Photovoltaic power potential on Gotland: A comparison with load, wind power and power export possibilities

Emil Zaar
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Emil Zaar

Supervisor: Rasmus Luthander
Evaluator: Joakim Munkhammar
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Photovoltaic power potential on Gotland: A comparison with load, wind power and power export possibilities

EMIL ZAAR

Zaar, E., 2016: Photovoltaic power potential on Gotland; comparison with load, wind power and power export possibilities. Master thesis in Sustainable Development at Uppsala University, 52pp, 30 ECTS/hp

Abstract: The Swedish Island of Gotland provides an interesting case of how renewable energy technologies can be combined and integrated into the electricity system. The study simulates the load, wind power production and PV power production to estimate the PV power potential for existing buildings on Gotland. The theoretical PV power potential on Gotland is calculated to be 667 MW. The PV power potential is split between 28% for dwelling buildings, 9% for multi-dwelling buildings, 7% for industry and 56% for other buildings. The current limit for wind power on Gotland is 195 MW. With the installed capacity of 194 MW wind power, an additional of 22 MW of PV power is possible to integrate without increasing the hours of overload on the power cable. With the prospected submarine power cable, a total of 529 MW PV power is possible to integrate with the existing 194 MW of wind power.

Keywords: Sustainable Development, Gotland, Photovoltaic, Solar Panels, Wind Power, Potential, Load

Emil Zaar, Department of Earth Sciences, Uppsala University, Villavägen 16, SE- 752 36 Uppsala, Sweden
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Summary: Energy from the sun can be transformed into electricity by using solar panels. They can be found in household items such as calculators and battery chargers as well as satellites and caravans. As solar panels have become more affordable, the interest from homeowners and businesses has increased and more solar panels are being installed on buildings. This study investigates the maximum amount of solar panels that can be installed on existing buildings on the Swedish Island of Gotland. The study simulates how much electricity solar panels and the existing wind turbines produce, how much electricity that is being consumed and how much electricity that can be exported from the island. A combination of solar panels and wind power will increase the total amount of renewable electricity production on Gotland by 22 MW. With additional export possibilities in the future, the maximum installed solar panel capacity will be 529 MW.

Keywords: Sustainable Development, Gotland, Photovoltaic, Solar Panels, Wind Power, Potential, Load

Emil Zaar, Department of Earth Sciences, Uppsala University, Villavägen 16, SE- 752 36 Uppsala, Sweden
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Nomenclature

\( A_{\text{Roof}} = \) Total roof area (m\(^2\))

\( A_{\text{Flat roof area}} = \) Area measured from above (m\(^2\))

\( \beta = \) Angle of roof inclination (°)

\( P_{\text{kin}} = \) Power (W)

\( \varphi = \) Density (Kg/m\(^3\))

\( V = \) Wind Speed (m/s)

\( A = \) Area (m\(^2\))

\( PV\ Power_{x\ MW} = \) Simulated PV power production per hour

\( X = \) Maximum PV power production without causing overload on the export cable

\( Wind\ Power_{194\ MW} = \) Simulated wind power production per hour

\( \text{W/m}^2 = \) Unit of measured global solar radiation used by SMHI
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heating and Power</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DSO</td>
<td>Distribution Systems Operator</td>
</tr>
<tr>
<td>GEAB</td>
<td>Gotlands Energi Aktiebolag</td>
</tr>
<tr>
<td>GWH</td>
<td>GigaWatt Hour = 1000 MWh</td>
</tr>
<tr>
<td>HVDC</td>
<td>High Voltage Direct Current</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IVA</td>
<td>The Royal Engineering Academy of Sweden</td>
</tr>
<tr>
<td>KV</td>
<td>Kilo Volt = 1000 V</td>
</tr>
<tr>
<td>kWh</td>
<td>Kilo Watt Hour = 1000 Wh</td>
</tr>
<tr>
<td>MWh</td>
<td>Mega Watt Hour-1000 kWh</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>RETs</td>
<td>Renewable Energy Technologies</td>
</tr>
<tr>
<td>SCB</td>
<td>Statistics Sweden</td>
</tr>
<tr>
<td>SEA</td>
<td>The Swedish Energy Agency</td>
</tr>
<tr>
<td>SEPA</td>
<td>Swedish Environmental Protection Agency</td>
</tr>
<tr>
<td>SMHI</td>
<td>Swedish Meteorological and Hydrological Institute</td>
</tr>
<tr>
<td>STA</td>
<td>Swedish Tax Agency</td>
</tr>
<tr>
<td>STC</td>
<td>Standard Test Conditions</td>
</tr>
<tr>
<td>TSO</td>
<td>Transmission Grid Operator</td>
</tr>
<tr>
<td>TWh</td>
<td>Terra Watt Hour = 1000 GWh</td>
</tr>
<tr>
<td>VRE</td>
<td>Variable Renewable Energy</td>
</tr>
</tbody>
</table>
1. Introduction
A sustainable future requires a transition towards a fossil free energy usage and a renewable electric production. Future electric energy solutions have to accommodate increased demand, energy efficiency and renewable production (Sheffield 1998). With an annual growth rate of 2.6% the worldwide energy demand is predicted to increase by 60% in 2050 compared to 2010 (Reilly et al. 2015, p.4). Sweden has the third largest electricity consumptions per capita among the International Energy Agency (IEA) members (IEA 2013, p.107). The energy demand in Sweden is predicted to increase in the future due to increased immigration as well as economical and industrial growth (IEA 2013, p.23). There is also a predicted increase of electricity as an energy carrier during a transition towards heat-pumps instead of oil, electric motors instead of gasoline engines and diesel engines (Sköldberg et al. 2010, p.15). At the same the remaining ten nuclear reactors built in the 1970s which are providing between 40-50% of the Swedish yearly electricity demand are getting old and there are no current plans to replace them (IEA 2013, p. 95).

Renewable primary energy sources such as wind, hydro, biomass and photovoltaics account for about 60% of the yearly generated electricity in Sweden (IEA 2013, p78pp). 80% of the renewable energy production comes from hydro power, making it the largest contributor when Sweden reached the 2020 targets of 50% renewables in 2013 (IEA 2013, p.85). Sweden has fully developed its hydro power potential and the remaining large rivers are preserved due to environmental concerns¹. Therefore, other types of renewables have to be utilized to meet the future demands if carbon- emissions are to be kept on similar levels (IEA 2013, p.129). One particular region that has a large share of renewables is the island Gotland. The local power company and distribution systems operator (DSO) GEAB has worked together with the municipality, private and government-owned companies to promote wind turbines (Region Gotland 2006). Gotland was the first test site for large turbines in the late 1970s and has currently 194 wind turbines operational (Wizelius 2007, p.44); The Wind Power 2016).

Apart from favourable wind conditions, Gotland has the most sunshine hours in Sweden and excellent conditions for Photovoltaic (PV) power systems (SMHI 2016). PV power is becoming more popular with both residential and commercial use (Lindahl 2014). Decreased costs and governmental support are two contributing factors as the installed capacity has doubled every year since 2010 (Lindahl 2014, p.3). Just as wind power development requires wind resource maps to estimate the potential production, PV power can be assessed in a similar way. Multiple regional studies have been carried out to determine the PV power potential on existing buildings. For example Lingfors & Widén (2014), Weiss & Widén (2012) and Kamp (2013). Gotland is located about 80 km from the mainland of Sweden and recieves its electric power supply by two submarine power cables (GEAB 2016). The capacity of the power cables determines how much electric energy Gotland is able to export and consume at any given time (Axelsson et al. 1999). A prospective submarine power cable with increased capacity is planned to be installed in 2021 to enable further renewable energy technologies (RETs) development (SEA 2016). Gotland provides a unique case of a region with great wind and solar resources limited by the electricity export capacity by the power cable.

¹ To maintain the landscape as hydropower requires river diversions and dams (IEA 2013, p.129).
1.1. Aims and objectives
This paper aims to investigating the theoretical solar PV power potential on existing buildings on the Swedish island Gotland by including existing wind power production, electric load and the power cable during 2010-2012.

1.1.1. Research Questions
What is the theoretical PV power potential for existing buildings on Gotland?

How is the theoretical potential spread between industrial buildings, dwelling buildings, multi-dwelling buildings and other buildings?

How will a combination of a large share of PV power and wind power perform on Gotland with the restrictions of the current and prospective submarine power cables?

How much PV power can be installed on Gotland considering the current and prospective submarine power cables?
1.2. Background
The energy mix in Sweden relies heavily on hydro- and nuclear power. Any future scenario without nuclear power requires an increased share of renewables (IEA 2013, p.24).

Fig. 1. Generated electricity in Sweden by energy source during 2013 (SEA 2014).

The Swedish island of Gotland has a large proportion of RETs in the energy mix. 194 wind turbines with a combined output of 194 MW provide about 40% or 417 GWh per year of the total electricity demand (Region Gotland, 2015; SCB, 2013). The regional municipality has a vision of a climate neutral electricity production in 2025 as well as being cutting edge when it comes to island based climate and energy solutions (Region Gotland 2010). As part of this vision, the county administrative board runs a yearly energy seminar to discuss and assess current and potential RETs opportunities (Region Gotland 2011). Current campaigns in the latest energy plan from 2010 focused on local renewable resources such as wind power, biogas, biomass and solar power. In the future, an increase to a total of 500 turbines with a rated output of 1500 MW is regarded to be possible (Region Gotland 2006). The Energy plan states that an installed capacity of about 20 MW PV power in 2025 is possible, which would only provide a small share to the total electricity demand, about 2% of the total end use (Region Gotland 2006). There is no official regional statistics for installed capacity for PV power in Sweden but as seen in (fig. 1), the yearly production was only 35 GWh in 2013. According to Lindahl (2014) the cumulative installed PV power capacity was 79.4 MW in 2014.

When it comes to solar radiation, Gotland has the best conditions for PV power in Sweden as seen in (fig. 2), with an annual irradiance of about 1050 kWh/m² per year. Regardless of the good conditions for PV power, wind power has been the dominating RETs on Gotland since the first experimental wind turbines were developed in the late 1970s (Wizelius 2007, p.18).

Increased local electricity generation will require reinforced infrastructure and an additional submarine power cable to export surplus electric production (Region Gotland 2011). The
existing power cable consists of two high-voltage direct current (HVDC) links with a capacity of 160 MW each (GEAB 2016). One of the power cables is designated for one way transmission to Gotland and the other is bidirectional so a total of 160 MW can be exported at any given time (Axelsson et al. 1999). A prospective submarine power cable is planned to be installed in 2021. The current limit, due to electricity export limitation for RETs on Gotland is 195 MW and the prospective power cable will increase the limit to 500 MW (Gotlands Kommun 2010; SVK 2016).
Solar Radiation in Sweden

Fig. 2. Solar Radiation in Sweden. Used with permission from SMHI (SMHI 2014).
1.2.1. Environmental goals and Future scenarios

The future for the Swedish electricity sector needs to be decided in the coming years due to aging nuclear power stations and the estimated increase in electricity demand. Sweden’s national environmental policy is divided into 16 environmental quality objects. The objectives are to be met within one generation (2050) and the actions required to achieve these goals are stated in the generation goal policy (SEPA 2016). To meet these 16 objectives until 2050, a transition towards a sustainable thinking in every sector and part of society is required. This means that the energy sector has to change and different future scenarios are currently being investigated. Four of these goals are directly linked to electricity generation:

- Reduced Climate Impact.
- Clean Air.
- Natural Acidification Only.
- A Good Built Environment.

SEPA (2016)

The Royal Engineering Academy of Sweden (IVA) has investigated the different pathways Sweden can take to meet the environmental goals and the electricity demand (Byman & Nordling 2016). The available electrical generation options, hydro, nuclear, biofuel, wind power and PV power are reviewed with regard to their maximum potential. IVA estimations are based on a future scenario with a peak demand of 26-30 GW and an annual demand of 140 – 200 TWh².

The prospective power potential displayed in (table. 1) can be combined in multiple ways and not all of the production potential for each energy source has to be utilized. Each energy source has its own advantages and disadvantages when it comes to economic factors, technical factors and social acceptance. An increase in hydro power would for example require diversions and an increased number of reservoirs in the few remaining unexploited rivers in the north of Sweden. Wind power would change the landscape and be a common sight along the coasts which got the best wind conditions. Biomass would require long transports and responsible farming. The issue with nuclear waste hasn’t been solved yet and the fear of accidents can reduce public support (Byman & Nordling 2016). PV power is available for both household and commercial use today. The advantage is that PV arrays can be mounted on existing buildings without interfering with the landscape and are virtually maintenance free during its lifetime of 15-30 years³ (Chen 2011, p.127)

Table. 1. Potential for different energy sources in Sweden today and in the future (Byman & Nordling 2016).

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Capacity today (TWh per year)</th>
<th>Future Potential (TWh per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro</td>
<td>65</td>
<td>100</td>
</tr>
<tr>
<td>Wind</td>
<td>15</td>
<td>≥100</td>
</tr>
<tr>
<td>Photovoltaic Power</td>
<td>0,1</td>
<td>50</td>
</tr>
<tr>
<td>Bio</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>Nuclear</td>
<td>65</td>
<td>≥100</td>
</tr>
</tbody>
</table>

According to Byman & Nordling (2016) the difference in cost per produced kWh between the prospective options is negligible when including the levelized cost of electricity. Wind and

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² The Swedish electricity demand was approximately 150000 GWh during 2014 (SEA 2014).
³ The inverter has a lifespan of about 15 years (Chen 2011, p.36).
PV power is regarded as variable renewable energy (VRE) as the electricity production changes with the weather and the seasons. The IVA report does not state that all of the peak demand need to be met by Swedish production but it requires the annual demand to be met (Byman & Nordling 2016). This is because the national grid has 16 international connections so Sweden can export and import electricity when needed to meet short term deficits (Byman & Nordling 2016).

1.3. Sustainable development and research mode
The first adopted definition of sustainable development derives from the Bruntland report which stats: "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (Brundtland et al. 1987). Robèrt et al. (2010) has expanded the original definition and formulated four principles that can be used as guidelines when taking actions towards a sustainable society:

In a sustainable society, nature is not subject to systematically increasing …

1. concentrations of substances from the earth’s crust.
2. concentrations of substances produces by society.
3. degradation by physical means.

(Robèrt et al. 2010, p.99)

These guidelines can be used when assessing the actions we take towards sustainability as they emphasize the earth to be viewed as a closed system (Robèrt et al. 2010, p.99). An important part of sustainable thinking is to improve and rethink current technologies as well as investigating future scenarios (Robert et al 2004, p.20). When sustainability is referred to in an energy context it is often synonymous with renewable energy. This is correct when renewable energy sources comply with the sustainability definitions. Compliance with all three sustainability principles requires not only a sustainable energy production but also a sustainable system approach, including construction, maintenance and local impact (Ramachandra & Shruthi 2007). Hydro power and wind power can for example degrade the nature by altering the landscape and interfere with the wild life (Wizelius 2007, p.194). Sustainable electricity production is one part in the challenge to a sustainable future and should be seen as a part in a larger system approach (Ramachandra & Shruthi 2007). Sustainable electricity production requires pilot studies of the different renewable options to assess the potential power output for specific regions and the environmental impact (Ramachandra & Shruthi 2007).

One research field is to calculate the potential for PV systems on existing buildings. The problem is that not all buildings are suitable for PV systems with regard to shading, tilt and azimuth angle (Chen 2011, p.83). The energy content of the solar radiation is also regional specific, making general estimations uncertain. Regional PV power potential studies has been carried out in Sweden by Lingfors & Widén (2014), Weiss & Widén (2012), Ekström (2012) and (Kamp 2013). All of these are based on methods by Weiss & Widén (2012) and Kjellsson (2000) using global irradiance data from the SMHI model STRÅNG (SMHI 2016. Weiss & Widén (2012) found the largest PV power potential to be on dwelling buildings, 443 GWh per year in Dalarna. A total potential of 670 GWh per year included dwelling buildings, multi-dwelling buildings, supplementary building and industrial buildings if the available roof area of 6956000 m² were used (Weiss & Widén 2012). In Blekinge, the total PV potential was

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4 Further explained in Section 3.
calculated to be 1200 GWh per year with an available roof area of 17000000 m² and 440 GWh for dwelling buildings (Lingfors & Widén 2014). More detailed studies using light detection and ranging (Lidar) data have been performed by Jakubiec & Reinhart (2013) and Brito et al. (2012) to determine the PV power potential in Cambridge and Lisbon. When studying the regional PV power potential it is also of interest to know when the electricity production will occur. An increased share of renewables in the energy mix will make these kind of predictions extra important as electricity output from renewables fluctuate more compared to thermal power stations (Rowlands et al. 2011). The electricity price is also dependent on the supply and demand of electricity and knowing when PV systems will generate electricity helps with the investment calculation (Rowlands et al. 2011).

The combination of wind power and PV power has been studies by Buttler et al. (2016). They compared PV power and wind power production with load data on a national and regional level in the EU member states. By using time series data from the transmission grid operators (TSO) their results displayed a variation in wind power production with peak production during the winter and PV power production peaks during the summer. Less variation were found in wind power compared to PV power (Buttler et al. 2016). In all EU membership countries the maximum PV power production was 66% of the installed capacity and for wind power 61%. On a national level the wind power production reached 100% of the installed capacity and PV power between 70-90% of the installed capacity (Buttler et al. 2016).

1.3.1. Previous Photovoltaic power potential studies on Gotland

One previous study of PV power potential has been performed on Gotland by (Ekström 2012). Ekström (2012) calculates the PV power potential from the gross space area of the type building found in the real estate tax assessments by Swedish statistics (SCB) and estimations on building size for non-residential buildings by Weiss & Widén (2012). The number of buildings derives from the building statistics supplied by Swedish statistics and the DSO GEAB for non-residential and industrial buildings. The study includes a net debit model in which the generated electricity on a monthly or yearly basis can be deducted from the electricity bill. The PV power potential was calculated to be 117 GWh per year for dwelling buildings and a total of 242 GWh per year for all investigated building types during 2010 (Ekström 2012). If heritage buildings were to be excluded the PV power potential was instead 231 GWh per year. The potential PV power capacity is not declared. The net debit model did not change the PV power potential if used on a yearly basis but reduced the potential if used on a monthly basis for dwelling and multi-dwelling buildings (Ekström 2012). The study focuses on the correct sizing of PV power for each type building during different economical compensation schemes.
1.4. Delimitations
The investigated building categories are those that are available from Statistics Sweden. It excludes military buildings, power stations, and other special government and private buildings such as communication buildings and waste-water treatment plants (SCB 2016a). The building data is only available for 2010, compared to the solar radiation data which is available on a yearly basis since 1999 (SMHI 2016). However, the building stock decreases and increases slowly over time. On a national level about 1% per year (SCB 2010), therefore it should not impact the accuracy of the PV power potential estimations significantly. Other methods to determine the PV power potential derives from studying Lidar maps which provides more accurate results as the roof area is being directly mapped from above. The Swedish mapping, cadastral and land registration authority (Lantmäteriet) are currently working on a Lidar map for Sweden and the project is estimated to be finished in 2017 (Lantmäteriet 2016). Lidar maps for certain areas are available as of today and there is also studies using Lidar data derived from private and municipal initiatives, for example (Jonsson & Lindberg 2011). As there is no high resolution Lidar data available for Gotland and the detailed vector property map is not available for students, this paper follows similar methods to the work by Kjellsson (2000) and Weiss & Widén (2012). Possible limitations of the local distribution and regional grid are also not included in this paper, only the limitation for the current and prospective submarine power cables. The PV power production, wind power production and load data are all derived from simulations over a three year period. Therefore the results should be used carefully. Wind speeds in particular can vary significantly over time and when comparing simulated production with real production a wind index can be used. The average wind speed at a site is measured over several years and the amount it deviates from a single year’s measurements is referred to as the wind index (Wizelius 2007, p.52). This study uses hourly values to determine the electricity production and overload. Electricity is however consumed and produced instantly; leaving a bias that it can display peaks and dips within the hour. This could potentially lead to overestimations of the PV power potential.

1.4.1. Solar PV Potential method
There are many methods and definitions when determining the PV power potential. This study examines the PV power potential for existing buildings by determining the roof area from the ground space area. Each building category is assigned a roof tilt and a set of limiting factors, azimuth angle, shading, and obstacles. The political and economic potential is not investigated. This is a widely used method but with the development of Lidar data more accurate results can be achieved.
2. Theory
This chapter describes the theory behind PV systems, wind power and the electric grid.

2.1. Solar Radiation
Direct radiation is the radiation that hits the ground unimpacted by the atmosphere. During a cloudy day the direct radiation measured on the ground will be zero as the direct radiation has been scattered by the clouds. Instead it is measured as diffuse radiation. Smog and water vapour can also scatter the direct radiation, even on a sunny day, the surface of the earth will experience a combination of direct and diffuse radiation. Albedo, or the reflection coefficient of surrounding surfaces describes how much radiation that is being reflected from an object or a surface (Ineichen et al. 1990). In Sweden the mean value is 20% but it depends on the properties of the surface, snow for example has an albedo between 50-80% (Weiss & Widén 2012). The reflected radiation deriving from both direct and diffuse radiation is called ground-reflected radiation.

Direct, diffuse and ground reflected radiation together determines the production of the PV cell and it is referred to as global radiation, measured in W/m² by SMHI. The average global radiation in Sweden is about 1 kWh/m² per year (Persson 2000).

2.1.1. Tilt, Angle, Latitude
The amount of global radiation hitting a flat surface depends on the latitude and the time of the day. The amount of direct radiation hitting a tilted plane is also dependent of the azimuth angle and the tilt of the plane.

2.2. Photovoltaic Cells
About 90% of the PV cells produced and used today are constructed out of crystalline silicon (Saga 2010). How they utilize the photoelectric effect to produce electricity as described below

Photovoltaic cells are constructed out of two or more semiconducting layers, usually made out of silicon. The different semiconducting layers are referred to as the p-layer and the n-layer. The p-layer is constructed of boron doped silicone, giving it a positive potential (Saga 2010). The n-layer is constructed so that it has an abundance of electrons from being doped in phosphororous, giving it a negative potential. The n-layer is on top of the p-layer, creating a band gap between the two layers. The band gap represents the minimum energy required to excite an electron from its bound state into its free stage. The energy of the incoming photons determines if they will interact with the layers, if the photon has less energy than what is required by the band gap it will not excite the electron (Saga 2010). If the photon's energy is equal or above the band gap it will be absorbed and excite the electron. When a photon with enough energy hits the n-layer it excites a negative charged electron, which migrates to the p-layer creating a potential difference. If the PV cell is connected to a load the electrons will flow through the load and create work (Chen 2011, p.150ff).

The voltage of the PV cell is determined by the band gap between its layers. The larger the band gap is, the higher is the voltage but a high band gap also requires high energy photons. The band gap is therefore matched with the energy content of the centre of the solar spectrum. A solar module consists of many PV cells which are serially connected to increase the voltage output (Chen 2011, p.130).
2.2.1. Inverter
PV cells produce direct-current (DC) and the power grid is designed for alternating current (AC). PV cells in a grid-connected PV system are connected to an inverter. The inverter changes direct current into alternating current to the desired voltage and frequency. Swedish standard is 230 V and 50 Hz (Moren 2013). Depending on the system design, multiple PV arrays can either be connected serial or parallel. Serial connection increases the voltage and parallel connections increase the current. There are also combinations of the two installation methods and the installation method depends on the inverter specifications (Chen 2011, p.176ff).

2.3. Types of Photovoltaic Cells
Crystalline PV cells can be divided in two main categories, monocrystalline and polycrystalline. Thin film PV cells can be made out of a number of materials in which silicone is one (Chen 2011, p.90). In order to compare the efficiency of different PV cells Standard Test Conditions (STC) following the IEC 60904-1 are used which states the following conditions (Muñoz-García et al. 2012).

- Irradiance: 1000 W/m².
- Cell temperature: 25°.
- Spectral distribution: AM 1.5 (according to IEC 60904-3) (Geneva, 2008).

(Muñoz-García et al. 2012)

2.3.1. Polycrystalline
Polycrystalline cells are made out of casted silicon which produces a mixture of crystal shapes. This makes them less efficient compared to polycrystalline cells but they are also less expensive and the production process produces less waste. They have an efficiency (STC) of 13-16% (Energy Informative 2016).

2.3.2. Monocrystalline
Monocrystalline cells are made out of very clear crystal in which the molecules are perfectly aligned with each other. This gives monocrystalline cells a better performance and the efficiency is usually between 15- 20% (STC). The production process is more demanding and only the best silicone can be used which increases waste in the production process (Energy Informative 2016).

2.3.3. Thin-Film
Thin-film PV cells have increased its market share lately to about 5 % of the installed capacity worldwide in 2015 (Energy Informative 2016). They can be made out of a number of photovoltaic elements. Some of the photovoltaic elements used are very efficient at capturing the solar radiation which is why they can be made very thin and they are generally considered to have an advantage over silicon cells to capture diffuse radiation (Energy Informative 2016). For commercial use the efficiency is between 10-16% but there are research projects that have developed thin-film cells with 20% efficiency which is 2/3 of the theoretical efficiency of PV cells (UU 2016).

2.4. Wind speed and the power of the wind
The wind speed at a specific site and altitude depends on a multiple of meteorological and terrain factors. Rough terrain and obstacles decreases the wind speed and creates turbulence and hills can increase the wind speed up to certain altitudes. The terrain can be divided into multiple roughness classes in which open sea is given roughness class 0 and large cities 4 (Wizelius 2007, p.42). This classification is used when creating wind resource maps for
suitable areas and in wind energy software to simulate the electrical production. The power of the wind is proportional to the cube of the wind speed and depends on the density of the air (Wizelius 2007, p.44ff).

The following equation is used for calculating the power of the wind:

\[ P_{kin} = \frac{1}{2} \varphi AV^3 \]

\( P_{kin} \) = Power (W)
\( \varphi \) = Density (Kg/m\(^3\))
\( V \) = Wind Speed (m/s)
\( A \) = Area (m\(^2\))

(Wizelius 2007, p.48)

Wind turbines are designed to work at certain wind conditions with a cut-in speed between 3-4 m/s and a cut-out speed of about 25 m/s. The rated output power of the turbine is reached at a certain wind speed which remains constant until the cut-off speed in which the turbine moves away from the wind to stop damage. This is referred to as the wind turbines power curve (Wizelius 2007, p.120ff). As the wind speed increases, a 2 MW turbine will produce less before it reaches its rated output power of 2 MW at 15 m/s and will continuously produce 2 MW while the power control reduces the speed of the turbine to avoid damage (The Danish Wind Industry Association 2003).

2.5. Electrical grid

The electrical grid in Sweden has originally been constructed to accommodate electric power production from hydroelectric power in the north with electric power consumption in the more populated southern parts.

2.5.1. National grid

The National grid is owned and operated by Svenska Kraftsnät (SVK) a state-owned electric transmission systems operator. SVK has the overall responsibility of the grid including balance management in which they have the authority to order power companies to increase or decrease production as well as cut of electricity to energy intensive industries in case of severe drop-outs. The voltage in the transmission grid is between 220 and 400 kV (SVK 2015).

2.5.2. Regional grid

The regional grid is owned by a number of private companies and is connected to the national grid to provide electricity to sub-regions. Certain industries can be connected to the regional grid as well as medium sized power stations or wind turbines. The voltage of the regional grid does not exceed 220 kV (SVK 2015).

2.5.3. Distribution grid

The distribution grid provides electricity to the household consumer, industry and utilities. The end user is usually connected to a 400 V three-phase system (SVK 2015).
2.5.4. Price areas
The Swedish electrical grid is interconnected to its neighbouring countries and the price of electricity for the northern and Baltic countries are set on the power exchange market Nord Pool. To comply with EU market regulations Sweden has since 2008 been divided into four bidding areas to enable fair market conditions between all bidding areas on Nord Pool (SVK 2015). Price areas are constructed so that areas with a lot of electric generation will have a lower price (Nordpool 2016).

2.6. Distributed generation
Electricity has traditionally been produced in large centralized power stations and transmitted in the national grid to high consumption areas. Hydro-electric production in the rivers in the north of Sweden, wind power parks in coastal regions such as Gotland with good wind resources as well as off-shore wind parks can be connected to the national or regional grid if they are large enough (Wizelius 2007, p.206). However with distributed RETs, production is becoming decentralized and production is shifted towards areas with favourable conditions such as a few wind turbines on farm land, PV systems on buildings and existing but very limited, residential wind turbines (SVK 2015). As the distribution- and regional grid is built for one way transmission from the power station to the consumer, distributed generation provides challenges for the DSO as the grid now have to accommodate bidirectional power distribution. However depending on the existing infrastructure, a certain amount of additional power production is usually possible. The upper limit of additional power production that can be connected to the grid is called hosting capacity (Kupzog et al. 2014). The hosting capacity has been described by Yang & Bollen (2008) as:

"The hosting capacity is defined as the maximum distributed generation (DG) penetration for which the distribution network still operates according to design criteria and network planning practices based on the European standard EN50160" (Yang & Bollen 2008).

The main issue with distribution generation in the local distribution grid is voltage rise and overload on the power cables and transformers. The power quality in the grid is regulated by the Electricity Act and states that the acceptable variations for a number of parameters (Moren 2013). The Swedish end consumer in the low voltage distribution grid is connected to a 400 V three-phase system with a frequency of 50 Hz. The acceptable voltage variation is ±10% and the unbalance between the three phases can’t exceed 2 % during any ten minute interval measured over a week (Moren 2013). PV systems connected to a single phase inverter can contribute to unbalanced circuits and therefore the recommendation is to install a maximum of 3 KW PV power to a single phase inverter (Chen 2008: 210). When production is high and the consumption is low, usually during noon in the summer, PV systems can increase the voltage in the distribution grid. The maximum hosting capacity of the distribution grid can therefore be estimated by the worst case scenario of which there is no consumption and maximum production (Yang & Bollen 2008). Studies of the hosting capacity in the Swedish low voltage distribution grid, for example Walla (2012, p.44) found larger hosting capacity in the city grids compared to those on the countryside.

2.7. Electrical grid on Gotland
The electrical grid on Gotland is connected to the Swedish mainland by two HVDC submarine cables. The current cables are designed so that one cable is bidirectional with the ability to export surplus electricity while the other remains one-way transmissions to Gotland to ensure electricity demand and grid stability as well as frequency reference (Axelsson et al. 1999). To supply Gotland with electricity during Island mode, two gas turbines of 60 MW each are located in Slite as the main backup power (GEAB 2016). There is also a diesel power
station in Visby producing 36 MW, four gas turbines in Bäcks of 12 MW and two 10 MW gas turbines operated by the industry Cementa (Lambert 2012). According to SVK and the local power company GEAB, the maximum capacity of the exporting submarine cable has been reached by the wind power capacity (SVK 2015; Geab 2016). The current capacity limit of RETs at Gotland is set at 195 MW installed capacity (Brodén 2013). This is more than the submarine cable can export but is considered to be the upper limit by the DSO (GEAB 2014). To enable further wind power development and Gotland’s long term energy stability, a prospective submarine power cable with a capacity of 300 MW will be installed in 2021. The prospective cable will operate together with the old cables increasing the RETs capacity to a total of 500 MW (SVK 2015).

2.8. Microgeneration

The majority of PV systems are connected to the low voltage distribution grid. No official statistics for the share of PV systems connected to the low voltage distribution grid are available in Sweden, but for Germany the share is over 85% in Germany (Kupzog et al. 2014). In Sweden, everyone with an electric meter has the right to install a RETs system and connect it to the meter. The power company is obligated by law to change the electric meter and reinforce the grid if necessary (SEMI 2015). As the electricity market is deregulated there is no obligation for a power company to purchase the surplus electricity from the micro producer but there are many companies to choose from that will buy the surplus electricity and it doesn’t have to be the same company as the grid operator (SEA 2016). Current regulations require the following two demands to be met to qualify as a micro producer:

- Maximum installed power production capacity of 43.5 KW.
- Larger electricity consumption than electricity production from RETs on a yearly basis.

(SEA 2016)

As of 2015 there is both a tax support system and an investment cost support system available for micro producers. The tax reduction is SEK 0.60 for every surplus kWh produced and is set to maximum SEK 18000 per year (STA 2016). The investment support system is frame-limited with a governmental contribution of SEK 225 million in 2016 and SEK 335 million each year from 2017-2019. The maximum support for each facility is SEK 1.2 million or 20% for private individuals and 30% for companies (SEA 2016).

2.9. Electric load

The electrical grid needs to be in balanced at all times with an electrical supply meeting the electrical demand. To guarantee power supply, production is split between base load power plants which provide stable and cheap electricity together with load following power plants. These should be easily adaptable to alter the output and gas-turbines and hydroelectric power plants provide this roll (Camacho et al. 2011). Wind power and PV power production depends on the weather and therefore require a larger share of load following power plants to step in and guarantee production (Chen 2011, p.46). The demand side or load changes with the seasons; more electricity is used for heating during the winter in northern countries compared to more electricity used for air conditioning in southern countries. In a domestic situation the consumption changes during the day with peaks during the morning and evening when people are home from work. Industries can have a steady load if they are operated day and night (Chen 2011, p.51).
The situation on Gotland with a large share of wind power and a limited population means that when the wind turbines output is maximized the production is greater than the load and electricity needs to be exported by the submarine cable to other users. A scenario with production from both PV power and wind power, requires that the output to be determined together with the load to see if the limit of the submarine cable is meet during any given time. The load profile on Gotland displays peak demand during the winter months regardless of the population increase during the summer (Lambert 2012).
3. Methods and Data
The method section describes the process of determining the available roof area for PV cells when being calculated from the ground space area and wind power production. This process can be seen in (Fig. 3).

![Flow Chart of the method of determining the PV power for building](image)

Fig. 3. Flow Chart of the method of determining the PV power for building (Weiss & Widén 2012).

3.1. Solar radiation
Solar radiation data has been collected by SMHI since 1961, and after 1983 due to increased climate concern the radiation measuring program increased in size and has of today 12 measuring stations in Sweden (Persson 2000). SMHI measures solar radiation on a horizontal surface at an altitude between 4-15 meters with a pyranometer, a type of radiometer used to measure solar radiation (Persson 2000). The uncertainty of the hourly measurements is estimated to be between 3-4% and 2% for the yearly values. The solar radiation database STRÅNG has hourly values over radiation in Sweden since 1999 and global irradiance can be acquired directly in the database (SMHI 2016). The following measuring station in (table. 2) is used throughout the study.

Table. 2. Visby Measuring Station (SMHI 2012).

<table>
<thead>
<tr>
<th>Measuring station</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Average Global Radiation per between 1999-2015 kWh/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visby</td>
<td>57.67 North</td>
<td>18.35 East</td>
<td>1046</td>
</tr>
</tbody>
</table>

3.2. Building types and building area
The building data is collected from SCB in which the total building area and ground space area can be extracted on both national and regional level. A building is according to the Swedish planning and building act:

“A permanent structure intended for occupation by people consisting of a roof and/or walls and is permanently placed on the ground or completely or partially below the ground or permanently placed in water” (SFS 2016, p. 252).

The data is being updated every five years and the only available data as of today is from 2010 (SCB 2010). The building categories in the SCB data derives from the real property register and are matched with the Cadastral map from The Swedish mapping, cadastral and land registration authority which displays property and land ownerships (SCB 2010). If the

5 Translated by the author
two registers don’t match the building is categorized as uncoded. The number of buildings and ground space area derives from the real property register. Ground space area is the area of the building including its outer walls (SCB 2010). The buildings are organized in four categories with the category other buildings including Building for public service purpose, Building for business purpose, Outbuilding, Supplementary building. The following building categories are used throughout the study.

- Dwelling
- Multi-Dwelling Building
- Industrial Building
- Other Buildings

3.2.1. Roof Shape and angle

All buildings in the same category do not have the same roof shape but according to Kjellsson (2000) there is a pattern for the different building categories. The majority of dwelling buildings are constructed with a saddleback roof as shown in (Fig. 4). Mansard, flat, one-sided and other types of roofs exist as well but are not as common. The most common tilt of the saddleback roof is 30 ° which is used throughout in this study (Kjellsson 2000). Industrial buildings roof shape have not yet been categorized but in studies such as Weiss & Widén (2012) and Lingfors & Widén (2014) a flat roof is used.

3.3. Building categories

Table. 3. Building category and characteristics (Kjellsson 2000; Weiss & Widén 2012).

<table>
<thead>
<tr>
<th>Building Category</th>
<th>Roof Pitch °</th>
<th>Roof Type%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwelling</td>
<td>30</td>
<td>Saddleback Roof</td>
</tr>
<tr>
<td>Multi-Dwelling Building</td>
<td>30</td>
<td>Saddleback Roof 85%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flat Roof 15%</td>
</tr>
<tr>
<td>Industrial Building</td>
<td>0</td>
<td>Flat Roof</td>
</tr>
<tr>
<td>Other Buildings</td>
<td>30</td>
<td>60% Saddleback Roof</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40% Flat Roof</td>
</tr>
</tbody>
</table>
3.3.1. Roof Type

![Roof Diagram]

Fig. 4. Most common building type according to (Kjellsson 2000). Dwelling building with 1.5 floors and a Saddleback roof with a tilt of 30 degrees.

3.3.2. Roof area

The following equation is used to determine the roof area:

\[ A_{\text{Roof}} = \frac{A_{\text{Flat Roof Area}}}{\cos \beta} \]

- \( A_{\text{Roof}} \) = Total roof area (m²).
- \( A_{\text{Flat roof area}} \) = Area measured from above (m²).
- \( \beta \) = Angle of roof inclination (°).

(Weiss & Widén 2012)

3.4. Azimuth angle

The azimuth angle describes the compass direction at which an object is located. South equals 0, West 90, East -90 and North 180 (Chen 2011, p.142). A building as seen in (Fig. 5), the pitched roof sides are facing 90 ° west respectively -90° east. A building with a saddleback roof will have one side shading the other, how much depending on the azimuth angle and the hour angle. A flat roof has no shading from the opposite side and the azimuth angle of the building is insignificant (Chen 2011, p.142). The tilt of the roof is measured in degrees° relative the horizontal. 0° equals a flat roof and 180° a roof turned upside down (Weiss & Widén 2012).
Fig. 5. Standard dwelling building in relation to the cardinal direction.

The azimuth angle of the building stock is regarded to be undiversified by both Weiss & Widén (2012) and Kjellsson (2000). However, Lingfors & Widén (2014) found that both dwelling and apartment buildings in the Swedish region of Blekinge displayed a predominantly angle towards North/South and West/East, as seen in (Fig. 5). Without available maps, the buildings are estimated to be equable situated on all 360° as seen in (Fig. 11).

3.4.1. Azimuth angles impact on a tilted surface respectively flat surface

Figures 6-8 displays the changes in solar radiation hitting a tilted and flat surface depending on the azimuth angle. The change in production corresponds to changing the position of the house in (fig. 5), 90° degrees at the time.
Fig. 6. Solar radiation hitting flat respectively tilted surface at 0°.

Fig. 7. Solar radiation hitting flat respectively tilted surface at 90°.
Fig. 8. Solar radiation hitting flat respectively tilted surface at -90°.

Fig. 9. Solar radiation hitting flat respectively tilted surface at 180°.
Buildings with saddleback roofs are distributed to have one side of the roof facing one of the six lighter areas towards the south, 1/6 in each, see (Fig. 11). The opposite side is facing north, which is regarded to be unsuitable for PV power due to unfavourable solar radiation conditions, resulting in very low production (Weiss & Widén 2012).

3.4.2. Buildings azimuth orientation
Distribution of building with saddleback roof. 1/6 in each light section with the opposite side facing north excluded from the calculation.

![Diagram of building azimuth orientation](image)

Fig. 10. Distribution of saddleback roofs by azimuth orientation (Weiss & Widén 2012).

3.4.3. Available area for PV arrays on a flat roofs
Flat roofs can seem to be optimal as the azimuth is not of importance as seen in (fig.6) to (fig. 8). But as seen in (fig. 6.), a tilted roof in the optimal azimuth angle receives the most radiation of all surfaces, almost twice compared to a tilted plane facing north as in (fig. 9). The optimal tilt depends on the distance from the equator and changes over the year. When PV arrays are mounted on a flat roof with a tilt, the larger the tilt the more shading occurs.
from the PV array in front which will reduce the PV power production. The optimal tilt for a flat roof installation is regarded to be 30° when both efficiency and space is taken into consideration (van Noord & Paradis 2011). PV arrays can’t be mounted to close to each other because the tilted PV array in front will shade the system behind it. The recommendation to optimize production on a flat roof is to install the PV arrays with a tilt 30° and a distance of 2.5 times the height of the PV-array. By doing so 60% of the flat roof area is available for PV arrays (van Noord & Paradis 2011).

![Diagram](image)

**Fig. 11.** Optimal installation for PV arrays on a flat roof surface in Sweden. X represents the height of the PV array Van Noord & Paradis (2011).

### 3.5. Additional limiting factors

Limitations for PV arrays on roofs include structures such as smoke and ventilation chimneys, Mansards, drainage, skylights and ladders. Kjellsson (2000) estimates the following reductions to be suitable for Swedish buildings.

Table 4. Obstacles on roofs (Kjellsson 2000).

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Reduction %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwelling</td>
<td>10%</td>
</tr>
<tr>
<td>Multi-Dwelling</td>
<td>20%</td>
</tr>
<tr>
<td>Industry</td>
<td>20%</td>
</tr>
<tr>
<td>Other</td>
<td>20%</td>
</tr>
</tbody>
</table>

In addition to structural objects of the roof, the surrounding structures such a building and trees can have a shading effect on the roof, reducing the output of the PV system. This is less of a problem for standalone buildings on the countryside as seen in (fig. 5.) but can be a significant limiting factors in cities where most of apartments and public buildings are located (Kjellsson 2000).

#### 3.5.1. Shading

Table 5. Losses due to shading (Kjellsson 2000).

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Reduction %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwelling</td>
<td>10%</td>
</tr>
<tr>
<td>Multi Dwelling</td>
<td>15%</td>
</tr>
<tr>
<td>Industry</td>
<td>10%</td>
</tr>
<tr>
<td>Other</td>
<td>20%</td>
</tr>
</tbody>
</table>
3.5.2. Snow and soiling losses
Two other factors to consider are snow and dirt on the panels. As PV arrays in Sweden usually are installed with a tilt of about 30° and the production is low during the winter, snow is not considered to be a large problem (Kjellsson 2000). Pollen, algae and pollution can soil the PV array but the reduction from soiling is debatable. However snow and rain will clean the panels and Mejia & Kleissl (2013) found that PV arrays during a period of 146 days without rain only suffered a reduction of 7.4% in efficiency. Therefore the effect of snow and soiling losses will not be included in this study.

3.6. Total reductions
Table 6. Available Roof area after reduction (Kjellsson 2000).

<table>
<thead>
<tr>
<th>Building Category</th>
<th>Reduction Obstacles %</th>
<th>Reduction Shading %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwelling</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Multi-dwelling</td>
<td>20%</td>
<td>15%</td>
</tr>
<tr>
<td>Industry</td>
<td>20%</td>
<td>10%</td>
</tr>
<tr>
<td>Other</td>
<td>20%</td>
<td>20%</td>
</tr>
</tbody>
</table>

Each of the building categories is given a certain type building that is based on the total available ground space area divided by the number of buildings. These are then used in the PV system software, PVsyst to simulate the electric production (PVsyst 2016). The results are then scaled up by the number of buildings to provide the total PV power potential on Gotland.

3.7. Data and building categorization
Table 7. Buildings, number of buildings and ground space area (SCB 2010).

<table>
<thead>
<tr>
<th>Building Category</th>
<th>Number of buildings</th>
<th>Ground space area of buildings m²</th>
<th>Average Size. Area m²/Number of Buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2010</td>
<td>2010</td>
<td>2010</td>
</tr>
<tr>
<td>Residential building</td>
<td>27591</td>
<td>3722818</td>
<td>135</td>
</tr>
<tr>
<td>Industrial building</td>
<td>473</td>
<td>388444</td>
<td>821</td>
</tr>
<tr>
<td>Building for public service purpose</td>
<td>1167</td>
<td>520503</td>
<td>446</td>
</tr>
<tr>
<td>Building for business purpose</td>
<td>752</td>
<td>345390</td>
<td>459</td>
</tr>
<tr>
<td>Outbuilding</td>
<td>50</td>
<td>14552</td>
<td>291</td>
</tr>
<tr>
<td>Supplementary building</td>
<td>46778</td>
<td>5615888</td>
<td>120</td>
</tr>
<tr>
<td>Other building</td>
<td>119</td>
<td>11653</td>
<td>98</td>
</tr>
<tr>
<td>Uncoded</td>
<td>Missing value</td>
<td>4957</td>
<td>Missing value</td>
</tr>
<tr>
<td>Total</td>
<td>76930</td>
<td>10624205</td>
<td>2371</td>
</tr>
</tbody>
</table>

Residential building includes both dwelling buildings, apartment buildings (more than 4 apartments) and small apartment buildings (less than 4 apartments). From the dwelling stock register, the area and number of dwelling buildings, apartment buildings and other buildings are used to separate the residential buildings into dwelling buildings and multi-dwelling buildings and others.
Table 8. Residential buildings divided by category (SCB 2016; SCB (2016a)).

<table>
<thead>
<tr>
<th>Building Category</th>
<th>Number of buildings</th>
<th>Ground space area of buildings m²</th>
<th>Average Size. Area m²/Number of Buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwelling</td>
<td>17594</td>
<td>2707762</td>
<td>154</td>
</tr>
<tr>
<td>Multi Dwelling Building</td>
<td>9997</td>
<td>1015056</td>
<td>102</td>
</tr>
</tbody>
</table>

From (table 7) the additional buildings are merged into two categories in which Building for public service purpose, Building for business purpose, Outbuilding, Supplementary building and other building forms one category and Industry buildings forms another. The categories are created to make the data handling and result presentation clearer.

Table 9. Ground space area and number of buildings for all building categories (SCB 2010; SCB 2016; SCB (a) 2016).

<table>
<thead>
<tr>
<th>Building category</th>
<th>Number Of Buildings</th>
<th>Ground space area of buildings m²</th>
<th>Average Size. m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwelling</td>
<td>17594</td>
<td>2707762</td>
<td>154</td>
</tr>
<tr>
<td>Multi Dwelling Building</td>
<td>9997</td>
<td>1015056</td>
<td>102</td>
</tr>
<tr>
<td>Industrial Building</td>
<td>473</td>
<td>388444</td>
<td>821</td>
</tr>
<tr>
<td>Other Buildings</td>
<td>48866</td>
<td>6512943</td>
<td>133</td>
</tr>
<tr>
<td>Total</td>
<td>76930</td>
<td>10624205</td>
<td>242</td>
</tr>
</tbody>
</table>

Table 10. Available area for PV arrays after all reductions.

<table>
<thead>
<tr>
<th>Building Category</th>
<th>Ground space area of buildings m²</th>
<th>Available Roof Area m²</th>
<th>Area available after Azimuth reductions</th>
<th>Available area after all reductions m²</th>
<th>Number of Buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwelling</td>
<td>154</td>
<td>178</td>
<td>89</td>
<td>71</td>
<td>17594</td>
</tr>
<tr>
<td>Multi Dwelling Building Tiled Roof</td>
<td>102</td>
<td>118</td>
<td>59</td>
<td>38</td>
<td>8498</td>
</tr>
<tr>
<td>Multi Dwelling Building Flat Roof</td>
<td>102</td>
<td>102</td>
<td>102</td>
<td>40</td>
<td>1499</td>
</tr>
<tr>
<td>Industrial Building</td>
<td>821</td>
<td>821</td>
<td>821</td>
<td>493</td>
<td>473</td>
</tr>
<tr>
<td>Other Buildings Tilted Roof</td>
<td>133</td>
<td>154</td>
<td>77</td>
<td>46</td>
<td>29320</td>
</tr>
<tr>
<td>Other Buildings Flat Roof</td>
<td>133</td>
<td>133</td>
<td>133</td>
<td>52</td>
<td>19546</td>
</tr>
</tbody>
</table>
The PV power potential is calculated from the solar power software PVsyst (PVsyst 2016). The simulation is performed with monocrystalline PV arrays and an inverter matching the size of the PV arrays. The PV power output is used in this study is taken from the power supplied by the inverter. The simulated output includes all transmission losses in the system as well as temperature variations to provide as accurate simulation results as possible.

### 3.8. Load data and electric energy consumption

Hourly load data is simulated to compare the production from the wind turbines and PV power with the consumption to investigate the capacity limit of the submarine cable.

The total electric energy consumption for each year and sector in MWh is available from (SCB 2013). Hourly load data has been calculated from the energy software Homer in which the yearly electric consumption and scaled annual average load is used. The annual average load has been collected from the DSO GEABs statistics over a 24 hours period GEAB (2016) together with previous work by Lambert (2012) and Brodén (2013). The load profile changes over the day and is set to have its peak load in January and is designed for multiple users. According to Lambert (2012) the load profile on Gotland displays a peak during the winter months regardless of the population increase during the summer months.

Table. 11. Electric energy consumption over different categories and years on Gotland (SCB 2016).

<table>
<thead>
<tr>
<th>Category</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>75434</td>
<td>65293</td>
<td>77583</td>
<td>74375</td>
<td>91131</td>
</tr>
<tr>
<td>Industry and Construction</td>
<td>290344</td>
<td>302187</td>
<td>294001</td>
<td>323069</td>
<td>84441</td>
</tr>
<tr>
<td>Public Sector</td>
<td>92108</td>
<td>73738</td>
<td>76460</td>
<td>84510</td>
<td>90005</td>
</tr>
<tr>
<td>Transportation</td>
<td>324</td>
<td>155</td>
<td>311</td>
<td>324</td>
<td>232</td>
</tr>
<tr>
<td>Other Services</td>
<td>156626</td>
<td>162321</td>
<td>152537</td>
<td>145851</td>
<td>293972</td>
</tr>
<tr>
<td>Dwelling houses</td>
<td>207525</td>
<td>186973</td>
<td>169752</td>
<td>172102</td>
<td>201998</td>
</tr>
<tr>
<td>Apartments</td>
<td>32741</td>
<td>38408</td>
<td>34431</td>
<td>34127</td>
<td>77172</td>
</tr>
<tr>
<td>Holiday Houses</td>
<td>0</td>
<td>53148</td>
<td>46634</td>
<td>48001</td>
<td>45676</td>
</tr>
<tr>
<td>Total</td>
<td>855102</td>
<td>882223</td>
<td>851709</td>
<td>882359</td>
<td>884627</td>
</tr>
</tbody>
</table>

### 3.9. Wind power simulation and data

Gotland has 194 wind turbines with a total installed capacity of 194 MW. The average output of each turbine is about 1 MW and the capacity ranges between 0.1 MW to 3MW per turbine (The Wind Power 2016). Hourly Wind data from two measuring masts have been used, located at Hoburgen and Fårösund (SMHI 2016a).


<table>
<thead>
<tr>
<th>Measuring Station</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Height above ground (m)</th>
<th>Average Yearly Wind speed m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hoburgen</td>
<td>56.92 North</td>
<td>18.15 East</td>
<td>39</td>
<td>6.2</td>
</tr>
<tr>
<td>Fårösund</td>
<td>57.91 North</td>
<td>18.96 East</td>
<td>13</td>
<td>5.8</td>
</tr>
</tbody>
</table>
Two different types of wind turbines have been chosen to simulate the wind power production at Gotland. Their respectively power curves are displayed below. The wind speed refers to the wind speed at hub height.

![Power Curve, Vestas V82 1650 KW](image1)

Fig. 12. Power Curve, Vestas V82 1650 KW.

![Power Curve, Enercon 330 330 KW](image2)

Fig. 13. Power Curve, Enercon 330 330 KW.
The turbines used in the calculations are matched with the current installed capacity and the number of turbines is split between the two wind resource sites. A roughness value of 1.5 is set to match the terrain conditions at Gotland (Wizelius 2007, p.42).

Table. 13. Turbines and wind resources used in the simulation.

<table>
<thead>
<tr>
<th>Turbine</th>
<th>Wind Resource Hoburgen. Number of Turbines</th>
<th>Wind Resource Fårösund. Number of Turbines</th>
<th>Hub Height (m)</th>
<th>Roughness</th>
<th>Total</th>
<th>Total Output Power MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vestas V82</td>
<td>49</td>
<td>49</td>
<td>59</td>
<td>1.5</td>
<td>98</td>
<td>162</td>
</tr>
<tr>
<td>Enercon 330</td>
<td>49</td>
<td>49</td>
<td>49</td>
<td>1.5</td>
<td>98</td>
<td>32</td>
</tr>
<tr>
<td>Total</td>
<td>98</td>
<td>98</td>
<td>1.5</td>
<td>194</td>
<td>196</td>
<td>194</td>
</tr>
</tbody>
</table>

3.10. Hourly comparison
The simulated hourly PV power production, wind power production and load simulation is compared during 2010-2012. The total PV power potential with the existing submarine power cable is given by the following equation for every hour 2010-2012.

The following equation is used to calculate the PV power potential with the existing power cable:

\[ PV \text{Power}_{x,MW} + Wind \text{Power}_{194,MW} \leq \text{Load} + 160 \text{ MW export capacity} \]

The following equation is used to calculate the PV power potential with the prospective submarine power cable:

\[ PV \text{Power}_{x,MW} + Wind \text{Power}_{194,MW} \leq \text{Load} + 460 \text{ MW export capacity} \]

\[ PV \text{Power}_{x,MW} = \text{Simulated PV power production per hour.} \]

\[ X = \text{Maximum PV power production without creating overload on the submarine power cable.} \]

\[ Wind \text{Power}_{194,MW} = \text{Simulated wind power production per hour.} \]
4. Results
This section displays the results from the PV power simulation, wind power simulation and load simulation. Figures with hourly data and type building specifics can be found in Appendix A-C.

4.1. Summary of the PV power potential 2010-2012
Table. 14. Total PV power potential on Gotland 2010-2012. The total PV power potential is calculated to be 667 MW.

<table>
<thead>
<tr>
<th>Building Category</th>
<th>Available area for PV arrays. m²</th>
<th>Number of Buildings</th>
<th>Output MW</th>
<th>Yearly Production MWh. 2010</th>
<th>Yearly Production MWh. 2011</th>
<th>Yearly Production MWh. 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwelling</td>
<td>1249174</td>
<td>17594</td>
<td>190</td>
<td>186000</td>
<td>185000</td>
<td>186000</td>
</tr>
<tr>
<td>Multi-Dwelling</td>
<td>382884</td>
<td>9977</td>
<td>62</td>
<td>57700</td>
<td>57100</td>
<td>57200</td>
</tr>
<tr>
<td>Industry</td>
<td>233189</td>
<td>473</td>
<td>44</td>
<td>38100</td>
<td>38000</td>
<td>38100</td>
</tr>
<tr>
<td>Other Building</td>
<td>2365112</td>
<td>48866</td>
<td>371</td>
<td>352000</td>
<td>351000</td>
<td>352000</td>
</tr>
<tr>
<td>Total</td>
<td>4230359</td>
<td>76910</td>
<td>667</td>
<td>634000</td>
<td>631000</td>
<td>633000</td>
</tr>
</tbody>
</table>

The total PV power potential between 2010-2012 can be seen in (table. 14) and (Fig. 14). The simulated result for each building type is found in (table. 15) which displays the potential for a single generic building.

Fig. 14. Total PV power production per month 2010-2012.
Table. 15. Summary of each building types potential 2010-2012.

<table>
<thead>
<tr>
<th>Type of Building</th>
<th>Output kW per building</th>
<th>Yearly Production kWh per building. 2010</th>
<th>Yearly Production kWh per building. 2011</th>
<th>Yearly Production kWh per building. 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwelling</td>
<td>1</td>
<td>10543</td>
<td>10530</td>
<td>10545</td>
</tr>
<tr>
<td>Multi-Dwelling</td>
<td>6.5</td>
<td>5787</td>
<td>5722</td>
<td>5730</td>
</tr>
<tr>
<td>Industry</td>
<td>91</td>
<td>80502</td>
<td>80426</td>
<td>80502</td>
</tr>
<tr>
<td>Other Building</td>
<td>8</td>
<td>7194</td>
<td>7186</td>
<td>7194</td>
</tr>
</tbody>
</table>

The simulated results for the building categories are proportional to how much roof area per building category that is available for PV arrays. The reason why single multi-dwelling buildings has less available roof area compared to dwelling buildings is that they contain more floors. Multi-dwelling buildings does therefore have a smaller ratio between ground space and gross space area providing less available roof area for PV arrays. The share provided by each building type to the total production is described in (table. 16).

Table. 16. Type Buildings share of total output.

<table>
<thead>
<tr>
<th>Building category</th>
<th>Output%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwelling</td>
<td>28</td>
</tr>
<tr>
<td>Multi-Dwelling</td>
<td>9</td>
</tr>
<tr>
<td>Industry</td>
<td>7</td>
</tr>
<tr>
<td>Other Building</td>
<td>56</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
</tr>
</tbody>
</table>

The minimum and maximum values derive from the hour during the year in which the production is at its peak respectively dips. This occurs during hours with maximum solar radiation respectively night time. More detailed hourly plots of production can be found in appendix A. The maximum production is lower compared to the installed capacity of 667 MW during any given hour during the time period. The buildings are situated at different cardinal (Azimuth) directions which impact the PV production as seen in (Fig. 6) to (Fig. 9). This is the reason why the peak production is lower compared to the full capacity of 667 MW.

Table. 17. Maximum and Minimum PV power production 2010-2012.

<table>
<thead>
<tr>
<th>Hourly Production (MW)</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>492</td>
<td>494</td>
<td>494</td>
</tr>
<tr>
<td>Min</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
4.2. Wind Power
This section displays the results from the wind power simulation in Homer Legacy. Hourly production data can be found in the appendix B.

Table. 18. Simulation of 194 MW Wind Power in Homer Legacy.

<table>
<thead>
<tr>
<th>Year</th>
<th>Total production MWh</th>
<th>Output MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>438000</td>
<td>194</td>
</tr>
<tr>
<td>2011</td>
<td>480000</td>
<td>194</td>
</tr>
<tr>
<td>2012</td>
<td>442000</td>
<td>194</td>
</tr>
</tbody>
</table>

Fig. 15. Monthly values over simulated wind power production 2010-2012.

The simulated wind power production displayed in (table. 18) and (Fig. 15) is calculated to provide as close results to the actual production as possible. The simulated yearly output and capacity matches the existing turbines. An installed capacity of 194 MW provides between 438-480 GWh per year. The maximum capacity of 194 MW is reached during wind speeds of approximately 14 m/s as seen in the power curves in (Fig. 12) and (Fig. 13). There is a significant monthly variation between the years due to wind speed variations. The difference in yearly production is as much as 42000 MWh between 2010 and 2011. The peaks and dips in production during the three simulated years is 194 respectively 0 MW. The wind speed is therefore 14 m/s respectively 0 m/s at hub height on both measuring stations during at least one hour for each of the three years.

Table. 19. Maximum and minimum wind power production 2010-2012.

<table>
<thead>
<tr>
<th>Hourly peak Value (MW)</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>194</td>
<td>194</td>
<td>194</td>
</tr>
<tr>
<td>MIN</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
4.3. Load and consumption data on average year
Generated load profile and consumption during an average year. Simulated in Homer Legacy

Table. 20. Load profile Gotland.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average MWh/d</td>
<td>2500</td>
</tr>
<tr>
<td>Average (MW)</td>
<td>104</td>
</tr>
<tr>
<td>Max demand (MW)</td>
<td>224</td>
</tr>
<tr>
<td>Min demand (MW)</td>
<td>24</td>
</tr>
</tbody>
</table>

Fig. 16. Hourly electric load during an average year.

The simulated load profile displays how the electric consumption changes over the hours on an average year. The peak demand is during the winter in which the maximum peak of 224 MW is reached. The minimum demand occurs during the summer with a demand of 24 MW.

The consumption per month compared to the PV power and wind power production is displayed in (Fig. 18) to (Fig. 20). However, the monthly values only give an indication to how well the generated electricity matches the demand as the electrical grid need to be in balance at any given time. The yearly electricity demand for Gotland is about 840000 MWh.
Fig. 17. Total consumption per month for average year.

**4.4. Monthly electric consumption and production**

Fig. 18. Total RETs production and consumption 2010.
The monthly production from PV power and wind power displays the characteristics of VRE with clear seasonal variations. The variation is due to weather conditions and is even greater when studying the hourly production. The difference between the three years is greater for wind power than PV power. The monthly variation is larger for PV power compared to wind power which provides more stable electric generation.
4.5. Potential PV power capacity with the current and prospective submarine power cable

On an hourly basis the installed wind power capacity exceeds the electricity consumption and export capacity during six hours in 2010 respectively 2011 and 9 hours in 2012. Different amounts of installed PV power compared to the hours of overload are seen in (table. 21). An hour of overload means that the combined electricity generation from both PV power and wind power is greater than the consumption and export capacity together. The existing wind power capacity is used and a variation in PV power capacity is displayed together with the current and prospected submarine power cable.

Table 21. Hours of overload 2010-2012 with the current submarine power cable. With the existing wind power of 194 MW and 0 to 667 MW of PV power.

<table>
<thead>
<tr>
<th>PV Power (MW)</th>
<th>Wind Power (MW)</th>
<th>Submarine power cable capacity (MW)</th>
<th>2010 Overload (h)</th>
<th>2011 Overload (h)</th>
<th>2012 Overload (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>194</td>
<td>160</td>
<td>6</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>10</td>
<td>194</td>
<td>160</td>
<td>6</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>20</td>
<td>194</td>
<td>160</td>
<td>6</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>30</td>
<td>194</td>
<td>160</td>
<td>7</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>40</td>
<td>194</td>
<td>160</td>
<td>7</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>50</td>
<td>194</td>
<td>160</td>
<td>7</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>60</td>
<td>194</td>
<td>160</td>
<td>7</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>70</td>
<td>194</td>
<td>160</td>
<td>7</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>80</td>
<td>194</td>
<td>160</td>
<td>7</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>90</td>
<td>194</td>
<td>160</td>
<td>7</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>100</td>
<td>194</td>
<td>160</td>
<td>8</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>110</td>
<td>194</td>
<td>160</td>
<td>9</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>120</td>
<td>194</td>
<td>160</td>
<td>9</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>130</td>
<td>194</td>
<td>160</td>
<td>10</td>
<td>7</td>
<td>11</td>
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<td>140</td>
<td>194</td>
<td>160</td>
<td>11</td>
<td>7</td>
<td>13</td>
</tr>
<tr>
<td>150</td>
<td>194</td>
<td>160</td>
<td>12</td>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td>200</td>
<td>194</td>
<td>160</td>
<td>25</td>
<td>22</td>
<td>30</td>
</tr>
<tr>
<td>667</td>
<td>194</td>
<td>160</td>
<td>1202</td>
<td>1282</td>
<td>1275</td>
</tr>
</tbody>
</table>

The amount of PV power capacity that can be installed without exceeding the existing hours of overload created by the wind power is seen in (table. 22). Without any additional PV power, the capacity of the current submarine power cable is breached during 6-7 hours per year. The amount of PV power that can be installed without increasing the hours of overload was 22 MW in 2010, 121 MW in 2011 and 28 MW in 2012.

Table 22. Maximum PV potential with the existing power cable with a capacity of 160 MW and 194 MW wind power 2010-2012.

<table>
<thead>
<tr>
<th>Year</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum PV power potential (MW)</td>
<td>22</td>
<td>121</td>
<td>28</td>
</tr>
<tr>
<td>Hours of overload</td>
<td>6</td>
<td>6</td>
<td>9</td>
</tr>
</tbody>
</table>
Table. 23. Hours of overload in 2010-2012 with the addition of the prospective power cable. With existing wind power of 194 MW and 500-667 MW of PV power.

<table>
<thead>
<tr>
<th>PV Power (MW)</th>
<th>Wind Power (MW)</th>
<th>Submarine Power cable (MW)</th>
<th>2010 Overload (h)</th>
<th>2011 Overload (h)</th>
<th>2012 Overload (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>194</td>
<td>460</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>510</td>
<td>194</td>
<td>460</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>520</td>
<td>194</td>
<td>460</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>530</td>
<td>194</td>
<td>460</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>540</td>
<td>194</td>
<td>460</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>550</td>
<td>194</td>
<td>460</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>560</td>
<td>194</td>
<td>460</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>570</td>
<td>194</td>
<td>460</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>580</td>
<td>194</td>
<td>460</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>590</td>
<td>194</td>
<td>460</td>
<td>3</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>600</td>
<td>194</td>
<td>460</td>
<td>4</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>667</td>
<td>194</td>
<td>460</td>
<td>14</td>
<td>8</td>
<td>21</td>
</tr>
</tbody>
</table>

When the prospected submarine power cable is included in the calculation the export capacity increases. A total of 460 MW can be exported at any given time. As seen in (table. 23) 530 MW of PV power is possible without causing overload during any given hour over the three years. The pattern in (table. 21) and (table. 23) is similar in the sense that the yearly variations are significant. Over this three year period the possible amount of PV power span between 22-121 MW and 537-565 MW. If the PV power capacity cannot increase the hours of overload at all, the more conservative PV power capacity should be used.

Table. 24. Maximum PV power potential with the addition of the prospective submarine power cable with a total capacity of 460 MW and 194 MW wind power 2012-2012.

<table>
<thead>
<tr>
<th>Year</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum PV power potential (MW)</td>
<td>537</td>
<td>592</td>
<td>565</td>
</tr>
<tr>
<td>Hours of overload</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
5. Discussion

The theoretical PV power potential on Gotland is 667 MW. The yearly production is between 631-634 GWh. The available roof area suitable for PV arrays is 4230359 m² on the investigated building categories. The maximum PV power production is between 492 and 494 MW during 2010-2012. The results corresponds well to those of Buttler et al. (2016) in which the production peak for PV power was between 70-90% of the installed capacity. The PV power potential of 631-634 GWh per year is considerable more than the 242 GWh per year Ekström (2012) found. One reason is the use of different building data, gross space area in Ekström (2012) which need to be adjusted for by the number of floors on the building compared to ground space and different building classifications in this study. This can be illuminated by the difference in yearly production for dwelling buildings between the studies, 186 GWh per year compared to Ekströms (2012) 117 GWh per year, indicating different data materials.

The results are comparable to those of Lingfors & Widén (2014) and Weiss & Widén (2012) in which the available roof area for PV arrays was 17000000 m² respectively 6956000 m² with a yearly production 1200 GWh respectively 670 GWh. Considering the potential for each building type, dwelling buildings provides about one third of the total potential and significantly more than multi-dwelling buildings. Gotland is a rural region and the abundance of dwelling buildings compared to multi-dwelling buildings is similar to the results of Weiss & Widén (2012) study of Dalarna. A city would probably display different results with a larger PV power potential share for multi-dwelling buildings. Other building is a large category providing more than half of the available roof area while industrial buildings provide about as much as multi-dwelling buildings. A different mix of building categories will provide different results. In line with Lingfors & Widén (2014) and Weiss & Widén (2012), dwelling buildings is the single largest building category for the rural regions of Gotland, Blekinge and Dalarna.

The electric energy consumption has its peak during the winter months as seen in (Fig. 16) and has a better match with the wind power production pattern compared to the PV power production pattern. The PV power production can almost be seen as the inverse of the load when comparing (Fig. 14) to (Fig. 16). The monthly variability is also larger for PV power compared to wind power (Fig. 20) to (Fig. 22) corresponding to the results of Buttler et al. (2016).

When comparing the monthly values in (Fig. 18) to (Fig. 20), the variation in wind power and PV power production complement each other well with their respectively production peaks during the winter respectively the summer. The simulation shows that 194 MW wind power provides almost half of the electricity demand on Gotland for any given month. 667 MW PV power provides about 10% during November-February. During March-April and September, it provides almost all of the electricity demand on a monthly basis. During June-August it provides about 30% more than the electricity demand.

The installed capacity of 194 MW wind power on Gotland is already breaching the capacity limit of the current submarine power cable during an average of 7 hours per year in this simulation. Even though 194 MW is within the limit set by the DSO at 195 MW. To determine how much PV power that can be installed without increasing the hours of overload requires a review of the difference in overload between the years. The results from the hourly comparison in (table. 21) to (table. 23) display a clear case of the variability in RETs. The maximum PV power potential is significantly larger in 2011 compared to 2010 and 2012. This is surprising since 2011 was the year with the largest wind power production, 480 GWh.
This shows that during 2010 the production peaks of wind power or PV power occurred at the same time or that the production of either was very high during multiple hours when the load was low. The yearly PV power production does not shift that much but the monthly values does. This is true for wind power production as well. Given these factors the limit of 195 MW RETs on Gotland seems reasonable for wind power as the installed capacity reaches full production capacity during multiple hours. As a PV system has a life span of about 30 years and the large variations in possible PV power potential over the investigated years, a conservative approach should be used. Therefore the amount of PV power that did not increase the hours of overload should be considered. An installed capacity of 22 MW PV power is possible together with 194 MW wind power with the existing submarine power cable without increasing the hours of overload. By combining two RETs technologies it is possible to increase the installed capacity by 22 MW without increasing the hours of overload. Multiple RETs technologies are therefore useful together as the variability in electricity supply is reduced. As seen in (Table. 21) and (table. 23), the relationship between the installed PV power capacity and the hours of overload is complex. The variability in production when combining two RETs sources provides additional installed capacity. It does also display the problem that a significantly larger amount of PV power could be installed if a small increase in the hours of overload would be possible. If five additional hours of overload were possible the PV power capacity would be 130 MW compared to 22 MW with the existing power cable.

At the moment the full PV power potential is not possible to realize. This is because the capacity of the current and prospective submarine power cables is limited. However with the prospective submarine power cable a total of 537 MW PV power is possible to install to complement the existing 194 MW of wind power. The maximum production of wind power in this simulation is equal to the installed capacity. If it was decided that only wind power would be installed, the maximum amount would be an additional 300 MW compared to 194 MW wind power and 529 MW PV power. The results derive from simulations to create as good results as possible. However electric production and consumption occurs constantly and there is the possibility that higher resolution data would provide different results. The results however correspond well to previous research, especially Buttler et al. (2016).

6. Future Work
This study found that a large share of PV power could supplement wind power without creating overload on an hourly basis. It would be interesting to see the results for a similar study using actual data from the power companies. The sensitivity analysis displays a very small change in the hours of overload corresponding to a large increase of PV power. It would be interesting to elaborate further on the combination of wind power and PV power to calculate their production relationship which I believe is regional specific. It would also be interesting with a higher resolution study (minutes) to see how much it would differs from hourly data and if it would increase or decrease the PV power potential under similar conditions.
7. Conclusion
The theoretical PV power potential on Gotland is 667 MW on existing buildings. The PV power potential is split between 28% for dwelling buildings, 9% in multi-dwelling buildings, 7% for industry buildings and 56% for other buildings. Wind power has a better load match compared to PV power on a monthly basis. Production peaks for wind power and PV power are differentiated which allows for a larger installed capacity than the submarine power cable capacity. With a combination of wind power and PV power the total amount of RETs can be increased on Gotland without overloading the submarine power cable. With the installed capacity of 194 MW wind power, 22 MW PV power is possible to install without increasing the hours of overload. With the prospected submarine power cable, a total of 537 MW PV power is possible to install together with the existing 194 MW wind power.

8. Acknowledgements
I would like to thank my Supervisor Rasmus Luthander for great support, technical advice and great suggestions for improvement. I would also like to thank my Evaluator Joakim Munkhammar for great suggestions, support and quick email responses.
9. References

9.1. Data


9.2. Literature


http://www.teknik.uu.se/solid-state-electronics+/research-areas/solar-cells/ [Accessed April 28, 2016].


Appendix A

1. A.1. Hourly and monthly PV power potential per year

Fig. A.1. Hourly PV power potential 2010

Fig. A.2. Hourly PV power potential 2011
Fig. A. 5. Hourly PV power potential 2012.
### A.2. Theoretical PV power potential for the different building categories

Table. A. 1. Dwelling buildings PV power potential 2010-2012.

<table>
<thead>
<tr>
<th>Dwelling Building</th>
<th>Available area after reductions m²</th>
<th>Number of buildings</th>
<th>Output kW</th>
<th>Yearly Production kWh 2010</th>
<th>Yearly Production kWh 2011</th>
<th>Yearly Production kWh 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type Buildings</td>
<td>71</td>
<td>1</td>
<td>12</td>
<td>10543</td>
<td>10530</td>
<td>10545</td>
</tr>
<tr>
<td>Total</td>
<td>1249174</td>
<td>17594</td>
<td>214338</td>
<td>185492258</td>
<td>185265293</td>
<td>185524389</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Multi Dwelling Roof type</th>
<th>Available area after reductions m²</th>
<th>Number of Buildings</th>
<th>Output kW</th>
<th>Yearly Production kWh 2010</th>
<th>Yearly Production kWh 2011</th>
<th>Yearly Production kWh 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type Building Tilted</td>
<td>38</td>
<td>1</td>
<td>6</td>
<td>5564</td>
<td>5558</td>
<td>5565</td>
</tr>
<tr>
<td>Type Building Flat</td>
<td>40</td>
<td>1</td>
<td>7</td>
<td>6973</td>
<td>6966</td>
<td>6973</td>
</tr>
<tr>
<td>Total Tilted</td>
<td>322924</td>
<td>8498</td>
<td>51853</td>
<td>47282831</td>
<td>47224977</td>
<td>47291022</td>
</tr>
<tr>
<td>Total Flat</td>
<td>60463</td>
<td>1499</td>
<td>10387</td>
<td>10455271</td>
<td>9863751</td>
<td>9873055</td>
</tr>
<tr>
<td>Total</td>
<td>383387</td>
<td>9977</td>
<td>62240</td>
<td>57738102</td>
<td>57088728</td>
<td>57164077</td>
</tr>
</tbody>
</table>

Table. A. 3. Industrial Buildings PV power potential 2010-2012.

<table>
<thead>
<tr>
<th>Industry Building</th>
<th>Available area after reductions. m²</th>
<th>Number of Buildings</th>
<th>Output kW</th>
<th>Yearly Production kWh. 2010</th>
<th>Yearly Production kWh. 2011</th>
<th>Yearly Production kWh. 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type Building</td>
<td>493</td>
<td>1</td>
<td>91</td>
<td>80502</td>
<td>80426</td>
<td>80502</td>
</tr>
<tr>
<td>Buildings Total</td>
<td>233189</td>
<td>473</td>
<td>43543</td>
<td>38077552</td>
<td>38041621</td>
<td>38077506</td>
</tr>
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</table>
Table A.4. Other Building PV power potential 2012-2012.

<table>
<thead>
<tr>
<th>Other Building Roof Type</th>
<th>Available area after reductions. m²</th>
<th>Number of Buildings</th>
<th>Output kW</th>
<th>Yearly Production kWh. 2010</th>
<th>Yearly Production kWh. 2011</th>
<th>Yearly Production kWh. 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type Tilt</td>
<td>46</td>
<td>1</td>
<td>8</td>
<td>6765</td>
<td>6757</td>
<td>6766</td>
</tr>
<tr>
<td>Type Flat</td>
<td>52</td>
<td>1</td>
<td>8</td>
<td>7838</td>
<td>7831</td>
<td>7838</td>
</tr>
<tr>
<td>Building Tilt Total</td>
<td>1348720</td>
<td>29320</td>
<td>222603</td>
<td>198351115</td>
<td>198108416</td>
<td>198385473</td>
</tr>
<tr>
<td>Building Flat Total</td>
<td>1016392</td>
<td>19546</td>
<td>148396</td>
<td>153200469</td>
<td>153055906</td>
<td>153200283</td>
</tr>
<tr>
<td>Total</td>
<td>2365112</td>
<td>48866</td>
<td>370999</td>
<td>351551584</td>
<td>351164322</td>
<td>351585756</td>
</tr>
</tbody>
</table>
Appendix B

1. B Wind power simulation

Fig. B.1. Hourly production 2010.

Fig. B.2. Hourly Production 2011.
Fig. B. 3. Hourly Production 2012.
Appendix C.

1. C. Figures and tables of the data material


<table>
<thead>
<tr>
<th>Year</th>
<th>Yearly Global Radiation kWh/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>1114</td>
</tr>
<tr>
<td>2000</td>
<td>1068</td>
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<tr>
<td>2001</td>
<td>1031</td>
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<td>2002</td>
<td>1132</td>
</tr>
<tr>
<td>2003</td>
<td>1056</td>
</tr>
<tr>
<td>2004</td>
<td>1092</td>
</tr>
<tr>
<td>2005</td>
<td>1084</td>
</tr>
<tr>
<td>2006</td>
<td>1061</td>
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<tr>
<td>2007</td>
<td>1117</td>
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<td>2008</td>
<td>1088</td>
</tr>
<tr>
<td>2009</td>
<td>1032</td>
</tr>
<tr>
<td>2010</td>
<td>902</td>
</tr>
<tr>
<td>2011</td>
<td>1026</td>
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<td>1028</td>
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<tr>
<td>2013</td>
<td>1091</td>
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<tr>
<td>2014</td>
<td>1092</td>
</tr>
<tr>
<td>2015</td>
<td>1106</td>
</tr>
<tr>
<td>Average year</td>
<td>1046</td>
</tr>
</tbody>
</table>

Fig. C. 1. Hourly wind speed at Fårösund measuring station 2012.
Fig. C. 2. Hourly wind speed at Hoburgen measuring station 2012.