CHALMERS

Investigating the impact of wave energy in the electric power system
-A case study of southern Sweden

Master's Thesis within the Sustainable Energy Systems programme

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

The aim of this thesis has been to investigate the impact of wave energy in the electric power system of southern Sweden. How does wave energy correlate with wind power generation in the area, and can a less variable generation pattern from wave energy allow it to have a higher investment cost than wind energy?

The study has been performed using meteorological data for the region from the European Centre for Medium-Rage Weather Forecasts, ECMWF, and a computer model of the electricity system. The weather data was analysed to gain a better understanding of wave power generation in general and in the area, and also to investigate the correlation between wave and wind energy. The effects of wave power on the electricity system have been analysed by using a cost-minimizing model of the electricity generation system, developed outside of this thesis.

The main outcome of this thesis is that there are benefits of combining wind power generation in southern Sweden with wave power generation on the Swedish west coast, compared to only increasing wind power generation equally much. The benefits are in terms of reduced system operational costs, and the savings are in the range of 1% of the system operational cost, explained by a reduction in peak cost, lower cycling cost and less curtailment of wave and wind power generation. Since the two sources are highly correlated in the area, wave power in general is available at the same time as wind power is available, and thus the gain of combining the two sources in this specific area is reduced. In an area with lower correlation between waves and winds, the gains of combining the two sources could be higher.

When it comes to the cost of the wave power compared to wind power, the outcome is that the determining factor for how the costs are related is the capacity factors. The higher capacity factor for one of the investigated technologies within this thesis was found to enable wave power to cost about 50% more than wind power per generator capacity. The system benefits of having a mix of wave and wind compared to wind only further increases this cost difference per generator capacity by one or two percentage.

Wave power also has other benefits compared to wind power, such as higher public acceptance and higher energy density in the resource. The wave power industry might be in the starting blocks of a great exploitation in the coming years. Experience from the wind and solar industry tells that once things start happening, the growth in installations may be explosive. Future development on prices, investment trends, public acceptance etc., will govern the development in the wave power industry.

Keywords: Wave power, variable power production, intermittent electricity generation, dispatch modelling, combining wind and wave power.

Nomenclature

Δ	Change in system operational cost	[€]
λ	Wave length	[m]
ρ	Water density	[kg/m^3]
σ	Standard deviation	-
b	Cost factor for wave power compared to wind power	[€/MW]
c	Wave speed	[m/s]
CO_2	Carbon dioxide	-
c_{wind}	Cost of wind power	[€/MW$\cdot$ year]
$e_{CO_{2:i,t}}$	CO_2-emissions from unit i at t	[ton/MWh]
g	Acceleration due to gravity	[m/s^2]
$g_{i,t}$	Generation from unit i at t	[MW]
$g_{low_{i,t}}$	Lower generation limit of unit i at t	[MW]
$g_{up_{i,t}}$	Upper generation limit of unit i at t	[MW]
GAMS	General Algebraic Modeling System	-
H_{m0}	Significant wave height	[m]
$on_{i,t}$	Turns from 0 to 1 when a unit is started	-
P	Energy flux per meter wave front	[W/m]
P_{wave}	Installed capacity of wave power	[MW]
P_{wind}	Installed capacity of wind power	[MW]
$spin_{i,t}$	A unit ready to run gives 1, not ready 0	-
T	Total number of time steps	-
T_E	Energy period	[s]
T_{start_i}	Start-up time for unit i	[s]

Contents

1

Introduction

If we are to have a chance in mitigating climate change, major changes in the electricity systems must be made. Since the beginning of the industrialisation, fossil fuels have been the dominant source of energy globally, and the total emission of greenhouse gases has been constantly growing for decades. In 2011, generation of electricity and heat was responsible for 41% of the annual global carbon dioxide emissions from fuel combustion [1]. To change these trends, conventional thermal generation based on fossil fuels must be replaced by renewable alternatives, and for this a combination of renewable technologies are desired due to issues of variability and security of supply. The past decades have seen a significant growth in wind power installations, accompanied in more recent years by an extensive growth in solar power installations. As the issue of climate change is getting more heavily debated the interest in renewable alternatives grows, which enables new technologies to come into play.

Electricity can be generated from the ocean in numerous ways, e.g from tidal energy, by utilizing differences in temperature or salinity or by absorbing the energy in the waves. Of these alternatives, the largest global potential lies within the waves.

The idea of utilizing energy from waves is old, and the global energy potential is huge, in particular at the coasts of Europe facing the Atlantic [2, 3]. Thousands of patents have been awarded to different proposals on how to utilize wave energy [2], but despite this, the lack of a clear winning technology has been a hallmark of the wave power industry and its research over the years [4]. One explanation to the multitude of soultions are the many challenges facing wave power, such as high investment costs due to the need of large infrastructures, a need of over-dimensioning due to the rare but recurring events of extreme wave climate, survivability of parts subject to the large power of the oceans [4] etc. Since the power in ocean waves grows with the square of the wave height, the wave energy converters occasionally have to handle huge power and forces, without the ability to stop as for example wind power plants have. In occurrence of smaller waves and calmer wave climates the converters are still supposed to absorb energy in an efficient way. There are however means to hide from the waves at least for some technologies, e.g by letting the waves pass over the device.

It has been suggested that there will be no *one size fits all*-solution for wave energy conversion, but that local conditions such as water depth and wave climate will determine the most suitable technology for every site [3]. The diversity in technology could be presented as a risk of longer time needed for price reduction. Several different wave power technologies have been tested in real sea conditions in large scale and some are now nearing a commercial stage, even if the maturity of the technology is far behind both wind and solar power. The first commercial wave energy park in Sweden is now under construction outside Sotenäs on the west coast.

Apart from being a non-depletable resource [2], wave energy has many important beneficial characteristics for efficient electricity generation. The energy density in waves is high compared to solar and wind, and the power output is more predictable and continuous than for wind power [5, 6]. In the oceans of the northern hemisphere, there is also a strong correlation between availability and demand over seasons, since most of the wave energy generally is available during winter in these oceans. The difference in wave energy when comparing winter and summer can be as high as seven times [3].

Waves are correlated with wind but offset in time in confined waters such as the North Sea [3]. Measurements at Horns Reef on the west coast of Denmark shows a time lag of three to four hours for waves compared to wind. However, sites exposed to open oceans will primarily experience swell waves, with longer duration and less correlation with the local wind conditions. If wave power is to be combined with solar power, one advantage is that the output from solar is likely to have the opposite pattern to wave, both with respect to weather and season [4].

Power systems with a high penetration of renewables have different characteristics than conventional fossil fuelled systems. In a conventional system a commonly raised issue is the security of supply and the risk of being dependent on other nations for fuels. Without access to domestic fuels there might be a risk of lack of supply or sharply higher prices. The risk is lower in a market with many players, and also if not being solely dependent on one type of fuel. Moreover, since the generation from fossil fueled power plants can be scheduled well in advance this means that with a highly predictable demand the power production could be secured by keeping sufficient amount of fuels stored. In a greener system, the map of resources will be repainted, with the regions who have had lots of fossil fuels often being others than those having the best conditions for wave, wind and solar power. Roles as importers and exporters will change, and many regions expect an increase in security of supply. The new fuels; winds, waves and solar irradiation is beyond our control and cannot be stored. Therefore, in a greener system, operators will be faced by new issues like increased demand for reserve capacity, storage and flexibility in the generating units. Geographical spread and a combination of different variable sources will be remedies to the challenge of variability. This thesis will handle the latter remedy, investigating the benefits of combining wave and wind power generation.

Besides clean energy and thus a reduction in CO_2-emissions, ocean energy resources can contribute to economic growth and job opportunities, mainly in coastal areas. The

European Union has stated that utilization of this resource can lead to up to 26 500 permanent and 14 000 temporary employees until 2035 [7]. They, along with many others, also stress that thanks to the installations being situated partly or entirely under the water surface issues like public acceptance and NIMBY[1] is not as troublesome as for many other renewables. Also, they relate to the recent years growth in the sectors of wind and solar energy as an indication that in order to create incentives necessary to gain results, suitable political and financial frameworks must be implemented in a coordinated way.

1.1 Aim and Objective

The objective of this thesis has been to investigate the value and effects of wave energy in the electricity system of southern Sweden. How does wave power correlate with wind power generation in the area, and what are the potential gains of combining these two sources? Futhermore, can electricity from waves be allowed to cost more because it has a less variable production pattern than wind?

When doing this, a linear cost-minimizing model of the electricity generation system already developed at the department of energy technology at Chalmers has been used, containing hydro-, nuclear-, gas- and wind power generation. The model is implemented in GAMS[2]. In this thesis, wave power generation has be added to the model, based on weather data for the region. In order to do this, the transfer from wave energy to electricity had to be understood to be modelled in a suitable way. Valid data for waves in the region had to be found, with satisfactory resolution both geographically and temporally.

The thesis has been performed as collaboration between Göteborg Energi and a research group at Chalmers, at the division of Energy Technology.

1.2 Scope

The geographical scope of this thesis has been southern Sweden. Trading of electricity with neighbouring countries has not be included in the model. Since Sweden in general is neither a net importer nor exporter on an annual basis, the impact of this simplification is assumed to be small.

Hydropower has been modelled as an import from the north, with a capacity limitation corresponding to the transmission capacity from the north into the area, and an energy balance restricting the maximum annual use.

The costs calculated in GAMS have only been based on running costs, and no consideration has been taken to investment costs neither of generating units nor transfer capacity. No consideration has been taken to bottlenecks in the electricity system within the modelled region.

[1] Not In My Back Yard.

[2] General Algebraic Modeling System; a modeling tool for mathematical programming and optimization. For more information visit the GAMS home page [8].

1.3 Previous work

Several aspects of wave energy conversion have been studied and presented in numerous published papers over the years. Many of these handle the benefits of combining wave energy with other renewables. Different gains are highlighted, and for wave and offshore wind examples like ability to reduce stuctural and maintenance costs when integrating relative to when not integrating [9], reducing the hours of zero power output and reduced interhour variability resulting in an ability to lower and more efficiently use the transmission capacity [10] and less need of reserve capacity and a higher capacity credit [11] have been found. The correlation between the wave power generation and its complementary source will be very important when quantifying the gains. An Irish study [12] compares combining wind power generation with wave power generation on the west and east coast of Ireland, and finds that due to the big difference in correlation the outcome is also very different with the gains being much higher on the coast with uncorrelated wave and wind power generation.

In a study on optimal combinations of solar PV[3], wave and wind power into the electric supply, the conclusion is that the optimal combination, specially of wave and solar PV, seems to depend on the total amount of electricity production from renewable energy sources [13]. It is also stated in that article that "the combinaton of different sources is alone far from a solution to large scale integration of fluctuation resources. This measure is to be seen in combination with other measures such as investment in flexible energy supply and demand systems and the integration of the transport sector".

An early study from 1981 on co-locating wave power and offshore wind power concludes that outside southern Gotland in the Baltic sea, a collocation can be beneficial under certain very limited circumstances [14].

Researchers at the division for electricity at Uppsala University have done a lot of studies on wave power generation [4, 15], often focusing on the more electrical part of wave energy conversion. They have also conducted studies on the wave climate off the Swedish west coast [16] i.e. within the scope of this thesis. Also experiences from their research site in Lysekil [17] have been presented in different papers, handling many different aspects of a wave energy converters in real sea conditions and again within the geographical scope of this work.

When it comes to the model used in this thesis, a lot of earlier work lies behind the construction of it, along with analysis on the dynamics of electricity generation systems that involve high levels of wind power [18, 19]. In this thesis, wave power generation has been added to the model, opening up for the ability to analyse the effects of wave power generation in the system, and its correlation effects with wind power in the area.

[3]Solar Photo Voltaic

2

Background & theory

THE AIM OF THIS CHAPTER is to provide the theoretical background necessary for this thesis. First waves will be described shortly; how they are formed, their characteristics and how energy can be extracted and transferred from them. Then some of the main wave energy conversion technologies will be presented. In the end of the chapter some theory on energy systems modelling will be explained.

2.1 Waves

The waves referred to in this thesis are ocean waves generated by wind, where the wave height is small compared to the wave length. Since wind is a transformed form of solar energy, also wave energy originates from the sun. Winds are generated when the sun shines on earth, heating the air, leading to air movements due to differences in density. Light, hot air rises, increasing the pressure at higher levels and decreasing it at lower levels. These pressure differences in the atmosphere is what drives the winds.

How waves are created when the wind blows over a water surface is somewhat more complex. It starts with a small pressure difference on the surface, appearing due to turbulence in the wind [15]. These differences in pressure will create small discontinuities on the water surface, visible as small waves. A resonance effect between the vertical wind pressure and these small waves, together with sheer stress due to higher wind speeds at the crests compared to the troughs then act upon the waves, making them grow. When they are big enough, other processes take over, the friction of the wind on the water and the pressure differences created by the sheltering effect of the lee side of the wave compared to the wind side causes the waves to continue to grow. The size that the wave ultimately reach depends on three things; wind speed, wind duration and the distance of water over which the wind is blowing; the fetch.

When the waves reach shallow water, they will loose speed, increase in amplitude and change in shape. Due to lost stability, the waves will finally break, as illustrated in

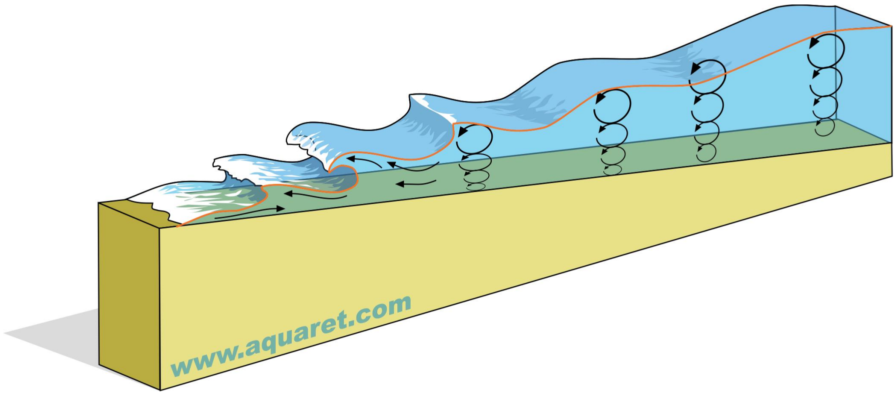

Figure 2.1: An illustration of ocean wind waves, and how their shape changes when propagating into more shallow waters [20].

Figure 2.1. Waves also break at larger depths in strong winds.

2.1.1 Definitions and characteristics

Ocean waves generated by wind are called wind waves as long as they are under the generating influence of the wind. After the wind has passed they keep propagating as swell [21]. Contrary to what it looks like when waves are rolling towards the shore, only very little mass is actually being transported but merely energy [15]. This can be seen if throwing a stick in wavy water; it will move towards the shore with a much slower speed than that of the waves. The water particles within a wave move in circular paths; forward at the wave crests and backward at the troughs. This circular movement is decreasing with increasing depth, as illustrated in Figure 2.2 along with the definition of some important wave properties.

The speed of waves is proportional to its wave length, according to Equation 2.1.

$$c = \frac{\lambda}{T} = \frac{gT}{2\pi} \tag{2.1}$$

where c is the wave speed, λ is the wave length, T is the wave period and g is the acceleration of gravity.

When looking at a stormy sea the typical appearance is often rather chaotic. A variety of waves with different heights, lengths and directions appear and disappear in what seems to be a completely random manner. However, what looks as an unstructured chaos of waves is in fact much more structured, and most wind seas at large depths can actually be described as a combination of a large number of perfect sine waves [15, 22]. As the speed of waves is proportional to the wave length, longer waves will travel at a higher speed than short ones. When the wind has passed by and lost its generating influence on propagating waves, the initial chaotic state will gradually be rearranged into a more arranged and periodic appearance. After a long stretch of water the waves will be arranged after wave length. When approaching the coastal line in absence of winds, wide, periodic waves will be rolling in, hitting the shore.

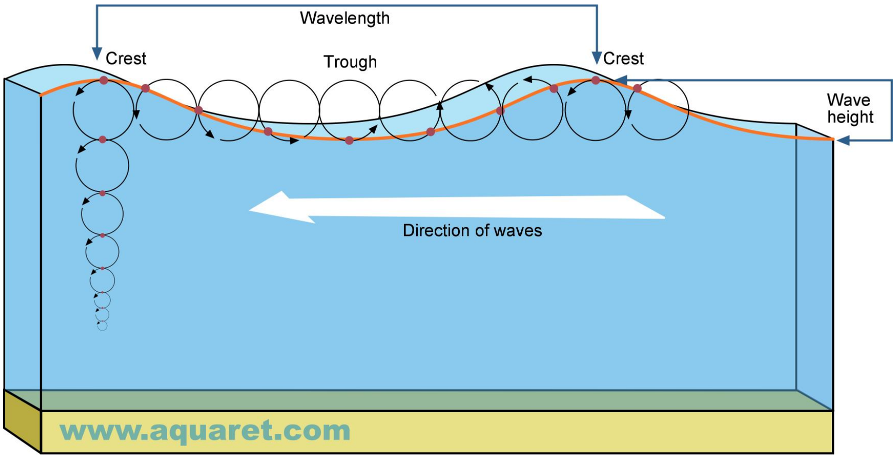

Figure 2.2: The definition of wave height and wave length. Also, an illustration of the circular movement of water particles in a wave, and how it is reduced with increased depth [20].

2.1.2 Wave energy

The total energy of a propagating wave front is the sum of its potential and kinetic energy [23]. The potential energy can be understood as the work needed to shape the wave profile, lifting water against gravity between the crests and the troughs. The kinetic energy is the sum of each water particles movement, its kinetic. Only the latter will propagate with the waves, while the potential energy shapes the surface and puts the water molecules in motion.

When waves propagate across the oceans, energy is transported with very low losses [22, 23]. In a natural state, this energy would ultimately transform into heat due to friction and breaking of the waves at the coasts.

Generally, the energy flow of ocean waves is expressed as the average power per meter wave front [W/m]. It can be explained as the average energy per second passing under one meter of wave crest from the surface to the sea bed [15]. However, the energy is not evenly spread over the depth of water, it is found to decrease exponentially with depth. Normally, 95% of the energy is captured in depths above one fourth of the average wave length [23].

The energy flux per meter front width, P, in surface waves can be calculated from the significant wave height and the energy period according to Equation 2.2.

$$P = \frac{\rho g^2}{64\pi} T_E H_{m0}^2 \tag{2.2}$$

where ρ is the density of water, T_E is the energy period, and H_{m0} is the significant wave height. Note that this equation is only valid for surface waves at water depths larger than half the wave length.

The density of sea water is about 850 times the density of air. Since kinetic energy is proportional to mass, a lot of energy is in motion when water waves propagate, which is also why the energy density of waves is high compared to other renewables, such as wind and solar.

2.1.3 The wave energy resource

Wave energy is a variable resource in the sense that the energy output at any instant is uncontrolled by humans. Instead it is governed by something beyond our control, in this case wind or more strictly the solar irradiation through the atmosphere. It is often possible to forecast the power of waves and their occurrence in a specific region a certain time period in advance, but it is not possible to control or govern the waves themselves. An advantageous feature of wave energy is its persistence, meaning that the most likely output from a wave energy converter the next hour is the same as during the previous hour [3]. Although the global wave potential is only a small share of the global wind potential, which in turn is only a minor share of the global solar potential [24], it is still an enormous source of renewable energy.

The wave energy resource can be defined in different ways. The theoretical resource i.e the hydrodynamic power captured in the ocean waves or the global wave energy flux was already in the seventies estimated to be in the order of 1-10 TW [25]. Later estimates have confirmed this result [24, 26, 27] with slightly different numbers depending on how potential is defined. The share of this energy hitting the coasts has been estimated to be around 1 TW [2, 4, 24]. How much energy that can be technically and economically harvested from waves varies enormously in the literature, with estimates in different sources ranging from 2 000 TWh to even 80 000 TWh. To put this in perspective; the annual global electricity generation in 2011 was a bit more than 20 000 TWh. Despite the fact that the estimates of the exploitable limit of wave power is so varying, the conclusion in any case is that wave energy most certainly could contribute to human energy needs globally.

As the energy from the sun is transferred into wind, the power flow is concentrated from typically 0.1-0.3 kW/m^2 horizontal earth surface to 0.5 kW/m^2 perpendicular to the wind. As energy is transferred further into ocean waves, just below the ocean surface the intensity is typically 2.3 kW/m^2 perpendicular to wave direction [24]. This stepwise increase in energy intensity is one of the advantages with wave energy.

The average energy flux hitting the coasts at the southern tip of South America, the Falkland Islands or parts of New Zeeland might be as high as 100 kW/m [15]. In contrast to this, our relatively mild wave climate on the Swedish west coast is in the range of just over 5 kW/m. Outside Norway the energy flux is about a factor of 10 higher. In Figure 2.3 the annual theoretical global wave power potential can be seen.

Areas where strong winds have travelled over long distances have the best wave resource. Therefore deep, well exposed waters offshore have a higher energy content, and the energy decreases due to friction with the seabed when approaching the coastline.

Figure 2.3: World wave energy resource. The numbers represent average energy flux [kW/m] [28].

2.1.4 Wave power technologies

Wave energy converters can be located on the shoreline, near shore or offshore. As already mentioned, there is a large variety of technology concepts. Many are designed to have a relative motion within the system. The technologies are often modular, meaning that the number of converters in each farm can be varied independently and thus a wave park can easily be scaled.

An important design parameter is what kind of sea state the converter will be subject to. In large ocean swells the device will experience large, slow forces, and in order to cope with this a large mass and more inertia to produce power is required. On the other hand, in more shielded oceans where the waves are smaller it is beneficial to have a small and light device, which can utilize the higher velocity of the motion. There are also concepts utilizing a turbine to generate electricity.

One difficulty for many technologies is the rare but recurrent occasions with waves being much larger than normal. Ways to handle this, as for example lowering a floating device underneath the surface, are under development.

In this section some major wave energy converting systems will be described briefly to give an overview of the multitude of technologies. This whole section is based on information presented in previous descriptions of wave power technologies [3, 20]. In Figure 2.4 illustrations and some photos of the different technologies can be seen.

I Point absorber

A point absorber is a floating body attached to a fixed device, often at the sea floor. Wave energy is absorbed from the relative motion between the floating and the fixed part of the system, either in a hydraulic system or by using a linear generator.

Point absorbers can be designed for different wave climates by adjusting the diameter and the weight of the floating device, larger and heavier devices fits with longer and slower waves.

The park now being built outside Sotenäs will have point absorbers with linear generators, built by the Swedish company Seabased [29].

II Attenuator

Attenuators are long, floating, segmented devices, aligned perpendicularly to the wave front. When the wave passes along the device, the different segments will move in relation to each other, in a bending motion. This movement is concentrated in the connection points, where a hydraulic piston is pressurised, pushing fluid through a motor which drives the generator.

The length of each segment of the attenuator should not be shorter than one quarter of the wave length, to avoid counteraction between different segments. Thus this technology is more suitable far offshore, with larger waves.

Since the attenuator should be aligned perpendicular to the wave front, a mooring system is needed, usually attached to the front of the device, allowing the attenuator to turn slightly on the sea surface.

III Over-topping devices

An over-topping device consist of a wall over which the waves crash, and a basin in which water is collected. The water creates a head of water, and when the water is released back to the ocean it flows through a turbine at the bottom of the basin, which absorbes energy. This device can be both on- and offshore, and if offshore either floating or fixed.

An advantage with the design is that it uses the same technology as in conventional hydro power plants; a very well known and mature technology.

IV Oscillating Water Column

This technique consists of a partially submerged, hollow structure, open to the sea below the water surface and to the air at the top, through a turbine. The waves will make the water surface rice and fall, compressing and decompressing the capsuled air, which will flow back and forth trough the turbine.

V Oscillating Wave Surge Converters

An oscillating wave surge converter is normally mounted on the sea floor, with a hinged plate or flap that is capturing energy from the wave surge by moving like an inverted

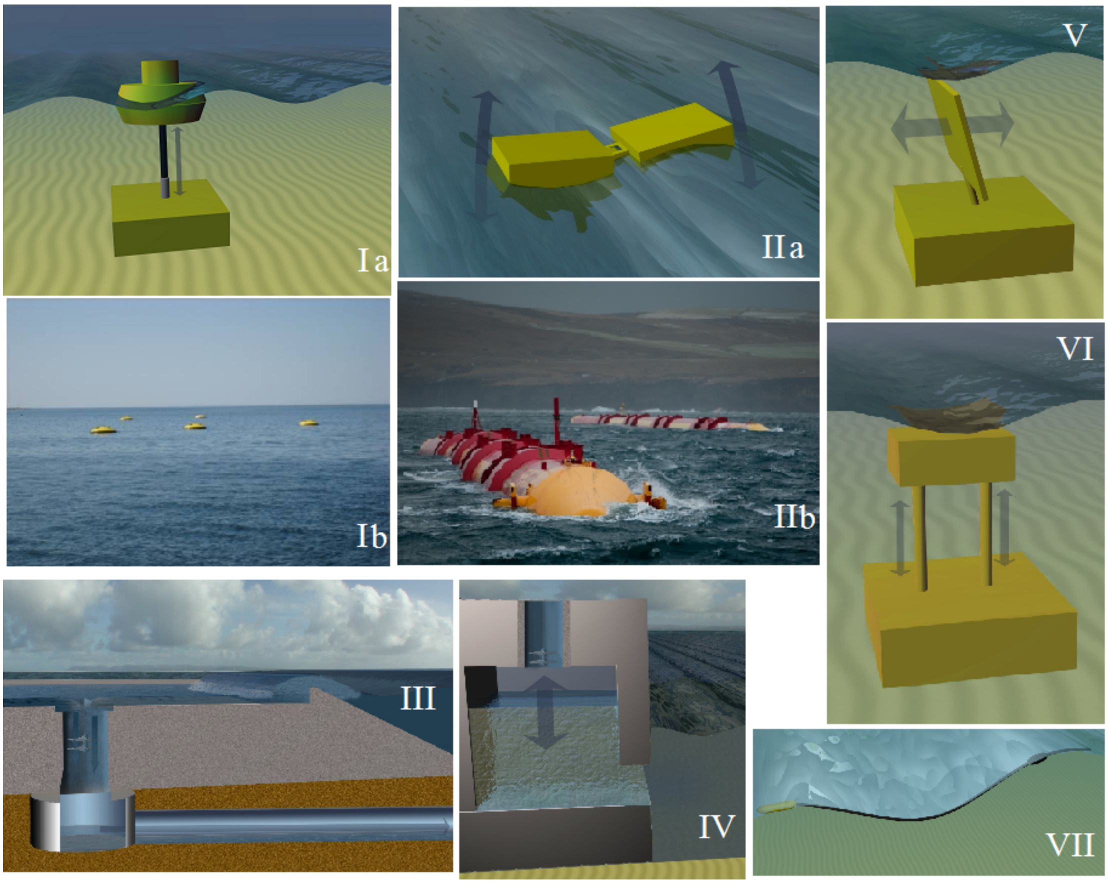

Figure 2.4: Illustrations of some wave power technologies. Ia Point absorber [20], Ib Photo of Point absorbers from Seabased [29], IIa Attenuator [20], IIb Photo of the Pelamis Attenuators, III Over-topping device [20], IV Oscillating Water Column [20], V Oscillating wave surge converters [20], VI Submerged pressure differential device [20], VII Bulge wave technology [20].

pendulum under the water surface. The energy is extracted via hydraulic converters. There are also example of devices floating under the surface, not mounted on the seabed.

VI Submerged Pressure Differential Devices

A partially merged device, placed close to the surface will experience pressure differences when the waves varies the sea level and thus the pressure above the device. This will make it oscillate along with the waves, generating electricity in a generator normally mounted on the sea floor.

VII The bulge wave technology

The bulge wave technology consist of a rubber hose floating on the water surface, connected to a turbine and a generator at the seabed. When sea water enters the hose, water and air batches are creating a bulge, which will grow as it travels along the hose. The water bulge will drive a turbine at the end of the hose, where the water returns to the sea.

2.2 Energy systems

The main task of the electricity generation system is to satisfy the demand of electricity at any instant. Historically, this has been done by burning fossil fuels. For conventional fossil fuel plants there is a trade-off between low running costs and flexibility [19]. A coal-fired power plant in general has low running cost but high start up costs, while the opposite is true for gas turbines which generally are not so expensive to start but very expensive to run.

The demand for electricity follows a daily pattern, with recurring peaks and periods of lower demand. The electricity system is currently designed so that the power generating units with low running costs cover the demand which is continuous throughout the week, while more flexible units with higher running costs cover the peak demand during working hours [19]. Thus, the running costs and flexibility will determine the dispatch of the electricity generating units in the system.

Unlike load variations, the variations of wave and wind power generation will not follow any specific pattern. Instead the variations are more irregular, hence the discussion of intermittency. On the other hand these technologies will have no start-up costs and unbeatable low running costs compared to thermal generation. Therefore, the combination of units that satisfies the demand at the lowest cost in every time step will depend on available wave and wind power generation. Also, due to the very high costs associated with starting a thermal unit, the level of wave and wind generation several hours both back in time as well as ahead in time will be important when minimizing the total system cost.

Apart from the high start-up costs that fossil-fueled plants with low running costs are associated with, they are also typically rather inflexible and less efficient when running on part load. Therefore there is an economic incentive for reducing variations in an electricity generation system. Thus, if a combination of wave and wind would allow smoother generation for the other units in the system compared to with wind or wave separately it would be beneficial for the system.

2.2.1 Computer modelling of energy systems

The term energy system can refer to anything from the combustion process in a boiler to the global fuel market or the electricity generation system in Sweden, depending on the system boundaries. Normally, when constructing a computer model of an energy system, not all parts can be described in detail due to issues of complexity and computational times. Which part of the system to describe in detail and where to simplify depends on what aspect of the system that will be studied. There are many different modelling techniques, and the question asked that the model aims at answering will govern the model design. A common approach is to combine several types of models in order to give a good description of the system, leading to appropriate results.

Energy system models are commonly classified as either being top-down or bottom-up models [30, 31]. Traditionally, top-down models aim at describing the entire macro economy, including the energy system as a part of this description. Then energy demand is a model result, governed by the relations described within the model. Entire sectors of the energy system are often modelled in a highly aggregated way, e.g a certain level of electricity can be produced with a certain input of labour and capital, expressed as a function for production.

In contrast to top-down models, bottom-up models focus on the technological aspects of the energy system, which are modelled with a high level of detail. For each technology, properties such as performance data and costs are specified separately. In bottom-up models, the demand for energy is treated either as a function of for example energy prices, or as a given input parameter [31].

Another common classification of computer models is as either being normative or descriptive. A descriptive model is designed to answer questions like *If this is what we know, what happens if ...?*, while a normative or prescriptive model rather would answer questions like *If this is what we want, how do we best ...?* When applied on large systems, open descriptive questions are often difficult to answer since it is hard to accurately capture the required level of detail.

Normative models are formulated as optimisation problems, with an objective function that shall be maximized or minimized. For example; if the aim is to reach a certain reduction in emissions at the lowest cost, the objective function would be the total system cost and there would be constraints on the emissions while the model would minimize the objective function i.e the total system cost. When constructing an optimisation problem, perfect foresight is usually assumed, e.g all future costs are assumed to be known with certainty. However, since in reality they are not known with certainty, the results from a normative model should rather be considered as a description of possible future scenarios than as a forecast.

The model used in this thesis is a normative, bottom-up optimization model, asking the question *How do we best satisfy the given demand of electricity, with the power generating units we have, at the lowest total system cost?*

The model is also a dispatch model, meaning that it includes the constraint that generation must equal the demand for electricity in every time step.

Since binary variables are used the model can be classified as a binary integer programming model, in order to account for cycling costs in thermal units as described in Section 2.2.2. It will lead to longer computational times compared to a non-integer model. However, since it is not a non-linear model, it will be more transparent and the effects from constraints will be easier to identify.

2.2.2 To account for flexibility in thermal generation

As already discussed, variability in generation is an unwanted property from an electricity generation systems perspective, burdening many renewable sources. Thus in an electricity generation system with a high penetration of renewables, flexibility is a desired property of the generating units, something that thermal units such as nuclear reactors or coal power plants generally lack. Cycling thermal units i.e. running them on part load or with frequent start/stops is associated with an increase in costs and emissions [19]. The magnitude of these additional costs and emissions depends on fuel type, unit size and technology. Good estimates of these costs are generally difficult to acquire, because the full cost of starting a unit or operating it on part load is often not fully known by the plant owner. The cost from thermal stress on materials will show up as increased operation and maintenance costs years later. Research shows that cycling units affects the system and the system costs [19], and the uncertainty in these costs should not be taken as a motive to disregard them.

In this thesis a Mixed Integer Programming-, MIP-approach [19, 32] has been used to account for flexibility related properties of thermal generation. This enables inclusion of the technical limitations of each thermal unit separately in the optimization. When considering that units have a minimum load level and that there is a start-up cost when starting a unit, the impact of changes on the systems are often difficult to foresee.

When considering start-up costs, $Z_{start_{i,t}}$, that cost shall be added to the total system cost every time a unit is started. In the MIP-approach, the binary variable $spin_{i,t}$ and the indirect binary variable $on_{i,t}$ are created to handle this. The value of $spin_{i,t}$ is set by equations 2.3 to 2.5.

A thermal unit can only be spinning in time-step t if it was spinning at $t-1$ or started T_{start} time-steps earlier, where T_{start} is the start-up time for the unit. This can be expressed as:

$$spin_{i,t} \leq spin_{i,t-1} + on_{i,t-T_{start}} \tag{2.3}$$

If the thermal unit was started T_{start} time-steps ago it must be spinning. Therefore:

$$spin_{i,t} \geq on_{i,t-T_{start}} \tag{2.4}$$

A unit with start-up time, $T_{start} \neq 0$, cannot be started when spinning. It holds that:

$$spin_{i,t} + on_{i,t} \leq 1 \tag{2.5}$$

If $spin_{i,t} = 0$, the unit is not spinning, and the model will set the generation from this unit to zero. If the unit it running, i.e. $spin_{i,t} = 1$, the generation is bounded by the upper and lower generation limits of the unit, $g_{up_{i,t}}$ and $g_{low_{i,t}}$;

$$spin_{i,t} \cdot g_{low_{i,t}} \leq g_{i,t} \leq spin_{i,t} \cdot g_{up_{i,t}} \tag{2.6}$$

The main disadvantage of this method is the calculation time which grows quickly with number of units in the system. Thus, this method is not suitable for very large systems with many generating units.

3

Method

Before implementing wave power generation to the model the weather data was analysed to gain a better understanding of the wave climate and also the correlation between wave and wind energy. Four methods on transferring wave data into wave farm output was used and compared. Also some variability measures was calculated on a constant output of 30 TWh from wave and wind power together but with different shares of the two sources.

When investigating the value and effects of wave power generation in the electricity system of southern Sweden, a cost-minimizing model of the system has been used. The construction of this model has not been part of the thesis, and further analysis on the model and the construction of it can be found in previous work with the model [18, 19]. Some parts of the model relevant for the analysis will be highlighted in the end of this chapter.

3.1 Input data

Most input parameters needed for the modelling were found in previous work with the model, apart from all things relevant for wave power generation. Parameters such as costs, emissions, start-up times, efficiencies, maximum and minimum capacities have been given separately for each power plant or technology in the model. The numerical values can be found in Appendix A.

The demand curve has been based on historical data over electricity consumption in Sweden, from ENTSO-E. This data has then been scaled, based on GDP-data over separate Swedish regions from Eurostat. All this was done in previous work with the model. The annual restriction on hydro power generation has been set based on data from Nordpool [33].

The time resolution of the model is in steps of three hours, limited by the resolution of the wave and wind data.

The power output curve used for filtering the wind data can be found in previous studies using the same weather data [34].

3.1.1 Wave data

The wave data used in this study is from the European Centre for Medium-Range Weather Forecasts, ECMWF [35], given as energy period, peak period and significant wave height. Data from the years 2007 to 2009 has been used.

To avoid the results being applicable to one year only, an average annual energy has been estimated based on three years, and then the wave pattern in every time step has been taken from year 2007. This is the same method as previously used for the wind power generation in the model.

The geographical resolution is $0.25° \cdot 0.25°$, corresponding roughly to $15{\cdot}25$ km^2 in Northern Europe, see Figure 3.1. In this figure, parts of Sweden, Norway and Denmark can be seen, and the grid of dots illustrates points where data is available. It is a part of a global grid, used also for other parameters not relating to oceans and thus there are also land based points. For wave parameters these points are of course not valid, and they are not represented by numerical values. A square around each point has been assumed to have the same wave climate, stretching to the square of the neighbouring point.

3.2 Electrical energy from waves

When energy is absorbed from ocean waves and converted into electricity there are inevitable losses. A rule of thumb is that 20% of the energy in the waves can be converted into electricity [3, 6, 36]. Since better accuracy was desired in this thesis, four other ways of turning wave energy into electricity have been modelled and compared.

When it comes to wind power generation, power curves are commonly used in the calculations converting wind energy into electricity. The curve initially grows until reaching a plateau where the power level stabilizes. At winds stronger than what the turbine is designed for the turbines can be stopped manually, hence there is normally an upper limit on wind speed.

The power in ocean waves depends on two variables, wave height and energy period, and thus the same approach would lead to a power matrix, with an output power level for each combination of wave height and energy period i.e for every wave climate.

A common approach for point absorbers is to assume that the stroke of the system is not limiting. Then, a power curve similar as for wind power could be constructed, where the power generated depends only on the energy period. In Figure 3.2 an efficiency curve depending on energy period can be seen [37], with data from measurements on a prototype named Elskling. It is a point absorbing oscillating water column, today further developed by the Swedish company Waves4Power [38]. This curve, further on referred to as the Elskling curve, together with the energy content calculated from the significant wave height and the energy period gives the power output in every time step.

This has been one method out of four within this thesis to get the power output curve over the year from wave power.

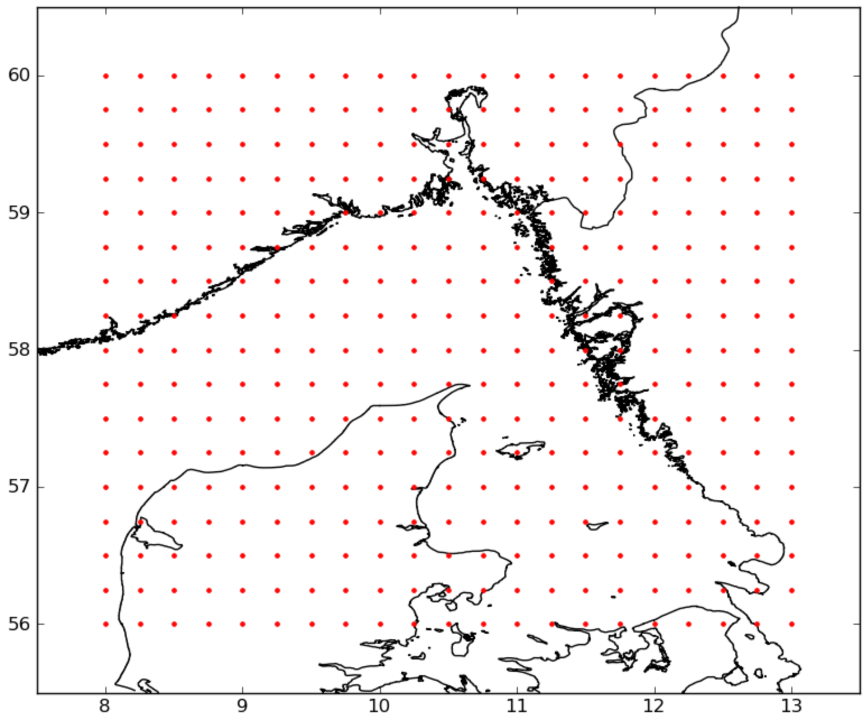

Figure 3.1: The area under investigation, with wave data available in every offshore dot. The numbers on the axes represents the latitude and longitude for the region.

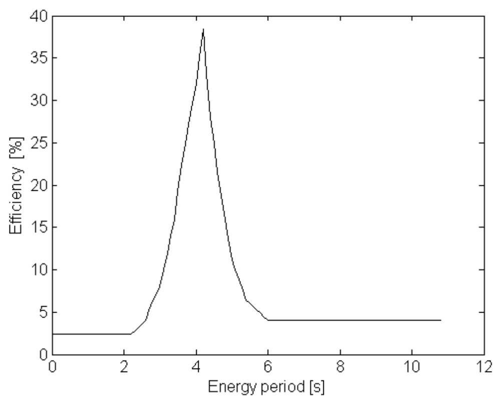

Figure 3.2: The efficiency when converting wave energy into electricity for different energy periods [37], referred to as the Elskling curve. Together with the significant wave height and the energy period in each time step this gives the power output in every time step.

The other three ways of simulating electricity generation used three different theoretical power matrices from a numerical modelling study, presented in Figure 3.3 to 3.5 [39]. These three matrices were chosen out of eight presented in the study, the choice based mainly on performance in the wave climate of the study and requirements on water depth. The first two technologies are point absorbers; a small bottom-referenced heaving buoy, Bref-HB, and a bottom-referenced submerged heave-buoy, Bref-SHB [39]. The Bref-HB has a linear generator and the Bref-SHB is submerged and uses a hydraulic power take off unit. The third technology, a bottom-fixed heave-buoy array, B-HBA, consists of many floats connected to a single fixed reference standing on the sea bed, and power is absorbed hydraulically from the relative motion within the system as the floats heaves with the waves.

The numbers given in the matrices are the power output in kW. The difference in magnitude for the three tables reflects the size of a single installation. In this thesis the output has been scaled to a common penetration level in all cases.

Due to the calm wave climate in the area of this study, a relatively large share of the power is in climates outside of the matrices shown in Figure 3.3 to 3.5. However, the researchers of the study were contacted and more extensive data was used for significant wave heights down to 0.5 meters.

When applying the matrices on the wave data linear interpolation was used for values in between the given values in the matrices. Note that the period in the matrices is the peak period, which also was available from ECMWF.

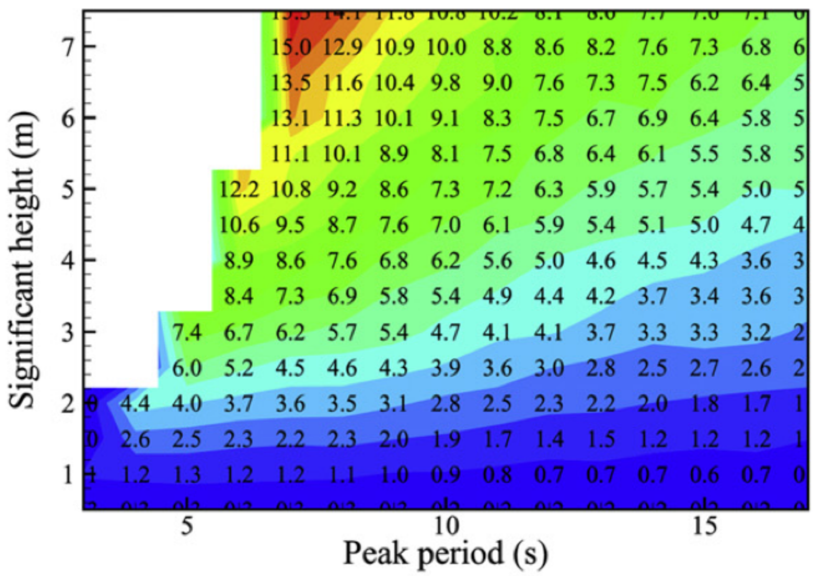

Figure 3.3: The power matrix for the small bottom-referenced heaving buoy, Bref-HB, with the output in kW [39].

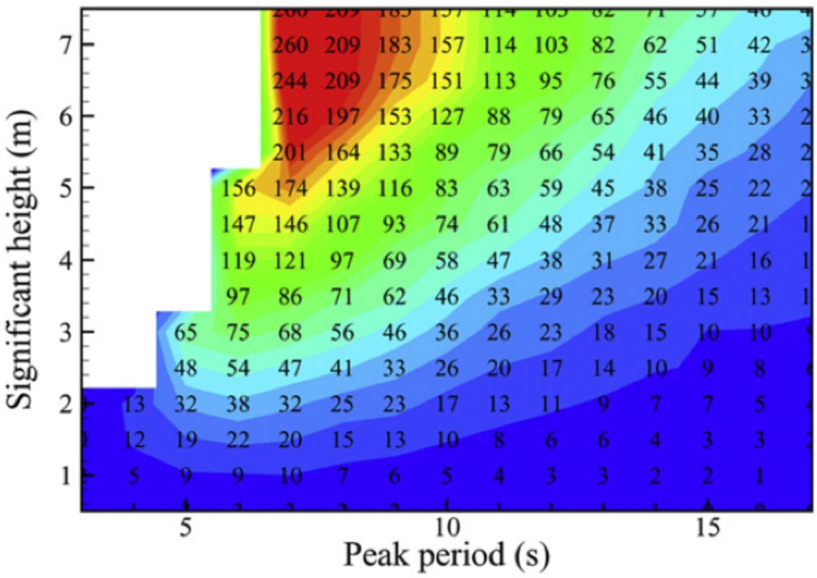

Figure 3.4: The power matrix for the the bottom-referenced submerged heaving buoy, Bref-SHB, with the output in kW [39].

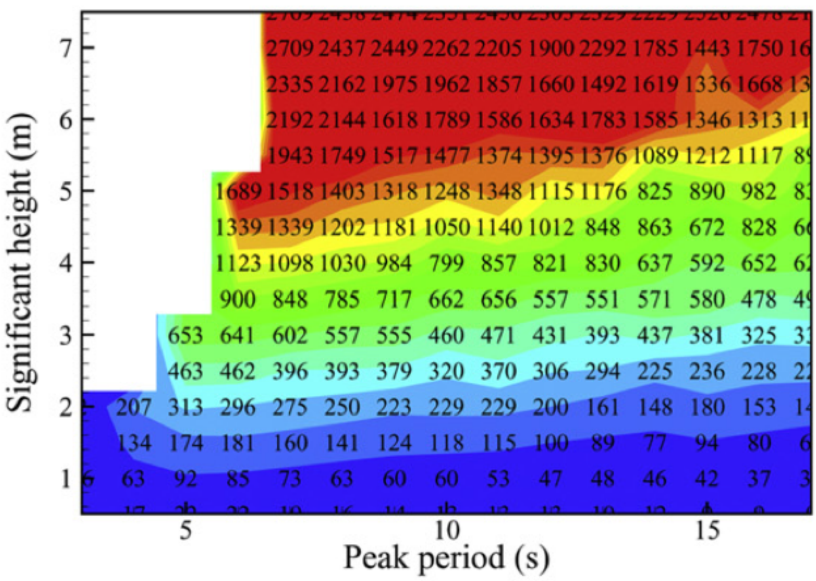

Figure 3.5: The power matrix for the bottom-fixed heave-buoy array, B-HBA, with the output in kW [39].

From the wave data a time series of the available wave power resource could be generated, both by using the Elskling curve and the matrices. These output curves could then be scaled into desired penetration level when added to the model. The base scenario has been a wave power generation of 6 TWh/year based on estimates on the potential off the Swedish west coast [3, 36], along with a belief in technological development. Higher penetration levels have been tested in the model, from a more theoretical point of view when investigating the potential benefits of combining wave and wind energy and the difference in how they affect the electricity generation system.

3.3 Installed capacity

To assume that a wave power installation has no cutoff, i.e that at any instant the maximum available power in the waves is extracted considering only wave climate and losses is not reasonable. Also the aspect of economics, thus the installed capacity must be taken into consideration. Dimensioning an installation after the instant maximum generation over a year, which might only occur once or very few times will not pay back. In this thesis, a cutoff has been set where the installed capacity still generates 95% of the theoretical maximum annual energy [40]. This will flatten the output peak from wave power and lead to several time steps at rated capacity, as will be discussed further in section 4.1.2.

The scaling can be understood as a cutoff in the generator capacity. In practice, this cutoff will mean that there are ways for the wave energy converter to not fully absorb the full power in the waves, e.g by letting waves pass over, drain out, increase the resistance or have an upper limit on the relative movement within the system. It should not be confused with the scaling of the wave farm or number of wave energy converters.

3.4 Cost comparison

A mature technology, which has experienced reduced production costs with increased production and learning by doing will stand a better chance of being less costly than an emerging technology. Today this is the case of wind power compared to wave power. If however wave power has a higher capacity factor than wind power, more energy will be generated on an annual basis from a given level of installed capacity of wave power than if installing an equal capacity of wind power. The capacity factor of a generating unit is the energy generated annually divided by the theoretical maximum energy that could be generated i.e the rated capacity times 8760 hours/year. More energy generated per installed capacity implies that wave power can be somewhat more expensive per generator capacity, without generating energy at a higher cost per unit of energy.

Moreover, if either wave energy or a combination of wave and wind has a less variable production pattern than wind, and if this leads to a lower system operational cost when installing a combination of wave and wind compared to wind only; also this would allow wave energy to cost more per generated unit of energy and still benefit the system.

The point of break even will be when the cost of a given installation of wave energy equals the cost of the level of wind power that generates as much energy on an annual basis plus the cost savings from having wave power in the system.

This equality is expressed in Equation 3.1. Here the cost of wave power is expressed as the factor b times the cost of a wind power installation. Since Δ is the cost saving for a specific year, the investment cost must be annualised for a fair comparison. The annualized investment cost for wind power has been set to 0.16 M€/MW·year [41].

$$c_{wind}P_{wind} + \Delta = b \cdot c_{wind}P_{wave} \tag{3.1}$$

where c_{wind} is the cost of wind power, P_{wind} is the capacity of wind power, Δ is the reduction in total system cost when having wave power installed compared to only wind and P_{wave} is the capacity of wave power. From this expression, the factor b, revealing how much more the wave power resource is allowed to cost can be found, expressed as in Equation 3.2.

$$b = \frac{P_{wind}}{P_{wave}} + \frac{\Delta}{c_{wind}P_{wave}} \tag{3.2}$$

The first term in Equation 3.2 refers to the difference in capacity factors between wave and wind, while the second term is linked to the model result of this thesis, the system operational cost savings modelled in GAMS.

3.5 Variability measures

To investigate and compare the variability of the wave and wind resource, two measures of variability have been used; standard deviation, Std, and Value at Risk, VaR. With these measures the possible benefits of combining wave and wind energy has been investigated, and they have been used when seeking explanation to the model results. The annual output from wave and wind power generation together was scaled to 30 TWh in all cases, with varying shares of wave and wind power generation.

Value at risk, VaR, is a measure of the level of the lowest or highest outcomes [34]. For $\alpha \in [0,1]$, the α-VaR is a threshold value, such that the probability that the outcome is below this value is 1-α. In this thesis, VaR with α of 0.1 and 0.9 has been calculated, further on referred to as 90-VaR and 10-VaR. Then 90-VaR is the level where there is a 10% risk that the output is below and 10-VaR the level where there is a 90% certainty that the output is below i.e there is a 10% risk of higher values than the 10-VaR value.

The standard deviation, defined as in Equation 3.3, tells how much variation there is from average. A higher standard deviation implies more fluctuating values.

$$\sigma = \sqrt{\sum_{t=1}^{T}(x_t - x_{t-1})^2} \tag{3.3}$$

where T is the total number of time steps.

The net load, defined as the demand in every time step minus the electricity generation by wave and wind together in that time step, is hypothesized to be interesting in these calculations. A high net load implies that there is a large need for power from other sources and thus it might imply increased fuel costs from peak generation, i.e back-up capacity, if addition of hydro and nuclear is not sufficient. A low net load means that not much additional power than wave and wind is needed and thus depending on the size and duration of the low-net load-periods it might lead to curtailment of wind/wave or cycling[1] of nuclear units, with the risk of imposing future start up costs.

Using these measures, the connection between the 10-VaR values and the fuel cost for peak generation along with the correlation between the 90-VaR values and the start-up costs for nuclear power will be further investigated for different shares of wind-and-wave of the 30 TWh/year of variable generation in the system. Starting a thermal unit is very costly, so if that can be avoided a lot of money can be saved. A lower standard deviation for the net load might give the possibility to run remaining generating units in the system more continuously, which is better from a system perspective both when it comes to costs, efficiencies and emissions.

3.6 Modelling

The objective of the model used in this thesis is to minimize the total system cost while ensuring that the demand for electricity is satisfied at any instant. The model only considers operational cost, and does not consider any investments of the generating units. Thus, difference in capacity factor between wave and wind is not obvious for the model, but only the output curves of the annual generation. The model optimizes the system every third hour, over the course of one year. The temporal resolution is restricted to three hours because of the resolution of the weather data. Further analysis of the model approach and the construction of it can be found in previous studies [18, 19].

The area under investigation in this thesis is southern Sweden, and the generating units in the system are ten nuclear reactors, wind power generation, peak power capacity comprising gas power plants and import of electricity from hydro power. The nuclear reactors have been modelled individually, while hydro power has been modelled as an import from northern Sweden, with an energy balance restricting the maximum annual use. This restriction was set to 29.2 TWh, based on statistics from Nord Pool [33]. When running the model on shorter time scales, the same statistics was used for intra year restrictions.

Available wind power generation has been given as an input to the model in every time step, taken from output data of the EPOD-model, also developed at Chalmers and based on weather data for the region and for the same year. For the peak generation, input parameters such as fuel costs, emissions, variable costs etc. was given in an aggregated way.

Electricity from combined heat and power generation is excluded from the model, since demand for heat and not electricity is governing the production of these units.

[1]Cycling means part-load operation and start-ups and shut-downs of a unit.

Because of this, the electricity demand had to be reduced to not underestimate the available power generation in the system. A scaling factor of 75% was used, making the total demand in the model 95 TWh/year. The scaling factor was set so that there was seldom that nuclear and hydro power was not sufficient to satisfy the demand. In this system, the 30 TWh variable production from a mix of wave and wind power represents a third of the total annual generation in the system. With one third being supplied by hydro power that leaves one third to be supplied by nuclear power and peak capacity.

3.6.1 Minimizing total system costs in GAMS

The total system cost, Z_{tot}, consists of three parts; generation costs, start-up costs and cost penalties for running on part load, as can be seen in Equation 3.4 [18, 19]. These three costs are calculated separately for every generating unit i, in every time-step t. This equation is the objective function of the model.

$$Z_{tot} = \sum_{i,t} \Big(Z_{i,t} \cdot g_{i,t} + Z_{start_{i,t}} + Z_{punish_{i,t}} \cdot (spin_{i,t} \cdot g_{up_{i,t}} - g_{i,t}) \Big) \tag{3.4}$$

The generation cost, $Z_{i,t}$ is depending on fuel costs, efficiency, emissions and variable running costs:

$$Z_{i,t} = \frac{Z_{fuel_{i,t}}}{\eta_i} + \frac{e_{CO2_{i,t}} \cdot Z_{CO_2}}{\eta_i} + Z_{O\&M_{i,t}} \tag{3.5}$$

where $Z_{fuel_{i,t}}$ is the fuel cost, η_i is the efficiency, $e_{CO2_{i,t}}$ is the CO_2 -emissions, Z_{CO_2} is the price of emission allowances and $Z_{O\&M_{i,t}}$ is the variable order and maintenance costs of each plant. Note that this cost must be multiplied with the generation in every time step before adding to the total system cost.

The start-up cost, $Z_{start_{i,t}}$, is represented by the cost of running the plant on part load during the start-up time. When running on part load the efficiency is lower, and therefore this cost can be expressed as:

$$Z_{start_{i,t}} = T_{start_i} \cdot \frac{g_{low_{i,t}} \cdot Z_{fuel_{i,t}}}{\eta_{partload_i}} \tag{3.6}$$

where T_{start_i} is the start-up time of the plant, $g_{low_{i,t}}$ is the lower generation limit of each unit and $\eta_{partload_i}$ is the minimum efficiency when running on part load. Since the nuclear power plants are the only generating units with start-up time greater than zero, these are the only units associated with a start-up cost. Due to these costs, it can be beneficial to keep a unit running in order to avoid the future start-up cost.

The cost penalty for running on part load depends apart from fuel costs and emissions also on the size of the unit and both the optimal and part load efficiency, expressed as:

$$Z_{punish_{i,t}} = \frac{1}{g_{up_{i,t}} - g_{low_{i,t}}} \left(\left(\frac{Z_{fuel_{i,t}}}{\eta_{partload_i}} + \frac{e_{CO2_{i,t}} \cdot Z_{CO_2}}{\eta_{partload_i}} \right) - \left(\frac{Z_{fuel_{i,t}}}{\eta_i} + \frac{e_{CO2_{i,t}} \cdot Z_{CO_2}}{\eta_i} \right) \right) \tag{3.7}$$

where $g_{up_{i,t}}$ is the upper generation limit of the units.

4

Results

IN THIS CHAPTER, the main results of this thesis will be presented. For clarity, the results are divided into five parts. The five topics are; Wave and wind power within the area, Correlation between wave and wind power, Variability measures, Model results on both separate months and on full year and Cost comparison.

4.1 Wave and wind power within the area

This section will be further divided into two parts; one part looking at the raw data of wave power, leading to a theoretical maximum power available in the waves. The other part considers the wave and wind data after being subject to a power curve or power matrix. All wind data will be after being subject to the power curve since this has been the input data to this thesis.

4.1.1 Raw wave data

The analysis in this first section of the results is on the theoretical wave power resource, without considering any power matrix or transfer function into electricity. The power generating potential in the area, calculated with Equation 2.2 in every data point, is presented in Figure 4.1. Note that the values have been normalised for better illustration. The highest power generating potential is found in the Atlantic waves hitting the western coast of western Denmark. However, an area of higher power availability than most part of the Swedish coastal line can be identified, located around 58N, 11E. Figure 4.2 is a zoomed in version of Figure 4.1, and it illustrates this area that further on will be referred to as the high potential area. It is spread over six data points, and within this area is where the wave power converters have been assumed to be located when implemented in the model. The specified point, Point 1 will be used when further investigating the correlation in the area.

In Figure 4.3 the theoretical wave power available in every hour of the year in the

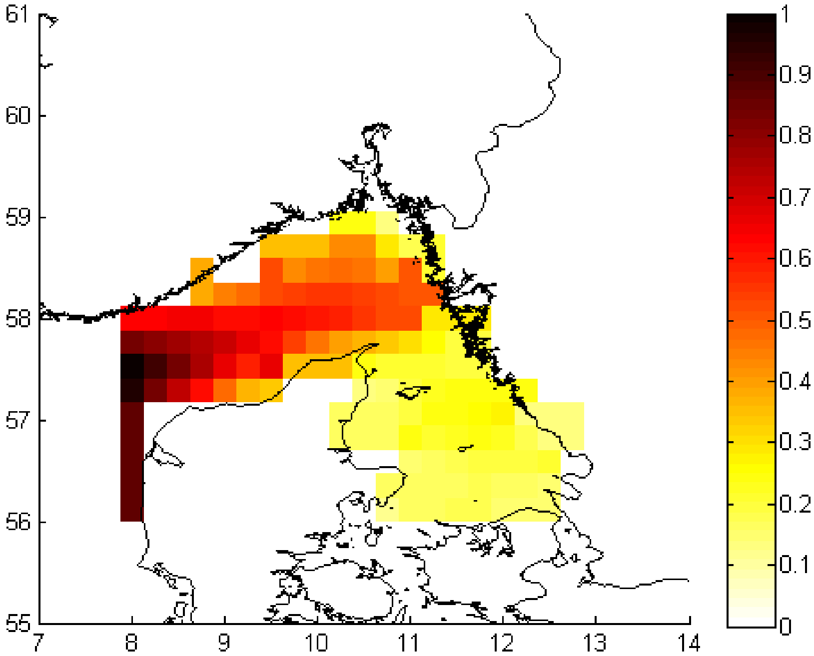

Figure 4.1: The normalised theoretical wave power generating potential in the investigated area. A stretch of higher power content can clearly be seen. The numbering on the axes are the coordinates of the region.

investigated area is presented, along with the duration curve. Here the three hourly raw data has been turned hourly by linear interpolation. The annual average wave power available in the high potential area is about 6.2 kW per meter wave front.

When further investigating the correlation between the available wave power in different parts of the area it was found that the wave climate was identical in three out of six points in the high potential area. Since waves can travel a short distance with very small energy losses, this could be expected. The correlation with other points was also high, specially with the closely located ones. In Figure 4.4, the correlation of the power generating potential in Point 1 from Figure 4.2 with every other data point in the area has been tested. A number 1 on the color scale represents identical time series, illustrated by dark red color. A number 0 on the color scale would imply totally uncorrelated time series. Note that points with low correlation to Point 1 still probably have a strong correlation to their neighbouring points. Note also that the color scale here goes from 0.5 to 1 because of the high correlation in the area.

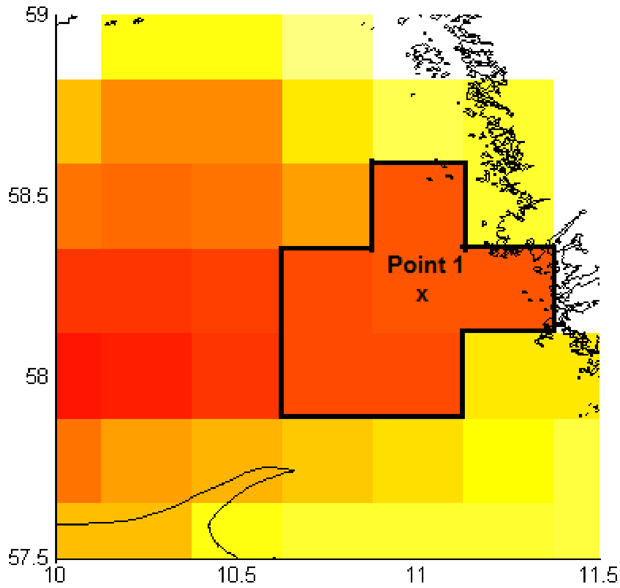

Figure 4.2: A zoomed version of Figure 4.1. The indicated area will further on be referred to as the high potential area. Point 1 will be used for investigating correlation coefficients between waves in different parts of the region. The numbering on the axes are the coordinates of the region.

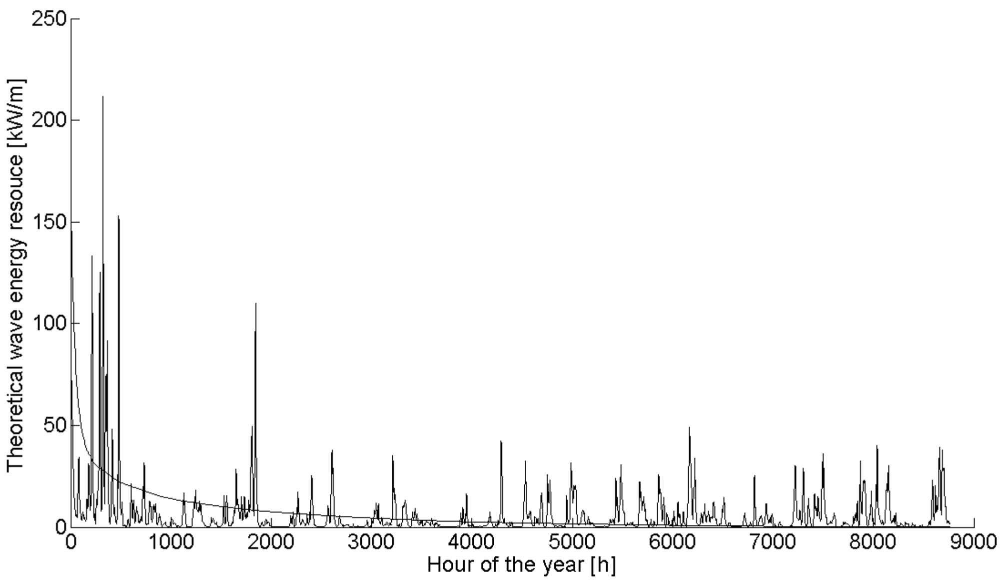

Figure 4.3: The theoretical wave power available in the high potential area in every hour of the year in kW per meter wave front, and its duration curve.

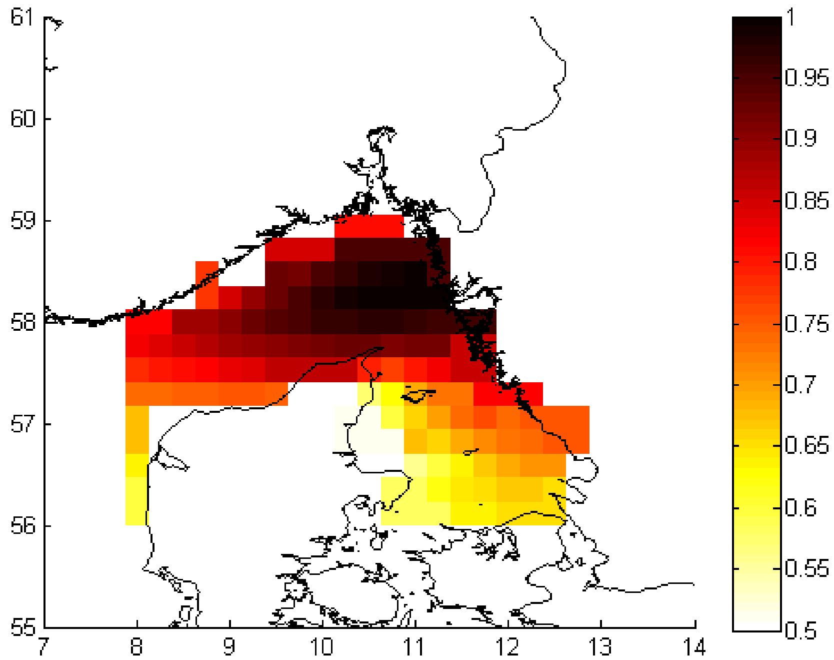

Figure 4.4: The correlation of the available wave power in every point with Point 1 from Figure 4.2. It is clear that correlation is high with neighbouring points, and decreasing with increasing distance. Note that the color scale goes from 0.5 to 1 because of the high correlation in the area. Do also note that points with low correlation to Point 1 still probably have high correlation to their neighbouring points. The numbering on the axes are the coordinates of the region.

4.1.2 Available electrical energy from waves and winds

In Figure 4.5 the available electricity generation from waves can be seen over the year, with and without the cutoff in installed capacity for the Bref-HB. The cutoff was set so that the annual generated output is only 5% lower than without the cutoff [40]. The total annual output was then scaled back to 6 TWh/year before implemented in the model. Thus installing about 1900 MW instead of 3800 MW still gives 95% of the output, but will reduce the investment cost substantially.

This scaling will govern the capacity factor of wave power. In Table 4.1, the capacity factors for the four different technologies of wave power can be found. For wind power the capacity factor was 0.24 in July and 0.26 in December.

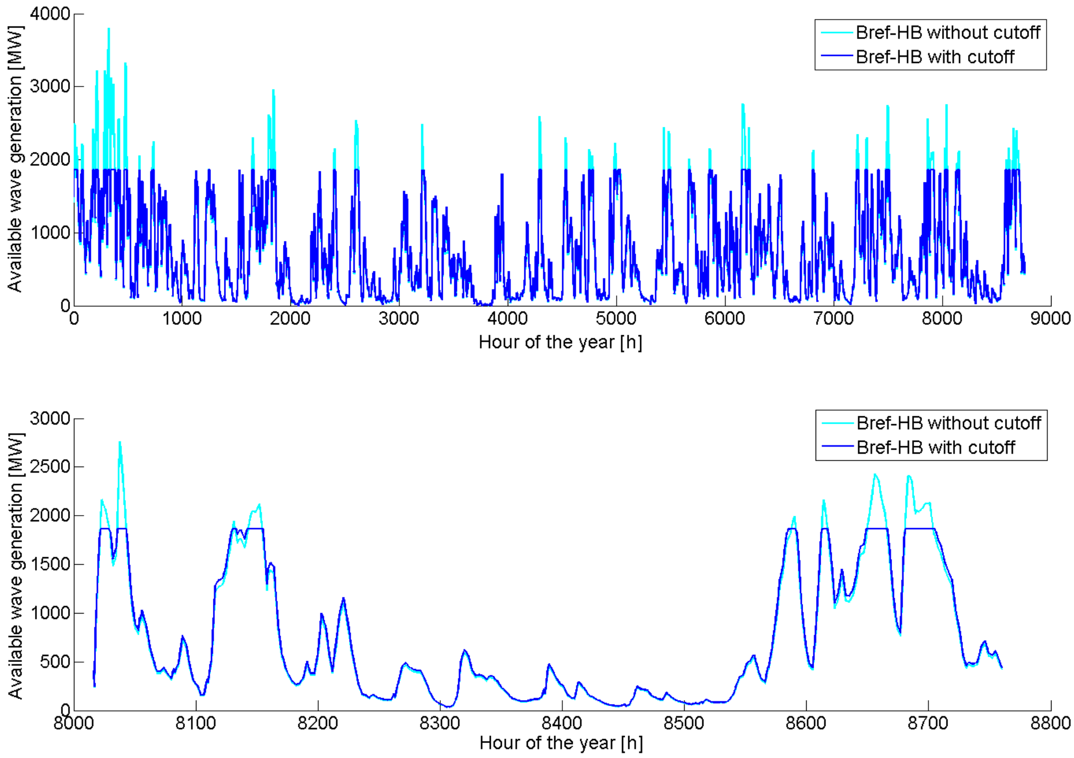

Figure 4.5: Available wave power generation for the Bref-HB, with and without the cutoff. All hours with more power available than the cutoff will be set to generation at rated capacity i.e the cutoff, resulting in many hours of rated output. The upper graph shows the full year and the lower December only.

Table 4.1: The capacity factors for the four different wave power technologies.

Capacity factors	Bref-HB	Bref-SHB	B-HBA	Elskling
July	0.39	0.33	0.24	0.23
December	0.39	0.31	0.24	0.25

One way of comparing wave and wind data is looking at the histograms for the two sources, as presented in Figure 4.6 which shows a histogram for a) the wind energy output, b) the raw wave energy without being subject to any matrix or the Elskling curve, c) the electrical wave energy output from the Bref-HB. The cutoff in installed capacity for wave power can clearly be seen, since it leads to many time steps of rated capacity i.e maximum output compared to the very few hours of maximum output without the cutoff.

When you look at the number of hours with zero or very low output it is clear that the number is higher for wind than for wave. Wind power generation is spread over a much larger geographical area, and if only spreading wind over an area as large as for

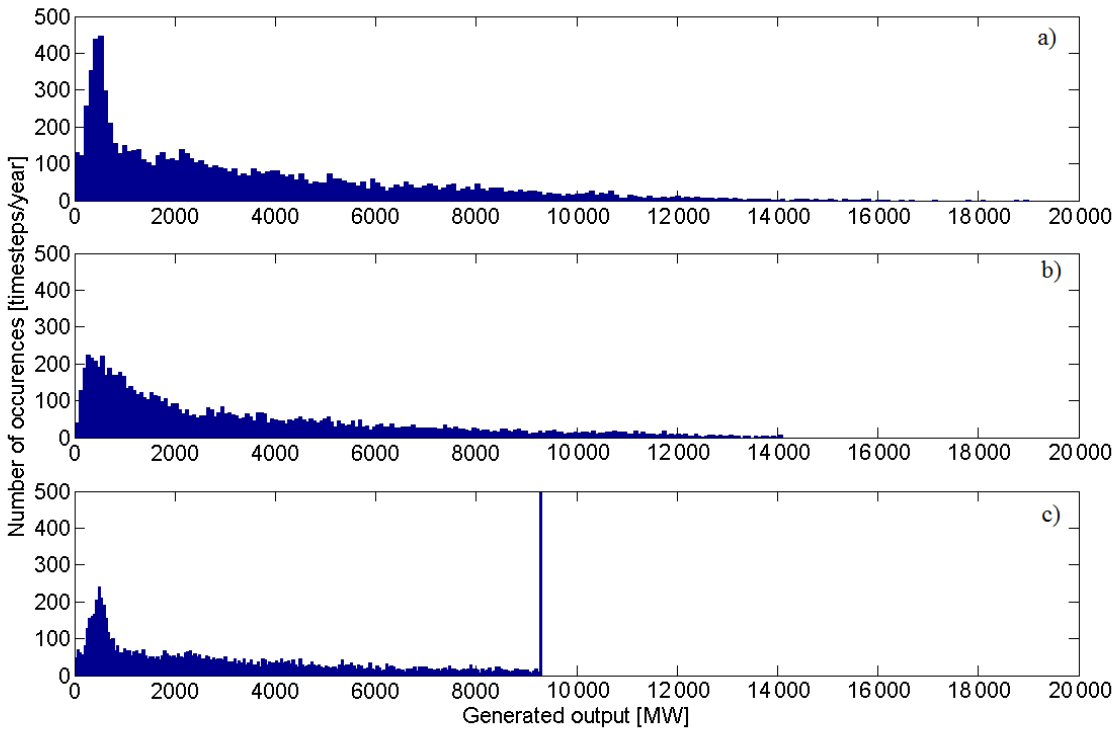

Figure 4.6: The histogram of the wave and wind power generation in southern Sweden. a) The available wind power generation. b) The raw wave power resource without being subject to a power matrix. c) The available wave power generation from the Bref-HB. The cutoff in installed capacity for wave power leads to many hours of rated power production, which clearly can be seen in c).

the wave energy converters, the difference in zero output would be even larger.

In Figure 4.7 the available wave and wind power generation can be seen for July and December separately. The connection between wave and winds are visible, as well as difference and similarities between the four conversion technologies for wave power. In these figures the annual available wave power generation was scaled to 6 TWh in all cases, and the annual available wind power generation was scaled to 24 TWh. When analysing the graphs, the effect of time needed for the wind to build up waves resulting in a time lag between wave and wind power availability can be glimpsed, even if this effect probably would be much clearer with finer time resolution on the data. Hours of land breeze which wind power can utilize but without time to generate waves, leading to wind power output but zero wave power output can also be seen. Since wind power generation is spread over a larger area; throughout southern Sweden, this can also be the effect of it being windy in other parts of the region than at the west coast where the wave converters are placed.

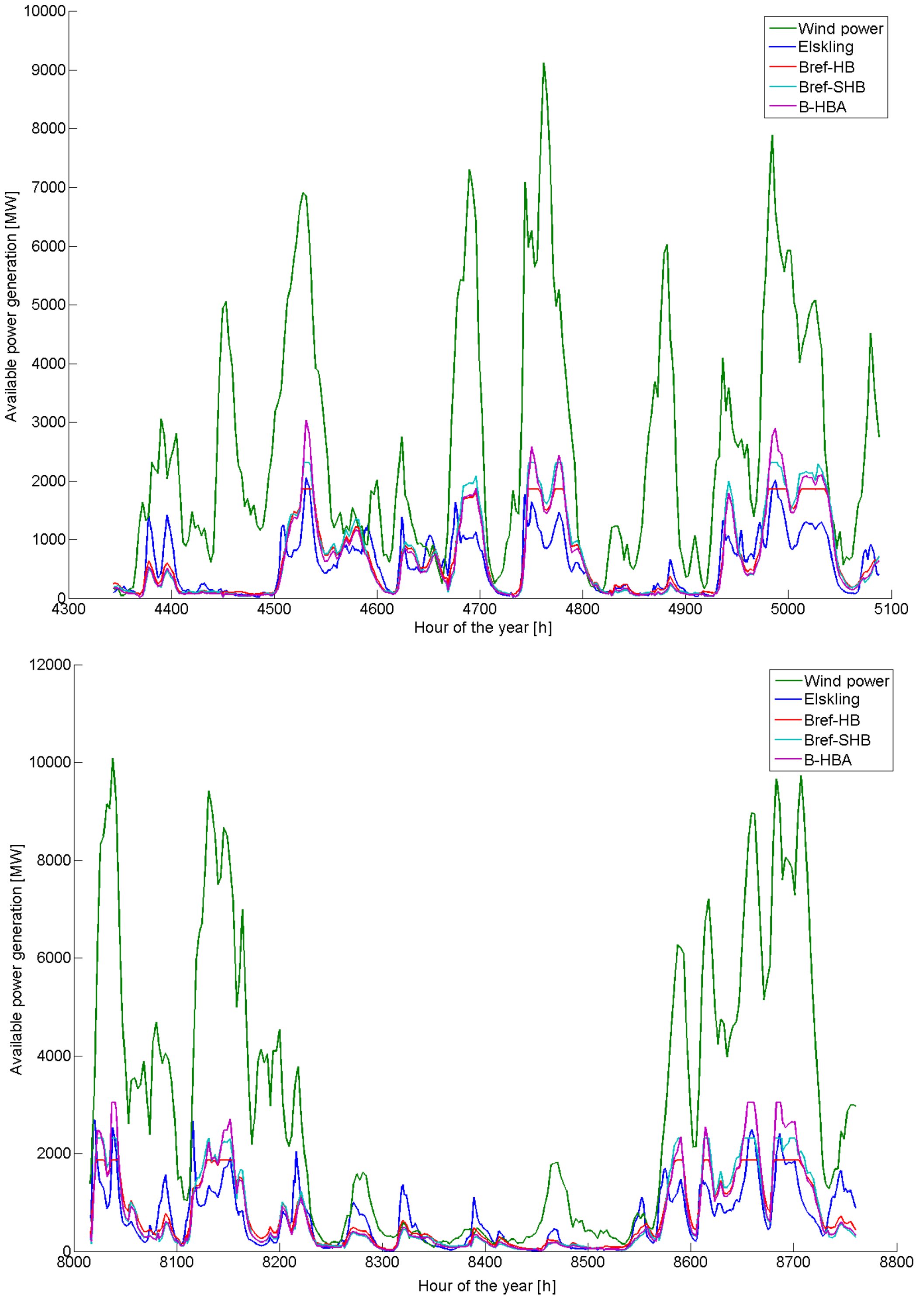

Figure 4.7: Available generation from wave and wind power in July on top December below, with 6 TWh/year wave energy and 24 TWh/year wind power annually. Note the correlation between the wave and wind power generation and the impact of the applied cutoff on the output curves.

4.2 Correlation between wave and wind

In this section analysis is done on wave power generation for the four different transferring technologies investigated in this thesis. The correlation between available wave and wind power generation has been found to be high within the investigated area for all four wave power technologies. In a previously mentioned Irish study [12], a correlation coefficient of around 0.6 is referred to as ”quite strong”, and here the results are even higher. In Figure 4.8 the correlation coefficients between the time series of available wave power and available wind power can be seen, for the four different technologies. Note that the amplitude does not affect the correlation coefficient, so the scaling into a certain annual generation is irrelevant for this part of the analysis. The correlation coefficient was found to be higher for the three technologies with a power matrix than for Elskling. When comparing the full year correlation with separate months it was found that the correlation is higher in December than for the whole year, and slightly lower but still high in July.

This high correlation between wave- and wind power implies that it is predominantly wind waves present in the area. A high correlation reduces the chances of having benefits from combining the two resources from a smoothing output perspective.

The correlation to the wind data in southern Sweden was also tested if wave power generation would be placed on the Danish west coast instead, presented in Figure 4.9. The generation was again spread over six points, as in the Swedish case. The correlation was still quite high, in line with the fact that waves can travel without much losses, in this case from west of Denmark to Swedish waters. Thus it is to a large extend wind waves also outside Denmark. As shown in the Irish study [12], on a coast where large ocean swells which are generated elsewhere by remote winds dominate, the correlation with the winds present in the area is likely to be much lower. Then combining wave and wind power generation can be much more beneficial.

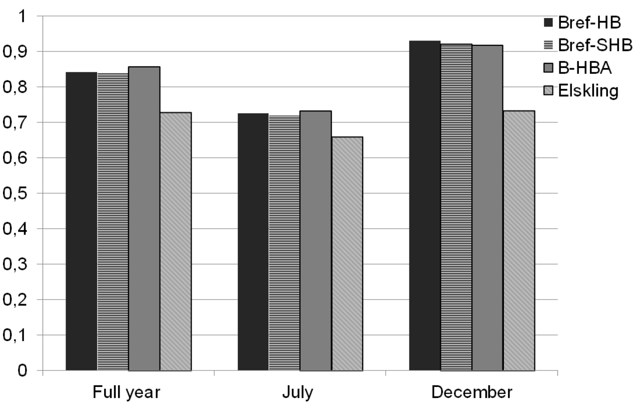

Figure 4.8: The correlation coefficients between wave power and wind power for the four investigated transferring technologies for the full year, in July and in December.

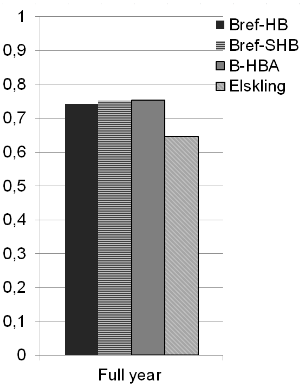

Figure 4.9: The correlation coefficients between wave power and wind power for the four investigated transferring technologies for the full year, with wave power generation situated on the west coast of western Denmark and wind in southern Sweden.

4.3 Model results

The aim of running the model on separate months was to compare the different power matrices and the Elskling curve, and to understand the possible consequences of only using one technology in the full year simulations. This is due to very long computational times for full year simulations. The month of July has been chosen to represent summer, and December represents winter. Based on the outcome of this, one technology has been chosen for the full year simulations.

4.3.1 July and December

In Table 4.2 some key numbers from the modelling results can be found, for both July and December, and for five different scenarios. In all cases the total available generation of wave and wind together was scaled to be 30 TWh/year. In the four first scenarios wave power was generating 6 TWh/year, one scenario for each technology. The fifth and last scenario was with no wave but 30 TWh/year from wind power.

From the key numbers presented in the tables the conclusion can be drawn that there is not a comparatively big difference between the four transferring technologies. The results are also not all pointing in one direction, towards one technology being better than the others. In July, both the Bref-HB and the Bref-SHB implies that 20% wave power is better than only wind power from the perspective of system operational cost. This is despite the cycling cost being higher for these two scenarios than in the wind only case. For the Bref-SHB the peak generation is comparatively high, and the highest out of the five scenarios in July. Note that the differences highlighted here are still comparatively small.

In December, the system operational costs are very similar, and not even distinguishable under the accuracy of the results.

The curtailment of wave and wind power and also the cycling cost are at the lowest

Table 4.2: Key numbers from the model when running it for two weeks in July and December, for the five different scenarios. The output from wave is 6 TWh/year, and wave and wind together is 30 TWh/year in all cases.

July	Bref-HB	Bref-SHB	B-HBA	Elskling	Wind only
System operational cost [M€]	54	54	55	56	55
Cycling cost [M€]	1.0	1.2	1.0	0.64	0.77
Peak generation [GWh]	0	0.092	0.067	0	0.026
Curtailment					
wave & wind [GWh]	36	40	44	35	40
December	Bref-HB	Bref-SHB	B-HBA	Elskling	Wind only
Total cost [M€]	102	102	102	102	102
Cycling cost [M€]	2.4	2.5	2.4	2.3	2.6
Peak generation [GWh]	9.3	10.9	11.0	7.9	10.9
Curtailment-					
wave & wind [GWh]	14	17	21	11	16

with Elskling in all cases.

The outcome of the interim simulations is that the differences between the technologies are small thus the choice of technology will not have a large impact on the results. When running the model over the whole year, the Bref-HB has been chosen as the transferring technology. This technology is very similar to what is now being built outside Sotenäs i.e in the high potential area. It is also the technology that has the highest capacity factor.

4.3.2 Full year

In Figure 4.10 and 4.11 parts of the full year dispatch, i.e how the generating units in the system are run, can be seen. For a more clear presentation a shorter time period is chosen, in this case the last two weeks of July and December. As for all full year simulations the Bref-HB is the technology chosen for wave power generation. In the figures the nuclear power units are grouped into three blocks, after the power plant they belong to.

Figure 4.10 shows that peak generation is dispatched even when nuclear power is far from its maximum capacity for Sweden which is 9.5 GWh/h. With 30 TWh variable generation from wave and wind power in the system all nuclear units in Sweden will never generate at full capacity. In Appendix B the full year dispatch can be seen.

When the output from wave and wind is reduced for a short period it can be better from a system operational cost perspective to run peak generation than to start up a nuclear power unit due to the high start up costs. However, when the period of lower

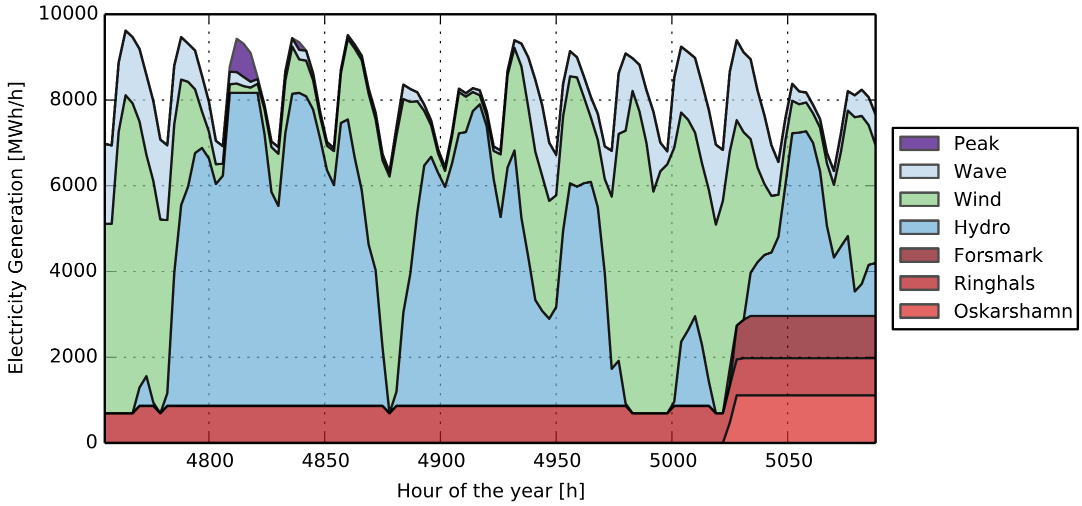

Figure 4.10: The electricity generation dispatch for the two last weeks of July from the full year runs. The nuclear units are grouped into blocks after the three nuclear power plants in the region; Oskarshamn, Forsmark and Ringhals.

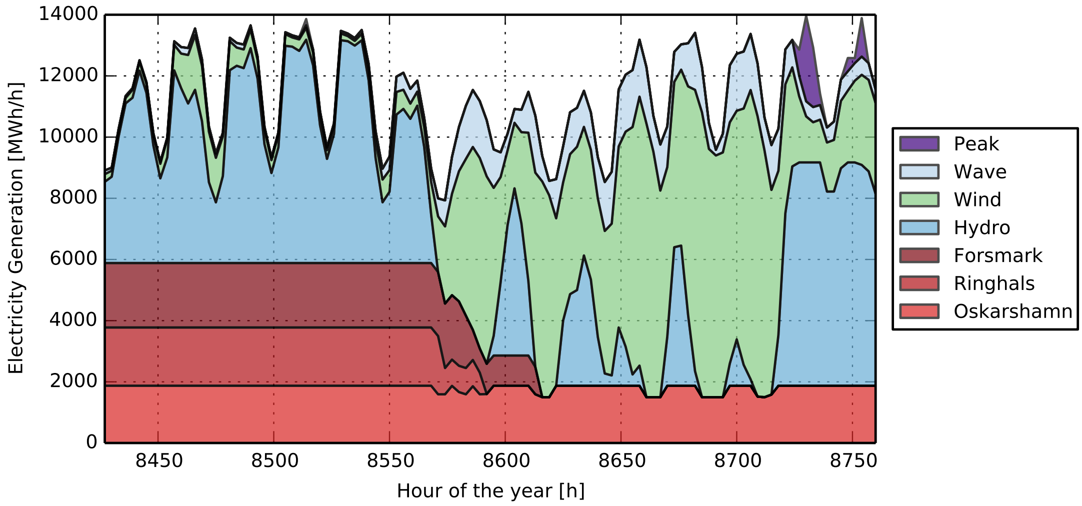

Figure 4.11: The electricity generation dispatch for the two last weeks of December from the full year runs. The nuclear units are grouped into blocks after the three nuclear power plants in the region; Oskarshamn, Forsmark and Ringhals.

output from wave and wind is longer, as can be seen in the end of the time period of Figure 4.10 and the start of Figure 4.11, it is better from the system perspective to start up nuclear power plants, in this case both in Oskarshamn and in Forsmark.

Figure 4.11 confirms that during periods of low output from wave and wind power generation together, more nuclear power is used to satisfy the demand. When the output from wave and wind power increases, nuclear power units will be shut down, as can be seen at around hour 8600 in Figure 4.11.

With an annual generation of 6 TWh wave and 24 TWh wind in the system, there are even a few days in August when all nuclear units in the system will be shut down. The demand during these days will be fully satisfied with wave, wind and hydro power generation i.e fully renewable, carbon free generation, as can be seen in Figure 4.12. However, unlike reality the model has perfect foresight and in reality the risk with false forecasts might be handled by keeping some conventional units running on part load, if the wave and wind power resource is reduced unexpectedly. How much a country can rely on its neighbouring countries for import of power if necessary will also have an impact on how a system with a large share of renewables will be operated during periods of high renewable output.

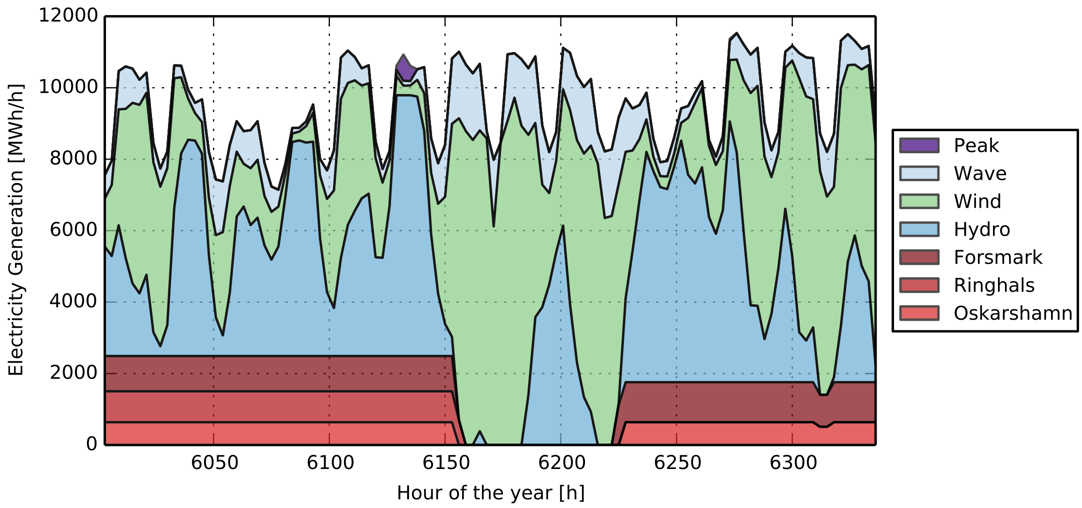

Figure 4.12: The dispatch in two weeks of August from the full year runs, when all nuclear units are shut down. The system is supplied fully by wave, wind and hydro power.

For theoretical analysis, wave power penetration levels of up to 30 TWh/year have been tested within the model. The aim of this has been to better understand the dynamics in the system and to be able to compare the effects of wave and wind power generation.

In Figure 4.13, the system operational cost can be seen for different penetration levels of wave power in the system. The figure shows that the system operational cost is reduced when adding wave power to the system, and a mix of wave and wind will result in the lowest system operational cost. This is both due to the change in peak cost and cycling cost for different shares of wave and wind, shown in Figure 4.14. Adding wave power generation reduces the peak cost, and a high share of wave power generation is beneficial from this perspective since the peak cost curve flattens out for a large share of wave power generation in the system. The cycling cost is more symmetric around its minimum value at a mix of sources.

The peak cost and the cycling cost together stands for about half of the reduction in system operational cost when adding wave power generation to the system. Another factor affecting the system operational cost is the curtailment of wave and wind power, shown in Figure 4.15. Curtailment represents energy from wave and wind not used in the model, due to for example part load restrictions or avoiding start-up costs. Since the running costs are equal, the model cannot differ between curtailing wave and wind.

The final conclusion is that a combination of wave and wind power generation is beneficial for the system, since it leads to a lower system operational cost. The slope of the curve is steeper in the beginning when starting to add wave power generation to the system, which means that the initial gains are the biggest. However, it must be remembered that the difference in the trends discussed here are not so big in amplitude. The maximum savings in system operational cost by adding wave power generation to the system is 10 M€/year, which is about one percent of the system operational cost. The savings can be explained by a reduction in peak cost by 50% and in cycling cost by almost 20%, and less curtailment of wave and wind power generation.

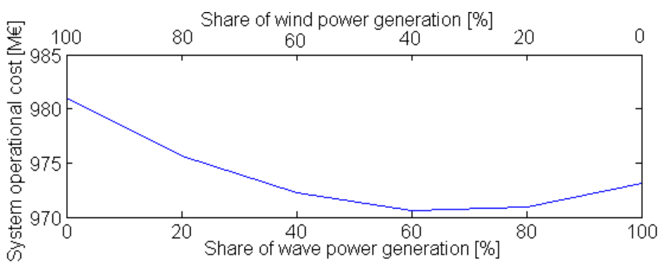

Figure 4.13: The system operational cost for different shares of wave and wind generation along the x-axis, adding up to 30 TWh/year in all cases. The trend is that adding wave power generation to the system leads to reduced costs, and a mix of sources is better from a system perspective. However, the absolute difference is not so big, and about 1% of the system operational cost can be saved from having wave power in the system compared to wind only.

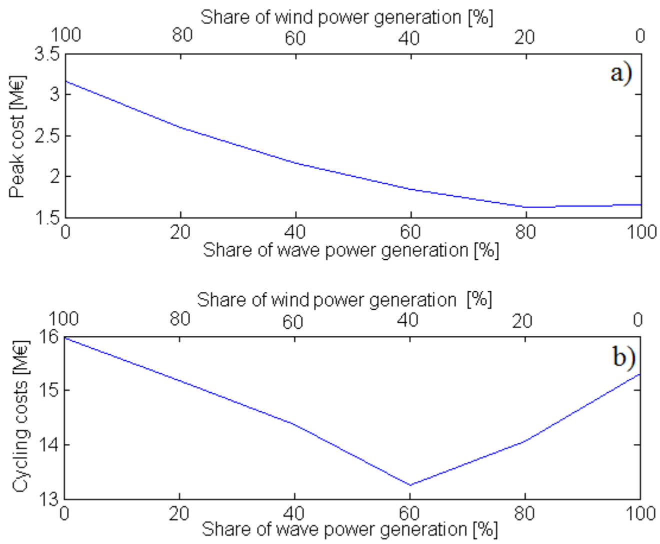

Figure 4.14: Two factors explaining the reduction of the system operational cost when adding wave power; a) Cost of peak generation, b) Cycling cost, for different shares of wave and wind generation along the x-axis adding up to 30 TWh/year in all cases. These two factors together stands for about half of the reduction in system operational cost when adding wave power generation to the system.

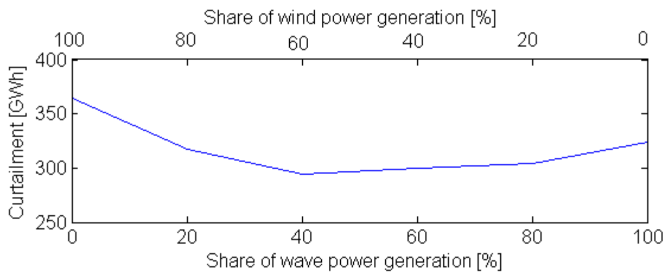

Figure 4.15: The curtailment of wave and wind power for different shares of generation from wave and wind power, in all cases adding up to 30 TWh/year in total. Curtailment represents energy from wave and wind power generation not used in the model due to for example part load restrictions or avoiding start-up costs.

In Table 4.3 the key numbers from the full year simulations with different shares of wave power can be seen.

Table 4.3: Key numbers from the model result when running the model for one year, with different shares of wave and wind but in all cases adding up to 30 TWh/year in total.

Full year	0 TWh wave 30 TWh wind	6 TWh wave 24 TWh wind	12 TWh wave 18 TWh wind
System operational cost [M€]	981	976	972
Cycling cost [M€]	16	15	14
Peak generation [GWh]	72	59	49
Curtailment- wave & wind [GWh]	364	318	295
	18 TWh wave 12 TWh wind	24 TWh wave 6 TWh wind	30 TWh wave 0 TWh wind
System operational cost [M€]	971	971	973
Cycling cost [M€]	13	14	15
Peak generation [GWh]	42	37	37
Curtailment- wave & wind [GWh]	300	304	323

4.4 Variability measures

To investigate and compare the variability of the wave and wind resource, and also when seeking explanation to the model results, two measures on variability has been used. In Figure 4.16, the value of the measures (Std, 10-VaR, 90-VaR) can be seen for different shares of wave and wind power generation. The total generation from wave and wind together is 30 TWh/year in all cases, but the share of wave and wind varies along the x-axis. A) shows the standard deviation of the wave and wind power generation. In B) the standard deviation for the net load i.e the load minus the wave and wind power generation can be seen. C) shows the 10-VaR of the net load and in D) the 90-VaR of the net load can be found.

A) is in line with what is frequently stated in the literature; that wave power has a less variable generation pattern than wind power, since the standard deviation is lower for only wave power generation than only wind power generation. However, the standard deviation only tells the deviation from average and is not a measure of all kinds of variability. Note that the wind resource is spread all over southern Sweden in this case, and the standard deviation for wind would be even higher for a reduced geographical spread. When spreading the wind over an equally large area as the wave energy converters, in a coastal area adjacent to the high potential area, the standard deviation of the wind was 30% higher than that of wave. For a mix of these two sources the standard deviation was constantly increasing when increasing the wind power penetration level. Since the

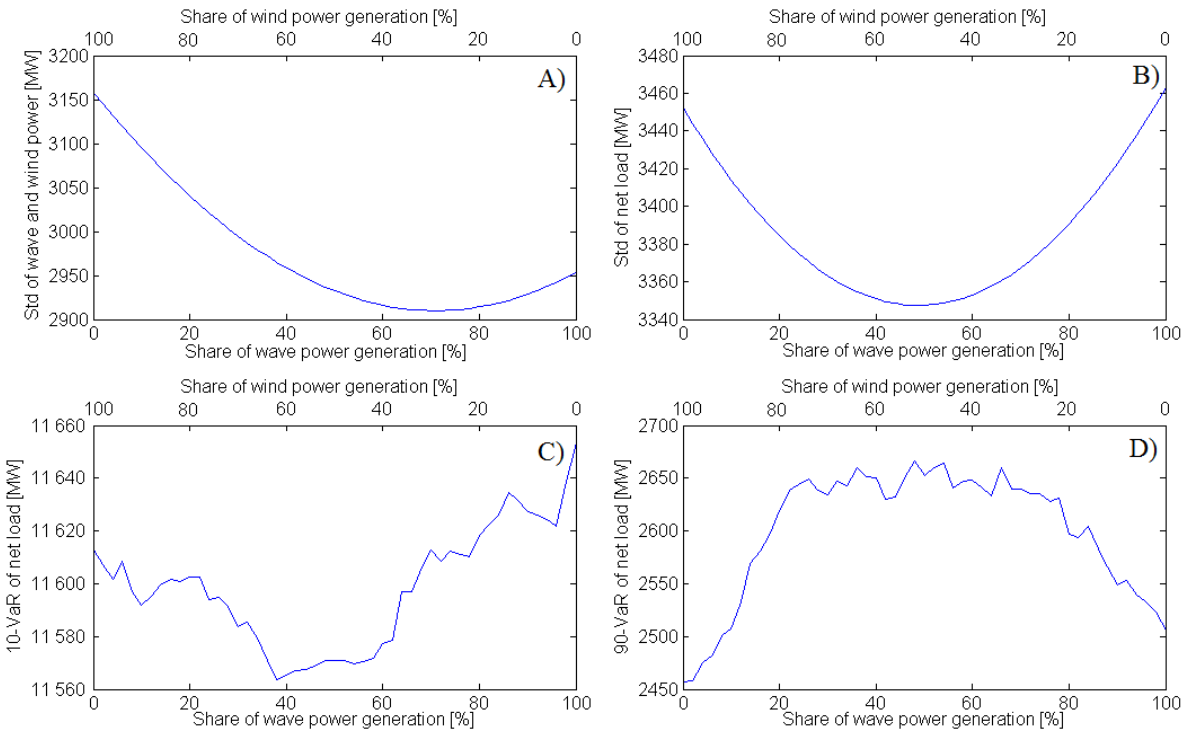

Figure 4.16: The value of the measures (A) the standard deviation of the wave and wind power generation. B) the standard deviation for the net load i.e the load minus the wave and wind power generation. C) 10-VaR of the net load. D) 90-VaR of the net load. In all cases, the total generation from wave and wind together is 30 TWh/year, with varying shares along the x-axis.

energy in the waves was found to be concentrated in the high potential area, and wind energy is easier to spread geographically, the assumptions on the geographical spread is assumed reasonable.

What can be concluded from B) in Figure 4.16 is that the standard deviation of the net load is lower for a combination of wave and wind than for any of the sources separately. A smoother standard deviation of the net load implies that the demand that must be satisfied by the other generating units in the system is smoother and can thus enable more stable running of these units which is beneficial both from a cost and low emissions perspective.

Figure 4.16 C) shows that the 10-VaR curve has a minimum for a mix of wave and wind power generation. Thus from this perspective a mix of sources is better than a wave or wind only approach.

When comparing the 10-VaR values and the cost of peak generation presented in Figure 4.14, the curves does not seem to indicate the same result. From a minimizing peak cost perspective the higher share of wave power the better, while from the perspective of minimizing 10-VaR a the optimum is for a mix of sources. Thus the peak generation cost can not be concluded to correlate well with the 10-VaR value, and as already mentioned one explanation to this can be that peak generation is not only used when the capacity of hydro- and nuclear power is not sufficient but also to avoid start up costs.

In Figure 4.16 D) it can be seen that the 90-VaR is higher for a mix of sources than for any of them separately. Thus, also from this perspective a mix of wave and wind power generation is better than any of the sources separate.

Looking at the correlation between the 90-VaR values and the cycling cost presented in Figure 4.14, the curves seems to be rather correlated, with the minimum value of the cycling cost and the maximum of the the 90-VaR values both for a rather even mix of the two generating sources.

From all the measures on variability the indication is that a mix of wave and wind power generation is preferable over any of them separate. The optimal proportion of wave and wind from the perspective of the variability measures varies, and these measures can not be used for finding the optimal share partly since the differences highlighted here are even if identified not so large in amplitude.

4.5 Cost comparison

The built in advantage of having a high capacity factor, that for each installed unit of power the annual generation of energy is higher, has been quantified to allowing the cost of wave power to be some 1.5 times the cost of wind power for the Bref-HB technology in the investigated area. For this the capacity factors were needed, which are 0.37 for wave power and 0.25 for wind power for the system investigated under the assumptions presented in Section 3.3.

The other reason for allowing energy from waves to have a higher cost, coming from the system benefits of wave compared to wind leading to a reduction in system operational cost is found from the model results. This would only be a cost benefit if the system had a x TWh wind and another y TWh wind or wave should be installed.

The two parts separate, and their sum b, can be found in Table 4.4 for different penetration levels of wave power. From these results it can be concluded that it is mainly the difference in capacity factors that govern the price difference allowed between wave and wind energy. The part evolving from reduced system operational cost is in the order of a factor ten lower than that relating to differences in capacity factor.

Table 4.4: The results from the cost comparison calculations. The factor b represents how much more costly wave power can be than wind power. It comprises the sum of the two other factors presented in the table. The table shows that the fraction related to differences in capacity factors is the main part of b, since the part related to reduction in system operational cost, Δ, is about a factor of ten lower. In all cases, wind power adds up to a total output from wave and wind together of 30 TWh/year.

	$\frac{P_{wind}}{P_{wave}}$	$\frac{\Delta}{c_{wind}P_{wave}}$	b
6 TWh wave/year	1.46	0.018	1.48
12 TWh wave/year	1.46	0.015	1.48
18 TWh wave/year	1.46	0.012	1.48
24 TWh wave/year	1.46	0.0086	1.47
30 TWh wave/year	1.46	0.0054	1.47

5

Discussion

Before drawing conclusions based on this thesis work, the relevance and implications of both the results and the methods applied will be discussed in this chapter. Also, some aspects of wave power generation and differences with wind power generation will be discussed in general.

The main outcome of this thesis is that there are benefits of combining wind power in southern Sweden with wave power generation on the Swedish west coast, in terms of reduced system operational costs. The reduction is not so big in amplitude, but the trend is clear. The high correlation between the wave and wind resource in the region reduces the gains of combining the two sources, and makes them more similar from a system perspective since often both are available at the same time. This result is however to some extent specific to the area under investigation. Nations or regions with coasts that experience swell waves, generated by remote winds can experience greater benefits of combining wave and wind power generation. As found in an already mentioned Irish study [12], the gains of combining wave power with an uncorrelated time series of wind power output is much higher than if combining with a correlated one.

When it comes to the allowed cost increase for wave power compared to wind power per generator capacity, the numbers presented are valid for the point absorber technology Bref-HB, in the investigated area. The governing factor for the allowed increase in cost was the difference in capacity factors. The capacity factor of an installation can be governed by scaling the generator, and a higher capacity factor can be achieved simply by reducing the generator size. However a smaller generator will generate less electricity on an annual basis, and thus will be less cost effective.

The temporal resolution of the weather data is an important factor when investigating the correlation between wave and wind power. What is often stated in the literature; that wave power has a less variable generation pattern than wind power, was in line with the outcome of the analysis on the weather data used. Since the temporal resolution of the data is three hours, differences on smaller time scales cannot be identified. A hypothesis which has not been possible to investigate in this thesis is that if the data would have finer time resolution, the differences between the two sources would be more clear. A further hypothesis is that wave power would benefit from a finer time resolution since wind gusts, too quick to affect the waves would be visible, increasing the fluctuation of wind power generation compared to with three hourly data. For this thesis the geographical spread of wind power will smoothen this effect. Earlier studies have shown that a temporal resolution of three hours is sufficient to identify the system effects of wind power in western Denmark [19]. Moreover, variations on different time scales have different implications for the system, where a finer temporal resolution rather would affect power balancing and if very fine resolution even frequency regulation.

To get valid data on how to transfer the energy in the waves into electricity has been difficult. Many wave power technologies are still in a state of sketches and prototypes, and only simulated or in other ways estimated data of the performance is available. Also, since the wave energy industry potentially is in the starting blocks of a strong exploitation, many companies see a risk in sharing their data. The three power matrices used are all from the same study while the Elskling curve is based on measurements on a prototype. This multitude of transferring methods is an attempt to reduce the sensitivity in the results, and if this kind of data will be more easily accessible in the future studies like this will benefit from it.

In the interim simulations, which months to choose is an open question. When it comes to winter months, January was not chosen due to the many steep output peaks. The calm period without both waves and winds in December can be argued not being typical for winter. However, since the aim of these simulations has been to compare the different power conversion methods, this has been neglected. Any year will have periods of high output and low output. The outcome of the interim modelling was that the technologies were very similar and the results were not all pointing in one direction towards one technology being fully advantageous. Thus selecting other months for interim simulations would not have an impact on the choice of technology for the full year simulations.

The investment cost of a wave farm will most probably be very technology dependent. Also the capacity factor is linked to technology, but for each technology the scaling of the generator will govern the capacity factor of that unit. A high capacity factor can be achieved simply by installing a small generator, but when designing it will be a trade-off between costs of generator capacity and that of logistics and any other cost apart from the generator. It is clear from the modelling results that it is mainly the difference in capacity factors and not the reduction in system operational cost that will govern the cost differences between wave and wind power that can be allowed. The impression that at least some actors in the wave energy industry provides is that if reaching mass production, wave converters have the ability to reach even a lower cost than wind power per energy output thanks to less material need.

In this thesis, wave power generation has been located in one specific area while wind power generation has been spread all over southern Sweden. Since the analysis on the weather data showed a clear stretch of higher energy content in the waves, this area will probably be the very interesting if planning for future wave energy projects.

Also, spreading wind power is easier than spreading wave power. A smaller geographical spread of wind power would make the wind power output more fluctuating, and thus the benefits of adding wave power generation would increase.

Another important aspect of this thesis is that wind power is completely land based. Offshore wind has a higher capacity factor but is also much more costly. Co-locating wave and offshore wind can have benefits such as better utilization of the expensive cable connecting to main land. Again, since there is a high correlation between waves at the west coast and winds in southern Sweden, this effect would be small in this case.

Survivability is a great challenge for wave power. To withstand the huge forces of stormy seas, and still being able to generate electricity in an efficient way in more calm climates is challenging. Weight is strongly related to survivability, but also to cost. For offshore installations, service and maintenance is costly. Also, an outage leading to lost revenues during a wavy period is severe, but performing service and maintenance in a wavy sea is very complicated if even possible. Thus an outage early in a wavy period might not be possible to handle until the wavy period and thus the period with high revenue is over.

Another great challenge for wave power is the logistics of building the wave farm and placing the cable to mainland. This will be very dependent on local conditions, type of technology, water depth, distance from the coast etc. Again, the multitude of technologies could be argued to be a disadvantage.

One infected question in many new wind power projects is the public acceptance, the NIMBY-issue. NGO's[1], residents in the area of exploitation, environmentalists of different kinds and people with other interests often oppose to these projects. Here, wave power has an important advantage, since the converters will be built sufficiently far out from the coast so that they will not be visible or audible from the main land. However, as for offshore wind power the fishery industry, marine shipping lanes, military and other protected areas must be taken into consideration.

The oceans of the world comprise a large area. In an advertisement for wave power one of the manufacturers have stated that an area of $20 \cdot 20$ km^2 on the Norwegian cost would be enough to satisfy the whole Norwegian demand for electricity. Whether or not this exact number is valid, lack of space will not be an issue for wave power generation.

[1] Non-Governmental Organisations

6

Conclusions

A dispatch model with a temporal resolution of three hours has been applied to study the effects of implementing wave power into the electricity system of southern Sweden. The wave power availability and the correlation to wind energy in the area has been investigated, and also potential benefits of combining the two sources. The analysis was carried out with a total annual output from wave and wind of 30 TWh, varying the shares of the two sources.

It is clear from the results that there are benefits of implementing a combination of wave and wind power to the electricity system of southern Sweden compared to only increasing the wind power penetration equally much, revealed as reduced system operational costs. The cost reduction is in the range of 10 M€/year, corresponding to 1% of the system operational cost. If looking into the origin of this cost reduction, it can be explained by a 50% reduction in peak cost, almost 20% lower cycling cost and less curtailment of wave and wind power generation.

Wave and wind power have been found to have a high correlation in the investigated area, which reduces the benefits of combining the two sources. It implies that there to a large extent are wind waves present, generated by local winds. If there would be more swell waves, generated by remote winds and thus much more offset in time the correlation would be much lower and thus the gains of a generation mix would be higher.

The built-in advantage of a higher annual energy output per installed capacity from wave power than wind power for the point absorber technology, the Bref-HB, allows wave power to be 50% more expensive than wind power per generator capacity. The allowed cost increase from the benefits of reduced system operational cost is in the range of 1-2%, hence more than a factor of ten lower.

7

Future work

Major changes in the electricity systems globally are needed if we are to have a chance in changing historical trends in climate impact. Wind power and solar power are main options for sustainable electricity generation, but which technologies that should complement them is less clear. Wave power could be a great contributor to sustainable electricity generation globally. Hence, investigating the effect of wave energy in other electric systems, specially in systems with low correlation between wave and the other renewable sources in the system, is a key issue for future work.

Also, is this high correlation between wave and wind energy common across the world, or is a lower correlation the more common situation? For understanding the global gains of a great development in the wave power industry, questions like these are relevant.

Moreover, if wave energy is implemented in a system with less correlated renewables, there could be a difference in what generating units the different renewables are replacing. The difference in system operational cost can be much lower than the difference in the value of the electricity for the investor, since the price of electricity is set by the marginal cost of the marginal unit and not on the average cost. What source of energy is at the margin when the output from wave power is high? With a different modelling approach, issues like this could be investigated, adding an actor perspective to the question of wave power integration .

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Appendices

A

Input parameters

In the table, O1 to O3 refers to the nuclear reactors in Oskarshamn, named 1 to 3, similarly does the R refer Ringhals, and F to Forsmark. In total there are ten nuclear reactors in Sweden, all located within the area of the model.

Table A.1: Input parameters for the model - unit properties.

Unit properties	Rated power [MW]	Minimum power [MW]	η [%/100]	CO_2-emissions ton/MWh
O1	473	378.4	0.33	-
O2	638	510.4	0.33	-
O3	1400	1120	0.33	-
R1	859	687.2	0.33	-
R2	866	692.8	0.33	-
R3	1045	836	0.33	-
R4	950	760	0.33	-
F1	987	789	0.33	-
F2	1120	896	0.33	-
F3	1170	936	0.33	-
Hydro power	7300	0	1	-
Wave power	Tech. dependent	0	1	-
Wind power	4515	0	1	-
Peak power	12000	0	0.35	0.202

The cost of emission allowances is assumed to be 20 €/ton. This is based on the recommended carbon tax in the proposed energy tax directive of the European Union [42]. The reserve requirements within the system was set to 230 MW of primary reserve and 1400 MW of secondary reserve.

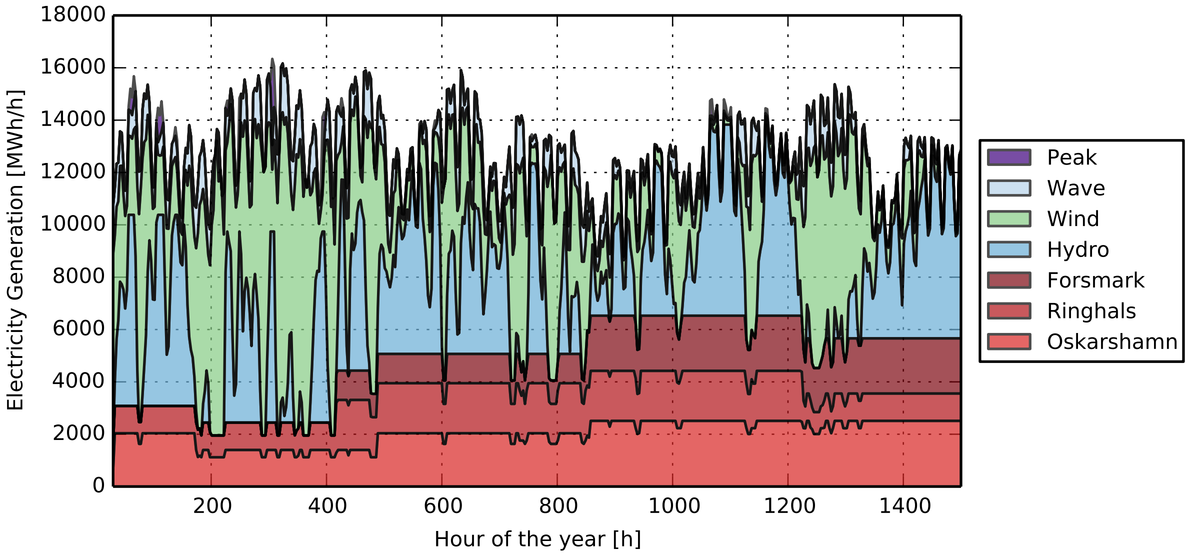
Table A.2: Input parameters for the model - Associated costs

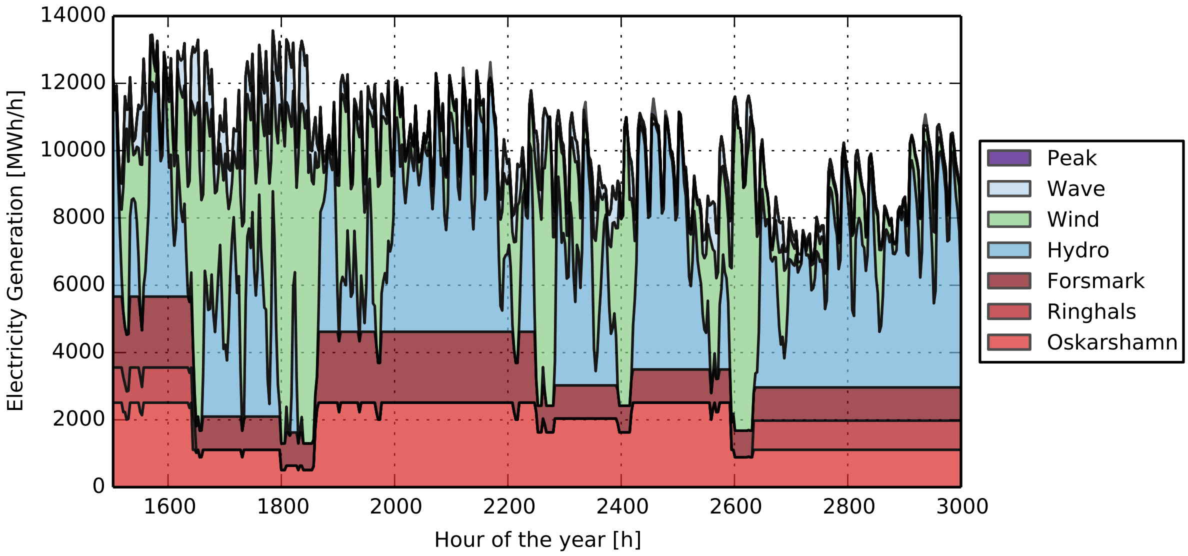
Associated costs	Fuel costs [€/MWh]	Variable O&M-costs [€/MWh]
O1	6.8	4
O2	6.8	4
O3	6.8	4
R1	6.8	4
R2	6.8	4
R3	6.8	4
R4	6.8	4
F1	6.8	4
F2	6.8	4
F3	6.8	4
Hydro power	0	1
Wave power	0	1
Wind power	0	1
Peak power	10.88	1

B

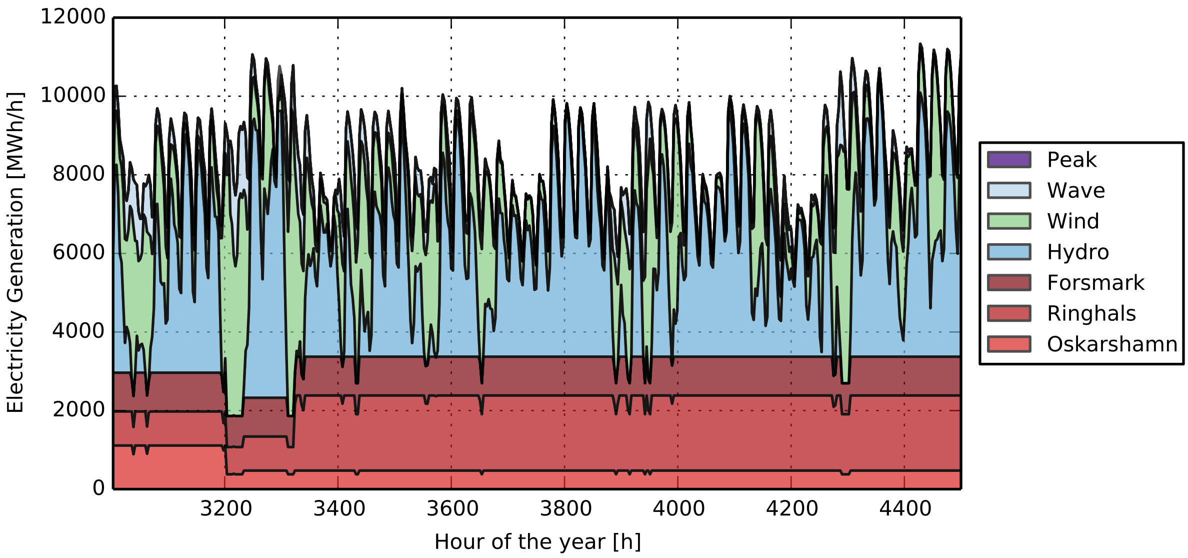
The full year dispatch

In this abstract the dispatch for the whole year, i.e how the units in the system are run, divided in 6 parts of 1500 hours each can be found. In all cases the annual wave power penetration is 6 TWh and for wind it is 24 TWh. The figures are presented i chronological order, with the hours of the year presented on the x-axis.

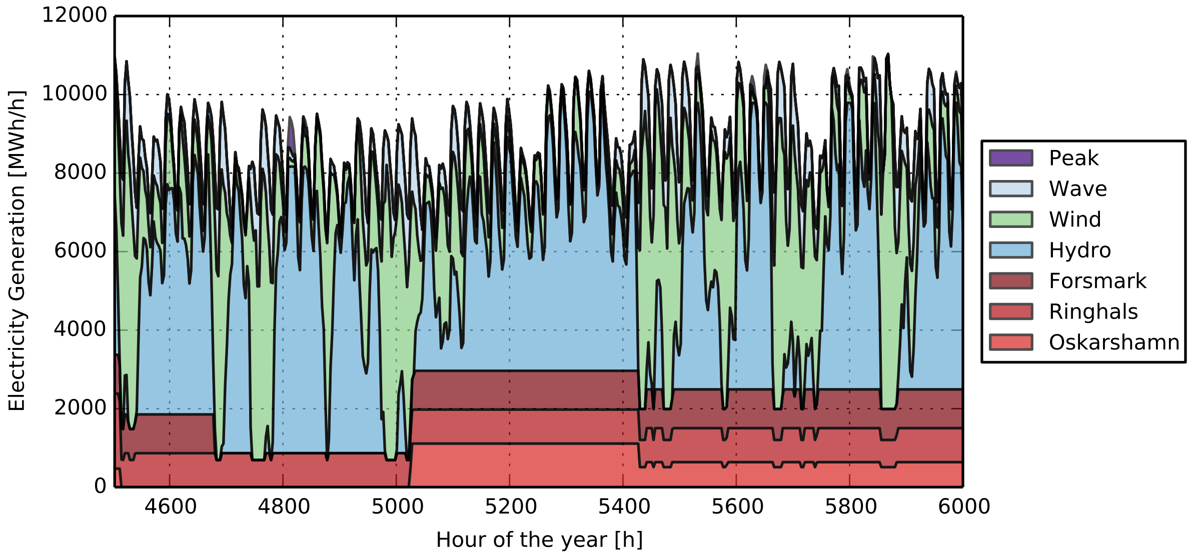




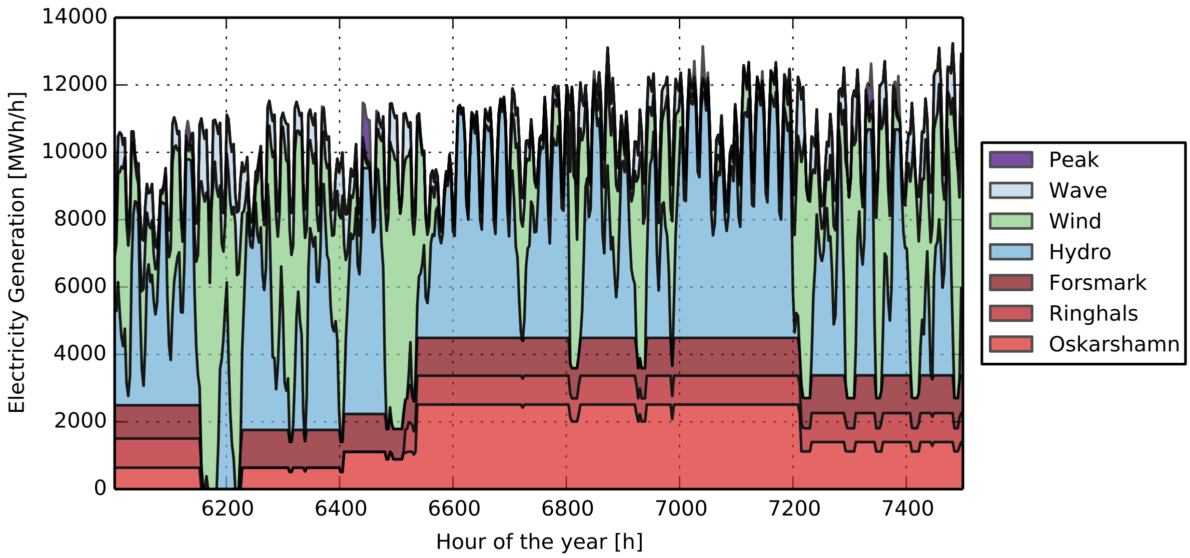
14000
12000
10000
8000
6000
4000
2000
0
Electricity Generation [MWh/h]
1600
1800
2000
2200
2400
2600
2800
3000
Hour of the year [h]
Peak
Wave
Wind
Hydro
Forsmark
Ringhals
Oskarshamn



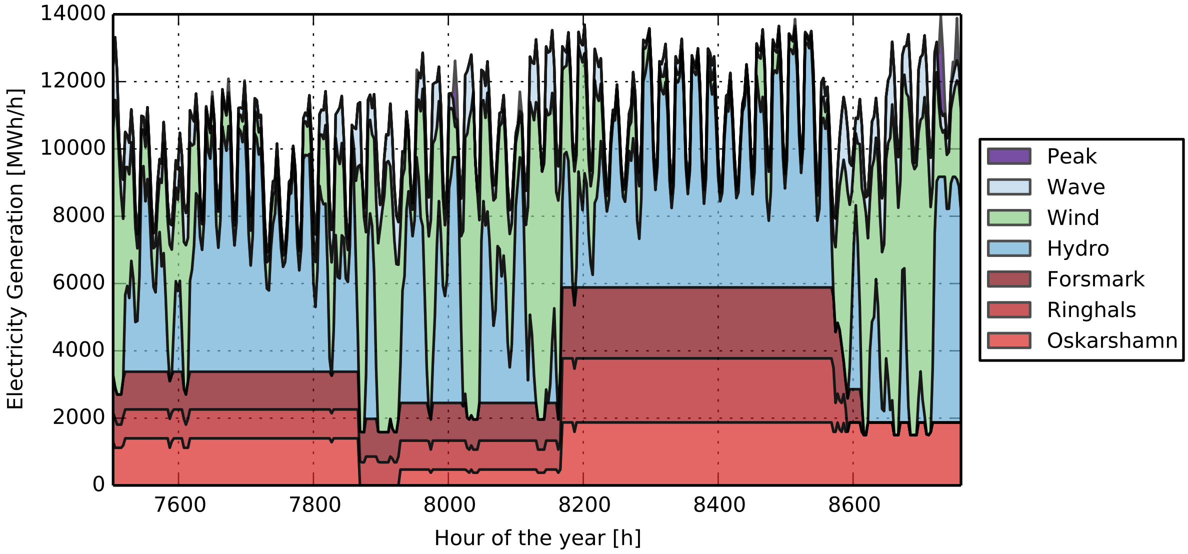
12000
10000
8000
6000
4000
2000
0
Electricity Generation [MWh/h]
3200
3400
3600
3800
4000
4200
4400
Hour of the year [h]
Peak
Wave
Wind
Hydro
Forsmark
Ringhals
Oskarshamn



Electricity Generation [MWh/h]
Hour of the year [h]
0
2000
4000
6000
8000
10000
12000
4600
4800
5000
5200
5400
5600
5800
6000
Peak
Wave
Wind
Hydro
Forsmark
Ringhals
Oskarshamn



Electricity Generation [MWh/h]
Hour of the year [h]
0
2000
4000
6000
8000
10000
12000
14000
6200
6400
6600
6800
7000
7200
7400
Peak
Wave
Wind
Hydro
Forsmark
Ringhals
Oskarshamn



Electricity Generation [MWh/h]
0
2000
4000
6000
8000
10000
12000
14000
7600
7800
8000
8200
8400
8600
Hour of the year [h]
Peak
Wave
Wind
Hydro
Forsmark
Ringhals
Oskarshamn