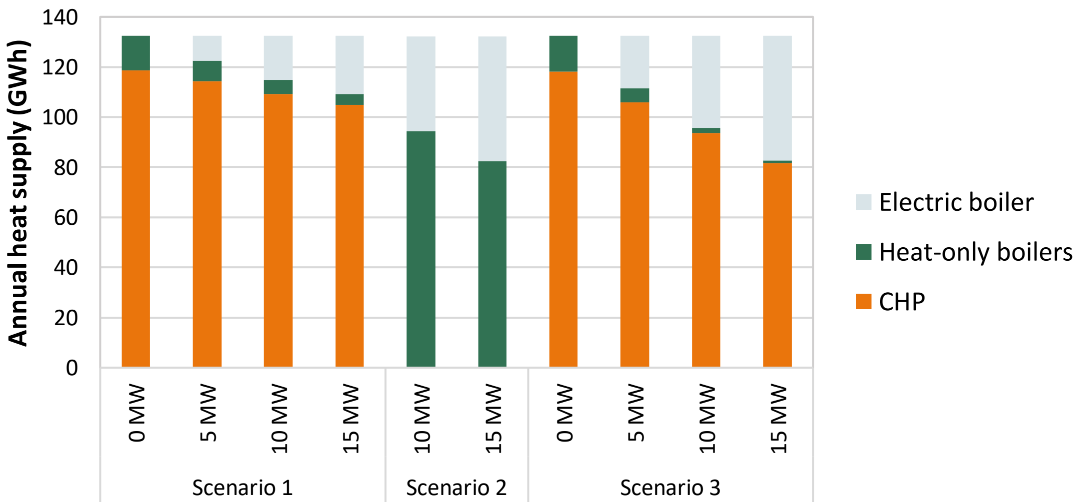

Figure 34. Annual heat supply in Scenarios 1-3 in relation to electric boiler capacity.

According to the results, electric boiler does not increase flexibility of the CHP unit as electric boiler and CHP unit partly compete of operating hours as applying an electric boiler to the district heating network reduces annual output and full load operating hours of the CHP unit. When compared to a scenario where no electric boiler is applied, adding a 5 MW electric boiler reduces annual output of the CHP unit by 3.6% and 10.3% in Scenarios 1 and 3, whereas a 10 MW boiler reduces the annual output of CHP by 7.8% and 20.8% in Scenarios 1 and 3, respectively. The reduction in the annual yield of CHP is more dramatic in Scenario 3, where high wind capacity increases the amount of inexpensive electricity available for heat conversion at VRE supply peaks.

As locally produced electricity is partly utilized in heating sector instead of trading it to the neighboring power areas, revenues from exported electricity decrease. Heat converted from excess electricity reduces annual profitability of CHP unit and heat-only boilers increasing their annual costs. Unlike in Scenario 2, low cost heat from electric boiler is not able to compensate the reduced annual profit from exports and thermal units in Scenarios 1 and 3. Therefore, applying an electric boiler as a flexibility element decreases annual net profit of Scenarios 1 and 3, whereas annual net profit of Scenario 2 remains stable. The results in Scenarios 1 and 3 could be different, if electric boiler was integrated to a thermal storage, as currently all heat converted via electric boiler are fed instantly to the district heating network, decreasing operational possibilities of the thermal units at the given time.

6.4.3 Electrochemical battery

Stationary electrochemical battery is expected to scale up integration of local VRE generation in Åland Islands by storing surplus VRE supply and releasing it during high power demand. Therefore, stationary electrochemical battery is expected to result in decreased need of power imports and in reduction in the annual amount of exported electricity. Electrochemical battery is also expected to provide short-term grid balancing services such as frequency and voltage control for the power grid. However, the capability of electrochemical battery in short-term balancing cannot be studied as the smallest time step of data applied in the simulations is one hour, and due to the fast response time of batteries (Argyrou et al., 2018), multiple operating cycles can occur within an hour.

Results show that the applied electrochemical battery storages of 5 MW and 5 MWh in Scenario 1 and 20 MW and 20 MWh in Scenarios 2 and 3 have no significant impacts on system level dynamics in any of the assessed scenarios. Annual discharge of electrochemical battery is only 5.3 GWh in Scenario 1 and 15.6 GWh in both Scenarios 2 and 3. The discharge values are small in comparison to the estimated power demand on the island in 2025 (350 GWh). Reduction in annual power exchange between Åland and the neighboring power areas can be only detected after the size of the electrochemical battery is significantly increased from the applied values as seen in Figure 35.

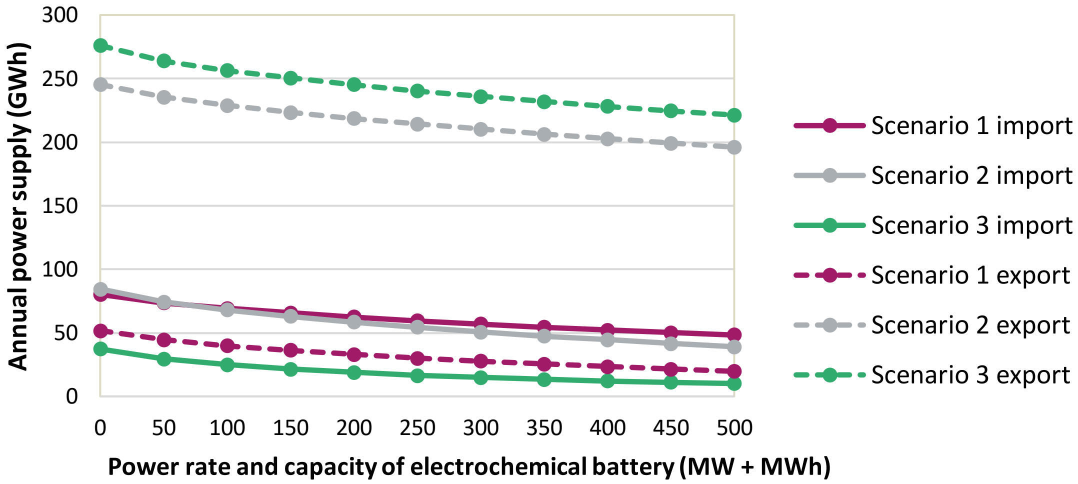

Figure 35. Annual supply of power import and export in Scenarios 1-3 in relation to electrochemical battery power rate and capacity. The ratio between power rate and capacity in the electrochemical battery is 1:1.

In Scenarios 1-3, only relevant system level impact from adding a stationary electrochemical battery to the energy system results in increased capital investments costs originating from the increased investment cost related to the electrochemical battery itself. Although increasing the power and capacity of the electrochemical battery seems to provide some benefits in relation to power self-sufficiency of Åland Islands (Figure 35), it should be noted that the globally largest existing electrochemical battery located in southern Australia has the power rate of 100 MW and the capacity of 129 MWh (Hornsdale Power Reserve, 2018). As seen from Figure 35, the system-level impact on annual import and export volumes of a 100 MW and 100 MWh stationary electrochemical battery is not significant in Åland Islands. However, annual system net profit of Scenarios 1-3 would decrease to -7.6 M€, -9.7 M€ and -9.1 M€, respectively, after the size of the electrochemical battery is increased to 100 MW and 100 MWh.

6.5 Biomass limitations

As availability and price of biomass varies in different regions of the world, the scenario-wise impacts of biomass availability and price on the annual energy supply balance and system economics are evaluated. The evaluation is done to study global replicability potential of the built energy system scenarios in areas willing to increase the level of energy self-sufficiency and the share of local renewables in the energy mix. The assessment is outlined to evaluate the availability and price variance of the studied energy system scenarios as a whole, excluding individual technologies.

Figure 36 displays the impacts of available forest-based biomass volume on annual energy supply in Scenarios 1-3. Power derived from wind, solar and biogas remain constant regardless of biomass availability, and hence these technologies are excluded from the graph. Available fuel energy potential from forest-based biomass (396 GWh; section 3.3.3) is not exceeded in the energy production of any scenario (238 GWh, 106 GWh and 189 GWh; Scenarios 1-3, respectively). Therefore, increasing the availability of biomass for combustion processes from the given maximum level does not influence operation of the thermal units nor the annual quantities of imported or exported electricity. System level variations result only when available biomass volume is cut below the annual fuel usage of each scenario. Therefore, Figure 36 represents changes in heat and power supply only, when availability of forest-based biomass is reduced from the current maximum level of 396 GWh to the point where the operation of the energy system becomes infeasible due to lack of biomass fuel. Decreasing the availability of forest-based biomass has greatest supply-level impacts on Scenarios 1 and 3, which both have relatively high biomass demand as bio-CHP is utilized as a source of dispatchable power supply in both scenarios. Supply impacts in Scenario 2 are small, as biomass is converted to only to heat at high conversion efficiency in heat-only boilers.

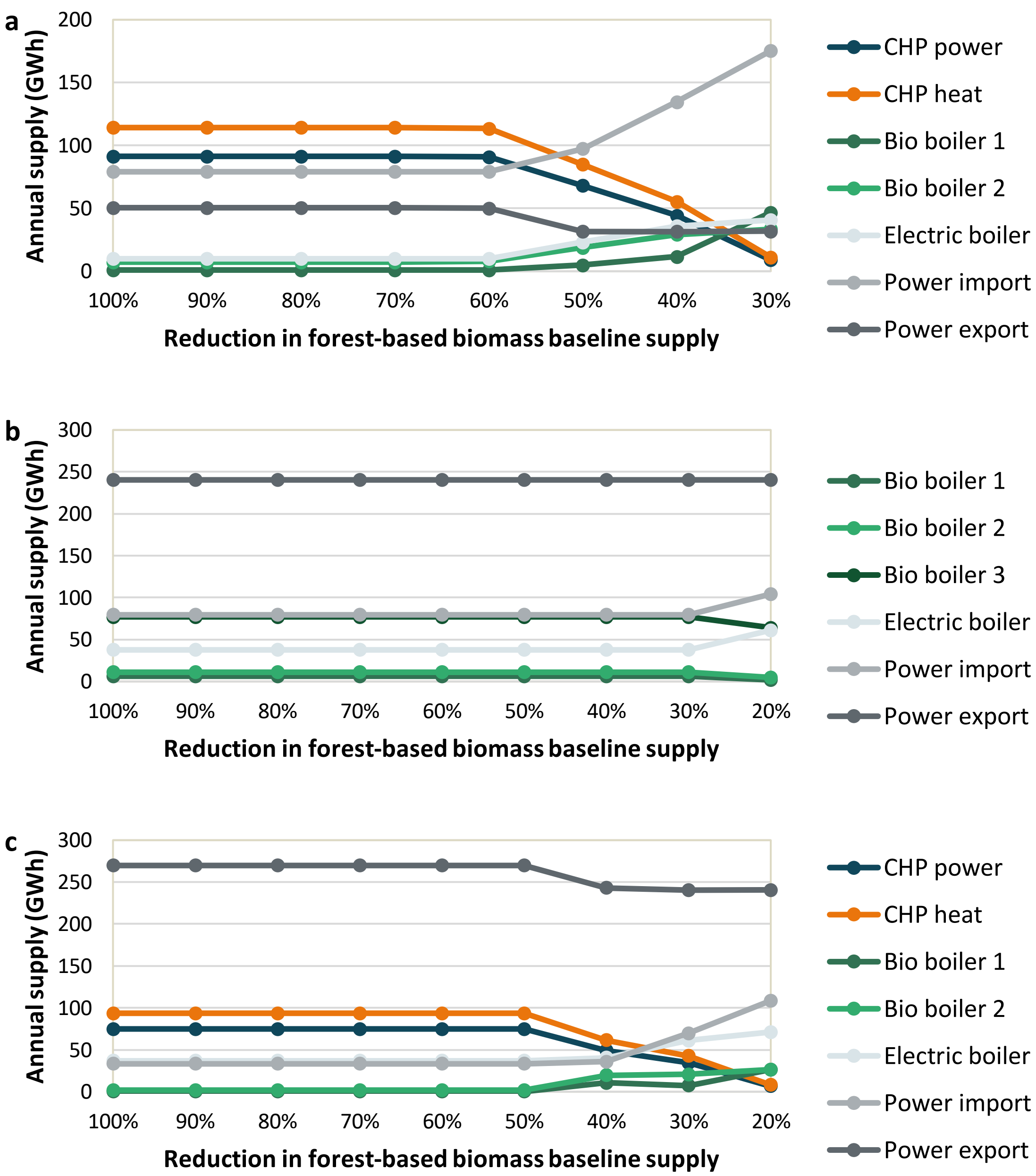

Figure 36. Impact of biomass availability on power and heat production dynamics in: a) Scenario 1; b) Scenario 2; c) Scenario 3.

As seen from Figure 36, total annual production of CHP falls, when availability of forest-based biomass is reduced below the initial annual utilization level, which is approximately 60% (238 GWh) and 50% (198 GWh) of the baseline volume (396 GWh) in Scenarios 1 and 3, respectively. Power production from biomass is compensated by increasing the supply of imported electricity in both scenarios. Thermal production units are not able to cover the heat demand due to reduced biomass availability for heat conversion. Therefore, supply of imported electricity does not only increase to compensate electricity derived from biomass, but also to serve as an input fuel for heat conversion through electric boiler. Increased utilization of electric boiler reduces annual amount of exported electricity, as more surplus VRE supply is utilized in domestic heat generation. However, as electric boiler is not connected to a thermal energy storage, heat converted for surplus VRE is fed directly to the district heating network. This can partly reduce the ability to utilize excess VRE supply in heat generation to compensate reduced heat output from thermal units.

Shortage in biomass availability decreases annual system net profit of Scenarios 1 and 3 as seen from Figure 37. Reduction in the net profit is a combination of multiple factors. When shortage in biomass availability occurs, profitability of CHP reduces due to lower utilization rate, which decreases annual net profit of the unit. Expenses related to annual imports increase, as power imports substitute CHP generation in both power and heat sector. Furthermore, income from exported electricity decreases as more excess VRE supply is utilized domestically in power-to-heat conversion. Economic impacts are especially emphasized in the first scenario, where profitability of CHP falls and the expenses related to imported electricity increase, as the utilization rate of the CHP unit decreases. In Scenario 3, annual system net profit remains stable after biomass availability is cut below 40% of the baseline availability, as the optimal capacity of the CHP unit is reduced from 15 MW_e to 12.5 MW_e, decreasing annualized investment costs of the unit. However, after biomass availability is decreased below 50% of the baseline volume in Scenario 3, annual system net profit decreases below Scenario 2, making CHP an unprofitable investment in relation to additional heat-only boiler investment. Decreasing biomass availability has lowest economic impacts on Scenario 2, as no impacts on supply dynamics occur before availability of biomass is cut below 20% of the baseline availability. Power-to-heat conversion through electric boiler is able to compensate the reduced profitability of heat-only boilers and increased costs related to power imports after biomass availability is cut below the initial fuel demand.

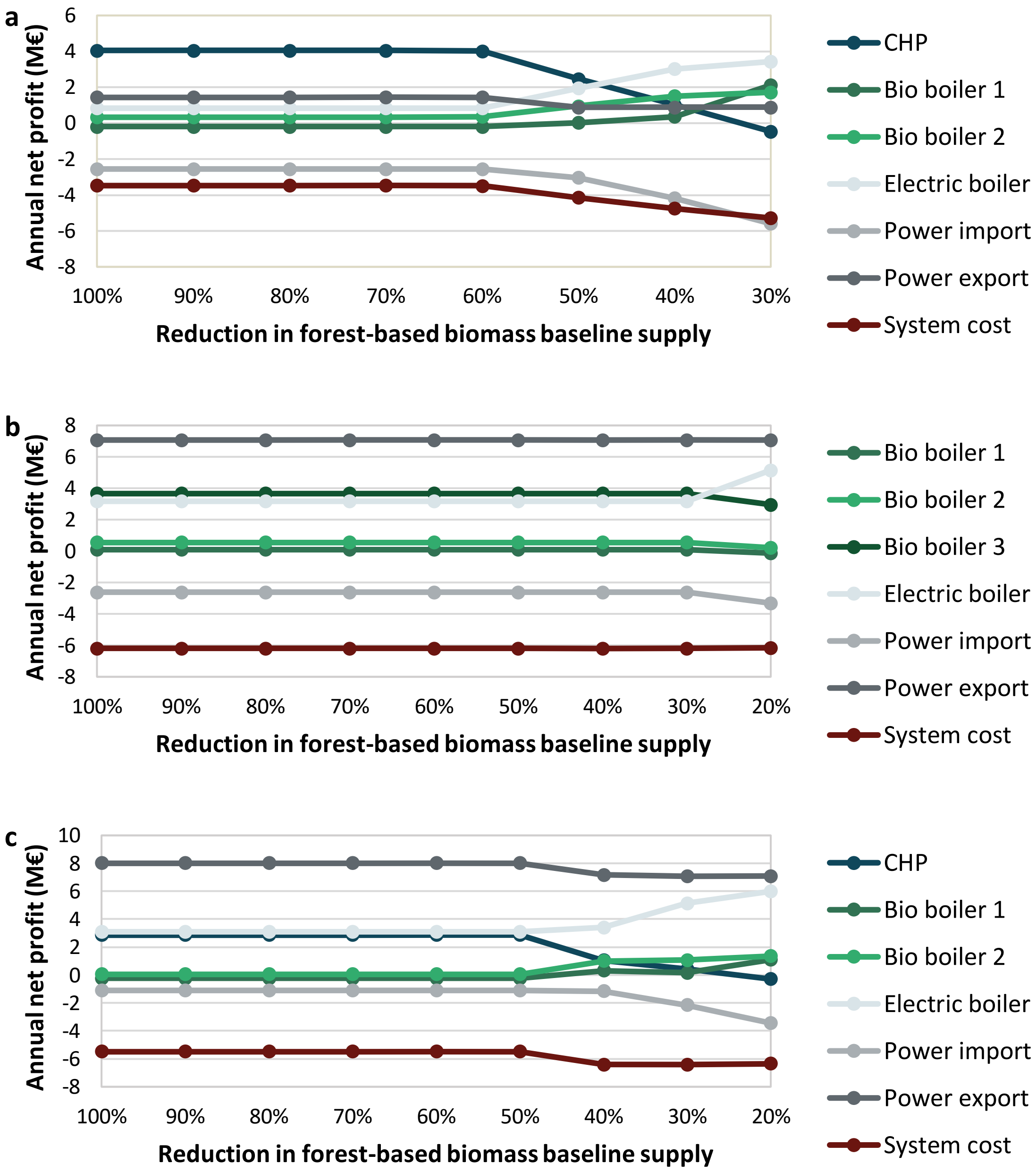

Figure 37. Impact of biomass availability on annual net profit in: a) Scenario 1; b) Scenario 2; c) Scenario 3.

Sensitivity analysis is carried out to evaluate system impacts of price variation related to biomass fuel utilized in the thermal units. The price of forest-based biomass is increased and reduced by steps of 10%. The reference price is set at 24 €/MWh as determined in section 5.2. Price of forest-based biomass has nearly linear impact on the annual costs of Scenarios 1-3. The impact of the price variation increases in accordance with the annual consumption of forest-based biomass. This is natural as all of the thermal production units excluding biogas turbine utilize forest-based biomass as the combustion fuel. Impacts of price variation are highest in Scenario 1, which also has the highest fuel consumption

(238 GWh) of the studied scenarios. In Scenario 1, a 10% change in the price of forest-based biomass has an average price impact of 610 t€ to the annual system net profit, whereas in Scenarios 2 and 3, the average impact is 260 t€ and 520 t€, respectively.

7 DISCUSSION

According to Laatikainen (2018b), one goal of the renewable energy transition in Åland Islands is to find society-scale solutions for cost-effective VRE integration that could be applicable throughout the world. Therefore, the energy transition pathways and their economic and environmental impacts as well the impacts of flexibility elements in improving VRE balancing of the energy system are not are not only discussed from the viewpoint of Åland Islands, but also from the global perspective.

According to the results of the thesis, a renewable energy system is technically achievable in Åland Islands by 2025 when local renewable energy resources and certain flexibility elements are applied in the energy system. Depending on the energy self-sufficiency criteria, Åland is able to achieve independency in power and district heat supply, if a region is considered as self-sufficient when it produces more energy than it consumes. However, if a region is considered as self-sufficient only when it is entirely independent from imported energy, full self-sufficiency is not achieved in Åland Islands by 2025 in accordance to the results of the thesis, as power imports cannot be entirely discarded in any of the studied energy system scenarios. Imported electricity is required at times when local energy measures are not able to cover deviations in power supply due to intermittency in VRE output.

Wind power is expected to lay the foundation for domestic power supply in Åland Islands by 2025, as Åland has great wind conditions due to its location. The significance of wind power in the future power supply of Åland Islands has been previously acknowledged for instance in Child et al. (2017) and Child (2018). As wind is expected to be the major power supply source in the future energy system of Åland Islands, great wind potential is a prerequisite for an area where any of the studied energy system scenarios could be replicable. Child et al. (2017) utilized the term of semi-offshore wind turbines, which was also applied in the thesis. Semi-offshore wind turbines are built on the small islets of the scattered archipelago in Åland Islands, and therefore semi-offshore wind turbines offer great potential to achieve offshore wind turbine output values with costs more similar to onshore wind turbines. Similar coastal characteristics with an opportunity for high wind yields at low cost can be hard to find in other locations. Good wind power potential is a decisive requirement especially for the global adaptability of Scenarios 2 and 3, where annual wind power output reaches significant quantities (530 GWh) in relation to population (29 500; ÅSUB, 2018) of Åland. When compared to annual wind power yield in Finland in 2018 (5.8 TWh; Finnish Wind Power Association, 2019), the ratio between produced wind power and population would be 17 times higher in Åland Islands by 2025, if the 185 MW_e wind capacity pathway was chosen.

Based on the simulations of the thesis, role of solar PV in power production is expected to be only complementary in Åland Islands by 2025 due to the heavy seasonal variability in its power output. The system-level contribution of solar PV is small in all the studied energy system scenarios (3%, 2% and 2% of annual power supply in Scenarios 1-3, respectively). Therefore, residential solar PV installations can be expected to have more prominent role in increasing energy efficiency of the buildings, where renewable electricity is produced on-site. Solar potential is not expected to become a barrier in replicating any of the energy system scenarios globally, as generation potential from solar PV is greater in almost any part of the world when compared to the potential in Åland Islands (The World Bank Group, 2019). Regions with weaker wind potential could compensate lacking wind resources by increasing the proportional share of solar PV in the power mix. Substituting wind generation with solar PV would however increase the need of seasonal dispatchable power supply, especially in higher latitudes, where seasonal variations in solar PV output are pronounced (Hakkarainen et al., 2015). Furthermore, intraday variation between power supply at day and night would increase if wind capacity was substituted with power derived from solar PV, although the power output of solar would correlate more with the daily power consumption curve in relation to wind.

Power potential of biogas (1.4%, 0.9% and 0.8% of annual supply in Scenarios 1-3, respectively) is limited by the availability of domestic feedstock of bio-based waste in Åland Islands and by low fuel conversion efficiency of the biogas turbine. A more feasible option on the island could be to prefer biogas a source of decentralized heat production instead of a power source at demand peaks. The biggest potential of bioenergy in Åland Islands relates to forest-based biomass. From system-level perspective, strengthening the link between power grid and district heating network by investing on a bio-CHP unit fueled by domestic forest-based biomass would enable to increase the share of local renewables in the power supply by decreasing the annual amount of imported electricity. In addition, bio-CHP investment was discovered to increase annual net profit of the energy system, when the capacity of the CHP is optimized in accordance to system economics. The results are supported by Pääkkönen & Joronen (2019) who studied unit-level feasibility of bio-CHP in VRE balancing in the future energy system of Åland Islands with increased VRE supply. The study concluded that bio-CHP can be utilized as a source VRE balancing, when affordable fuel costs and sufficient income for heat can be guaranteed.

In this thesis, the price of biomass was also found to have considerable system-level impacts to the profitability of bio-CHP in VRE balancing, as price variance of biomass had relatively the highest impacts in scenarios where CHP was utilized as a source of dispatchable power and heat supply. Multiple factors influence price formation of biomass, such as supply and demand, collection and harvesting costs as well as certain policy instruments such as tax incentives and subsidies (IRENA, 2014). Complexity of biomass price formation can hinder country- and region-specific price development prospects abating willingness on long-term investments related to thermal units utilizing biomass as a combustion fuel. Furthermore, if an energy system was to utilize bio-CHP as a source of flexibility, economical drawbacks would also occur in regions lacking of local biomass, as in accordance to the results of the thesis, sufficient availability of biomass for combustion processes is also a decisive parameter when evaluating the feasibility of bio-CHP as a flexibility element. Imported biomass could be an option; however, imported fuel fractions would reduce energy independence in the region where applied, just like any other imported fuel.

Pääkkönen & Joronen (2019) did not study the impacts of thermal energy storage on the operational flexibility of the bio-CHP unit in VRE balancing. According to the results of this thesis, benefits of bio-CHP as a flexibility element can be enhanced by combining the CHP unit with a thermal energy storage, as TES was discovered to increase full operating hours and annual output of CHP while increasing annual net profit of both CHP and the energy system. The discovered operational benefits of TES are globally adaptable; however, requirement for a district heating network is a necessity for the region where energy system flexibility would be exploited from bio-CHP and TES. Referring to Kiviluoma et al. (2017), building a district heating network to an existing city is expensive and inconvenient. Therefore, energy system flexibility from district heating network and elements integrated to it should primarily be harnessed in regions where district heating network already exists. Furthermore, if bio-CHP was to be invested to balance intermittent VRE generation in another region, local heat demand should be high enough to support the investment. Lower heat demand in the district heating network is an option in Scenario 2, as long as the demand is high enough to enable power-to-heat conversion from excess electricity to increase internal utilization of locally produced electricity.

The system-level role of electric boiler and electrochemical batteries in VRE balancing were also studied in the thesis. Centralized electric boiler did not increase flexibility in the energy system as no system-level benefits in annual system net profit nor in the level of power self-sufficiency were achieved after electric boiler was applied to the studied energy systems. However, electric boiler was proven to increase internal utilization of excess VRE supply by converting exportable electricity to heat to be utilized in the district heating network. From an environmental point of view, utilizing electric boiler for heat generation would enable to conserve biomass in Åland Islands, as the annual output and hence fuel consumption in the thermal units were noted to decrease after electric boiler was applied to the energy system. Decreased fuel usage would result in reduced CO_2 emissions from the heating sector, although in the Åland 2025 scenarios, the compensated carbon would origin from renewable sources, which do not increase the atmospheric level of CO_2 as carbon emission from fossil fuels (Koponen et al., 2015). Therefore, the potential of electric boilers in decarbonization could reach greater significance in areas, where thermal units in the heating sector are operated by fossil fuels.

Electric boiler could be a potential heat generator in regions lacking of local biomass. Assuming that the region is dependent of imported fractions of combustion fuel, electric boiler would result in increased level of energy self-sufficiency if the region where applied had a continuous supply of surplus VRE. In the studied energy system scenarios of Åland Islands, the level of self-sufficiency in power and heat sector remain constant after electric boiler is applied to the energy system, as heat generated from locally produced surplus electricity replaces domestic forest-based biomass. However, electric boiler could contribute to increase the level of self-sufficiency for instance in the transportation sector of Åland Islands, as conserved biomass fractions from power and heat sector could be converted to bio-based transportation fuels.

Electrochemical battery storage had no significant impacts on system-level dynamics in any of the assessed energy system scenarios. The role of stationary electrochemical battery could have been greater if power exchange would have been more restricted. The additional electrochemical battery investment had no system-level benefits in providing flexibility, as the studied energy system scenarios were able to utilize transmission lines as virtual batteries. The chosen temporal scale in the simulation tool prohibited to evaluate short-term balancing abilities of electrochemical batteries. The inability to study short-term balancing abilities was also restricted by time step constraints in a study by Pleßmann & Blechinger (2017) which simulated the future power network of Europe. The study concluded that electrochemical batteries can become a cost-effective source of short-term grid balancing in the upcoming decade although the grid stability and frequency control services were not able to be modelled.

Power transmission between Åland and the neigboring power areas of Finland and Sweden play an important role in all of the 2025 scenarios, as none of the assessed energy systems is independent from power imports. Similarly to the renewable island of Samsø (Parkkari, 2018b), backup power as in imported electricity is always available for Åland Islands from the continent to secure power supply during periods of low local VRE supply. Strong interconnections with the neighboring power areas also enable to adopt high capacities of VRE generation to Åland Islands, as high surplus VRE peaks can be exported instead of curtailed. The role of large interconnector capacity is especially significant in Scenarios 2 and 3 with high annual power export expectations due to large wind capacity. Interconnectors can be considered to act as virtual batteries, reducing the variance in VRE generation. Therefore, the global implementation potential of the energy system scenarios is restricted from areas where no option for power exchange exist. In addition, implementation potential of the scenarios is excluded from regions where interconnectors are volatile for transmission congestions, as congestions result in curtailment of renewable electricity causing loss of revenue.

Annual net profit in all studied energy system scenarios was discovered to be net negative (-3.5 M€, -6.2 M€ and -5.5 M€, Scenarios 1-3, respectively). Economic profitability could be increased by applying support schemes such as feed-in tariffs or subsidies for renewable generation. Feed-in tariffs for wind power could increase economic profitability especially in Scenarios 2 and 3, where the annual amount of generated wind power is significant (530 GWh_e). Multiple uncertainty factors can further influence economic viability of the scenarios in both Åland Islands and globally. Annual wind conditions can have short-term impacts on the economics of the energy systems, emphasized especially in scenarios with high wind capacity. If wind speeds are considerably lower in comparison to the wind speeds in Åland Islands at the reference year of 2017, capacity factor of wind turbines can be expected to decrease, resulting in longer payback times for the investments. Higher wind speeds can result in higher short-term revenues, if surplus wind is exported at decent price instead of curtailed for grid management purposes.

Future power prices are a mid-term factor influencing the economic viability of the energy system scenarios. If the market spot price of electricity increases by 2025, economic viability of all scenarios increase, as the net profit of CHP unit or net revenue from power exchange or both increase in the analyzed scenarios. However, it should be noted that the applied hourly cost of electricity in 2025 was derived from Nord Pool's day-ahead power market (SE3) from 2017 and that the price of district heat in 2025 was set at 80 €/MWh. Therefore, the price of electricity and heat in the simulations were fixed and not recalculated in accordance to local power and heat supply in Åland Islands in 2025. Economic viability of the scenarios could increase, if the market model for power and heat pricing would be adapted and the price of energy would be recalculated in relation to the local power and heat generation. Since feed-in tariffs and subsidies as well as other market mechanisms including the local pricing structure for the regional power and heat supply were excluded from the simulations, the resulting annual net profits of the energy systems should not be applied to make final conclusions related to the realization potential and economic viability of the analyzed renewable energy systems. The results should rather be applied to compare cost structures of the assessed energy system scenarios with each other.

As the domestic 2025 energy system emissions originate from local biomass, the increased CO_2 emissions in the evaluated energy system scenarios are not necessarily a problem from an environmental point of view. Carbon emissions from biomass do not increase CO_2 levels in the atmosphere like emissions from fossil fuels, as biomass binds the released carbon as it grows, forming a closed carbon cycle (Koponen et al., 2015). As biomass is considered as a carbon neutral source of energy, biomass derived CO_2 is not counted to the annual sum of greenhouse gas emissions in Finland (Statistics Finland, 2018a) nor considered as a carbon emission in EU Emissions Trading System (European Commission, 2019). The usage of forest-based biomass in energy production could have negative long-term impacts for atmospheric carbon balance, if intensive harvesting volumes would reduce the capability of a forest to bind carbon from the atmosphere (Koponen et al., 2015). The maximum forest-based biomass potential for energy use in

Åland Islands (396 GWh) is evaluated based on the most technically and economically sustainable annual harvesting volumes determined by Natural Resources Institute Finland (The Government of Åland, 2017b). As maximum fuel potential is not exceeded in any scenario, no negative long-term impacts related to carbon balance are expected to occur in the 2025 scenarios in Åland Islands. However, sustainable harvesting volumes of forest-based biomass can be a limiting factor for local thermal energy production from biomass in other regions.

To conclude, none of the built energy system scenarios built for Åland Islands in the thesis is a generic solution that could be implemented as a whole throughout the world without certain prerequisites. High wind power potential, availability of domestic low-cost biomass, existing district heating network with high or moderate heat demand and strong power transmission lines are requirements for a region, where similar approach for renewable energy transition as in Åland Islands in this thesis could be applied. However, certain individual elements of the energy system scenarios have the potential to be applied as more generic solutions to increase integration of VRE supply in an energy system. Potential of thermal energy storage in providing operational flexibility for bio-CHP promoting VRE balancing can be applied globally in regions, where district heat is at least partly supplied by CHP. Furthermore, electric boiler has the potential to be utilized in regions, where internal utilization of surplus VRE is aimed to be increased. In regions where no district heating networks exist, building level heating by decentralized hot-water boilers could offer similar demand-side flexibility options for VRE integration as a centralized electric boiler integrated to a district heating network in the thesis.

8 CONCLUSIONS

National policies of climate change mitigation and cost reductions in VRE technologies are driving global energy transition, where fossil-based energy is phasing out to be replaced by low-carbon energy sources. Variable wind and solar power are expected to reach significant importance in the future, resulting in increased intermittency in power supply. As the remaining energy system is required to adapt to more rapid changes in the residual load, additional costs are likely to occur. Increasing flexibility in the energy system can decrease additional system integration costs caused by high VRE deployment to facilitate the integration of VRE sources to the energy system.

The purpose of the thesis was to study how local characteristics and existing energy system elements can be utilized to achieve an energy system based on 100% renewable energy, and what additional unit and system level investments can be deployed to increase flexibility in an energy system. Energy transition of Åland Islands was utilized as a case study, as Åland is currently participating a project with the aim to convert the island into a demonstration site for a society-scale energy system running only on renewable energy. In the thesis, three renewable energy scenarios were designed for Åland Islands with the reference year at 2025, as by this time, the realization of the actual energy transition project in Åland Islands should be finalized. The evaluation of the energy system scenarios was done based on energy system modelling results derived from a simulation tool developed at VTT. The studied energy system was constrained to include the regional power grid and a district heating network located in the capital Mariehamn. In this thesis, attention was especially drawn on the role of district heating network in balancing an energy system with increased level of VRE supply, as flexibility potential of bio-CHP, thermal energy storage (TES) and electric boiler was studied, which are all elements integrated to a district heating network. Furthermore, system-level VRE balancing potential of a stationary electrochemical battery was evaluated.

Due to great wind conditions, wind power will evidently have an essential role in the energy transition of Åland Islands. Wind power was also discovered to supply the bulk power in the renewable energy island Samsø, which, in regards of renewable energy potential and power and heat demand, was discovered to share the greatest similarities with Åland Islands from the studied renewable energy islands Samsø (Denmark), Tilos

(Greece) and El Hierro (Canary Islands, Spain). In Åland Islands, wind power is expected to provide the backbone for power generation and reduce the dependency of imported electricity, which has covered over 75% of the power supply on the island during the current decade. The thesis assessed two different realization pathways of wind power projects currently in the pipeline in Åland Islands. The two pathways differed in installed wind capacities; wind capacity was set at 85 MW_e in low installation pathway, whereas baseline installation pathway of 185 MW_e represented the wind capacity after all wind projects currently on hold in Åland Islands are commissioned. In Scenario 1, a bio-CHP unit was added to the low wind installation pathway, whereas Scenarios 2 and 3 analyzed the baseline installation pathway, without and with a bio-CHP investment, respectively. Solar PV was expected have a supplementary role in VRE supply in 2025 with the capacity of 15 MW_e in all the studied energy systems. Total annual VRE generation was estimated to reach 235 GWh or 545 GWh in 2025, depending on the installed wind capacity. Although VRE generation in the baseline wind installation pathway is expected to exceed the estimated annual power consumption of the energy system in 2025 (350 GWh), VRE output is not able to cover power demand at all times due to variability in wind and solar power supply.

The results of the thesis indicated that a district heating network located in Mariehamn has potential to be utilized in balancing intermittent VRE supply cost-effectively in Åland Islands via a bio-CHP unit and a thermal energy storage (TES). In baseline wind installation pathway, an investment on a CHP unit (15 MW_e) and TES (350 MWh) would enable to cut annual reliance of imported electricity from 79.5 MWh to 33.2 MWh, resulting in 0.7 M€ (11.3%) increase in annual system net profit despite additional capital costs. When considering overall power supply and self-sufficiency, CHP investment (15 MW_e) and TES (350 MWh) would allow to reduce wind capacity in the baseline installation pathway by 100 MW_e with having a negligible impact on power self-sufficiency of the island. Optimal capacity of the CHP unit depends on the level of power self-sufficiency the island is aiming to achieve. Increasing the capacity of the CHP unit was found to reduce power imports and increase annual net profit of the energy system. However, after the optimal economic capacity of CHP from system viewpoint is exceeded, annual system net profit will decrease, although power independency increases. From economic point of view, optimal capacity of the CHP unit was 13 MW_e and 10 MW_e in low and baseline wind installation pathways, respectively.

Electric boiler was applied to all studied future energy systems to convert excess VRE supply to heat. Electric boiler was proven to increase internal utilization of local surplus VRE generation in both wind installation pathways by reducing annual amount of exported electricity. However, by substituting heat generation from CHP and heat-only boilers in the district heating network, electric boiler was noticed to decrease full load operating hours and total annual energy outputs of the thermal production units, which, in particular, was found to decrease the profitability of the CHP unit. The role of a stationary electrochemical battery in system level VRE balancing was found to be negligible in Åland Islands, as the energy system preferred to utilize power interconnectors as a virtual battery.

When cost assumptions made in the thesis were applied, renewable energy transition in Åland Islands was discovered to be economically unprofitable. Policy instruments such as feed-in tariffs or investment subsidies supporting renewable generation can be assumed to have a strong role in increasing the economic feasibility of the energy transition in Åland Islands as when realized, the reference model of a renewable energy system could bring additional value for Åland Islands and Finland through exportable knowledge. Apart from public investments, an alternative to increase economic viability of the renewable energy transition in Åland Islands would be to modify the local energy market to support local renewable generation on the island for instance by adapting the pricing structure of local power and heat generation.

In general, the low wind installation pathway combined with a CHP unit as a source of dispatchable power supply is the most profitable option in regards of annual system net profit. However, several uncertainty factors such as wind speed, electricity price and price of biomass can further influence the profitability and economic sustainability of the different energy transition pathways. The low wind installation pathway supported by CHP is less volatile for changes in annual wind speed and electricity price due to low income expectations from power exports, whereas baseline installation pathway is more volatile for these changes due to high amount of generated surplus electricity. Future projections of biomass price and national policies related to CO_2 costs are uncertainty factors to consider when biomass is applied as a source of dispatchable energy. By speculating that an additional cost is added to CO_2 emitted from renewable sources in the near-term future, system net profit decreases most in an energy system where biomass has an important role in power and heat supply.

Åland is able to increase the level of energy security and power self-sufficiency by investing on local energy production assets, most importantly on a bio-CHP unit. As long as the annual sustainable harvesting volumes of forest-based biomass for energy production purposes (396 GWh), are not exceeded in Åland Islands, negative long-term impacts for atmospheric carbon balance are not expected to occur. Utilizing biomass as an energy source also adds CO_2 emissions emitted from the energy sector, although the carbon is emitted from renewable sources. However, when local biomass is utilized in energy production to substitute imported electricity, the source of CO_2 emissions can be confirmed to origin from renewable sources at all times, unlike in the case of imported electricity.

The most feasible renewable energy transition pathway for Åland Islands depends on the primary goal of the island, as the nexus of economic and environmental impacts and the level of power self-sufficiency can be optimized only from one dimension at a time. If the essential aim of the energy transition in Åland Islands is to acquire a renewable energy system with lowest capital investment cost and reduced volatility related to income derived from power exports, the low wind installation pathway coupled with a bio-CHP unit is the foremost option. If the goal was to reduce CO_2 emissions, even if emitted from renewable sources, most feasible option would be to invest on the baseline wind installation capacity, without bio-CHP as a source of flexibility. If Åland is aiming to reduce the dependency of external power imports to its minimum, the foremost option would be to invest on the baseline wind capacity along with a bio-CHP unit as a source of dispatchable power supply. Similar approach should be applied to evaluate the adaptability of the studied energy transition pathways on a global scale. However, high wind power potential, availability of domestic low-cost biomass, existing district heating network with high or moderate heat demand and strong power transmission lines should characterize the region, where similar technical approach to achieve a renewable energy system as in Åland Islands could be applicable.

As a suggestion for future research, an essential study would be to examine the most beneficial market model to make the renewable energy transition in Åland Islands economically viable, as the economic model applied in the thesis did not support the renewable energy transition on the island. In addition, further studies should determine the cost-optimal ratio between CHP unit and electric boiler, if surplus VRE generation is aimed to be utilized in local heat production, as in the thesis, utilization of electric boiler reduced profitability of the CHP unit. The thesis assumed heat from electric boiler to be supplied instantly to the district heating network, without an opportunity for heat to be stored and supplied for instance at periods of high heat demand outside VRE supply peaks. Therefore, future studies should also investigate, whether integrating electric boiler to TES would enable to further increase internal utilization of excess VRE supply, without reducing operational flexibility of the CHP unit. Furthermore, additional studies are required to evaluate the applicability of a stationary electrochemical battery in short-term balancing of the power grid in Åland Islands, as the simulation methodology utilized in the thesis was not able to evaluate frequency and voltage control potential of an electrochemical battery due to time step restrictions.

If all the wind turbine projects currently on hold in Åland Islands are commissioned by 2025, Åland will evidently become a net exporter of electricity. The thesis assumed that the excess VRE output will be exported to Sweden or Finland or utilized in domestic power-to-heat conversion in local district heating network. Surplus VRE could bring additional value for local businesses and for Åland Islands, if excess VRE supply was utilized to upcycle materials with low value to products with higher quality. Further research is required to define the material flows in Åland Islands, where additional energy could be used to increase the value of a potential by-product or a waste stream. If excess VRE supply was discovered to increase net worth of a material flow cost-effectively, additional value generated by surplus VRE could drive additional investments on renewable generation and reinforce self-sufficiency in other sectors than energy as well.

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