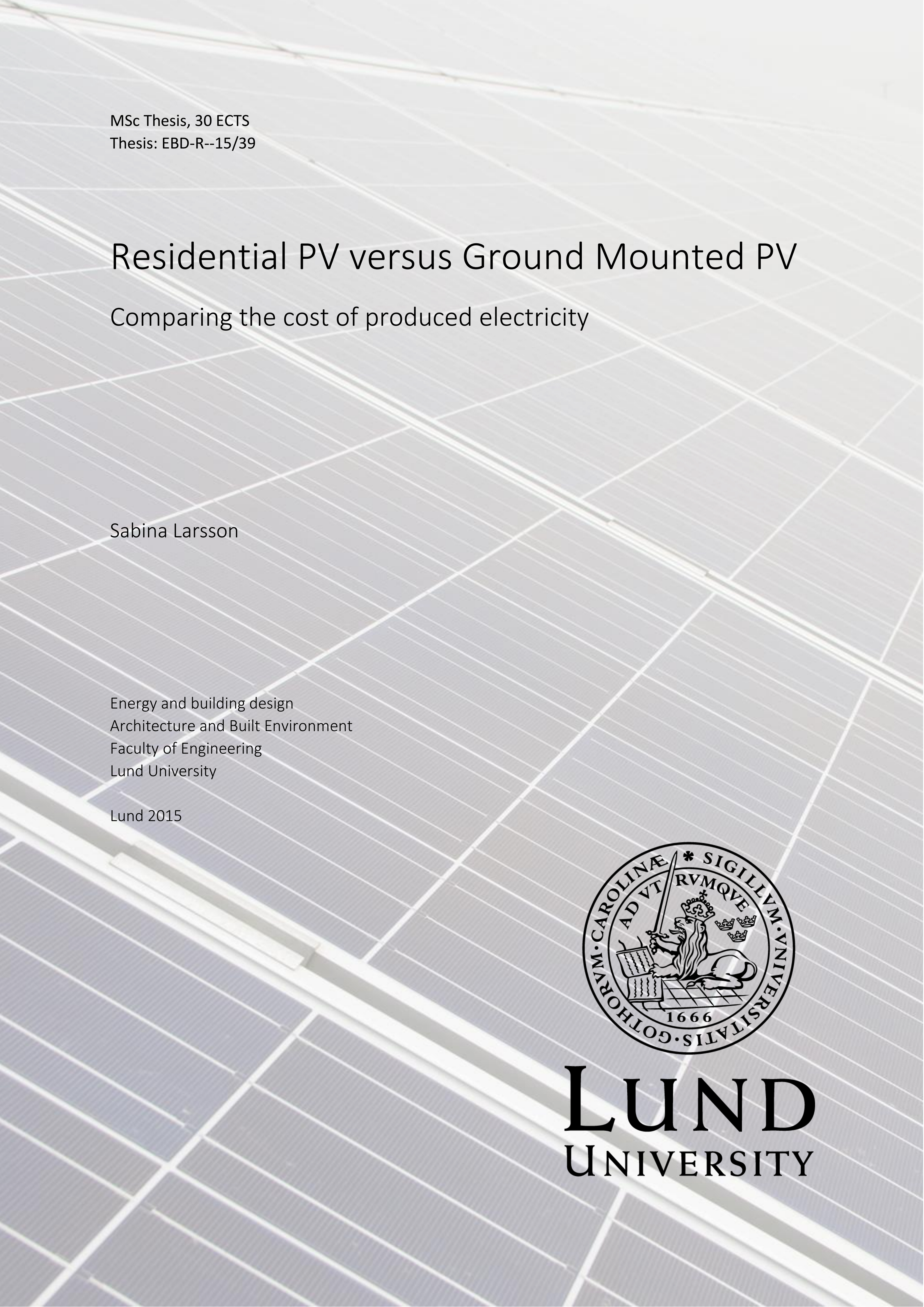

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Residential PV versus Ground Mounted PV

Comparing the cost of produced electricity

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Thesis work for Master of Science 30 ECTS
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Abstract

The electricity produced from photovoltaics represents only a small fraction of the total electricity consumption in Sweden, but the installed capacity in Sweden doubled for the fourth year in a row in 2014. If this trend continues it is both interesting and important to discuss where we want to see PV systems in our future society. Looking at the market share of different types of PV systems in other European countries there are great variations from one country to another, and it is obvious that integrating PV in the electricity mix can be done in several ways.

The same PV module can be placed on a roof top or on the ground, but might experience different conditions for producing electricity depending on tilt, azimuth angle and shading of the PV modules. Depending on where a PV system is installed it is also affected in different ways by capital subsidies, tax reductions and feed-in tariffs. By removing these aspects from an economic analysis the performance and cost can be compared between different systems, before other economic systems evens out the difference.

Two types of PV systems have been compared in this study; residential PV systems versus ground mounted PV systems. The objective of the study was to calculate a comparative cost of electricity for these two different ways of installing PV and at the same time briefly address the potential environmental impacts from the space required for solar parks.

The energy output was simulated with the program System Advisor Model. The azimuth angles and tilts of an average residential PV system were based on classifications used in the solar map of Lund. Two land alternatives were studied, forest and agricultural land, both covering large areas in Sweden. To include variations in cost of land and solar irradiation the simulations and calculations were performed for three different parts of Sweden; the southern, central and northern part.

The conclusion from this study is that PV systems should be placed on the ground to produce the most electricity per invested Swedish crown. Agricultural land is the least expensive land type option when compared with forest, since the ground is already flat and no shading forest edge has to be taken into consideration. The irradiation has a larger impact on the cost per produced kWh than the cost of land, making PV in the far north more expensive. The environmental impact from installing PV on the ground is not well known but an installation will result in land use – and land cover change to some extent.

Keywords

Solar energy, Photovoltaic systems, residential PV, ground mounted PV, economy, SAM, land use.

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Sabina Larsson

Lund 2015

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Terminology

Azimuth angle	Orientation from north, i.e. a module facing south has an azimuth angle of 180°
BAPV	Building Applied Photovoltaics
BIPV	Building Integrated Photovoltaics
Centralized PV	Photovoltaic system that works like a power plant, typically ground mounted PV
Distributed PV	Photovoltaics connected to the distribution grid and linked to a specific customer
g CO_2-eq/kWh	Grams of emitted greenhouse gases in CO_2- equivalents per produced kWh
Installed system power	Capacity of the system given in watt peak (Wp), estimated using STC
O&M	Operation and Maintenance
PV	Photovoltaic
STC	Standard Test Conditions, operating temperature 25°C, incoming solar radiation 1000 W/m^2, Air Mass of 1.5
VAT	Value Added Tax

1. Introduction

1.1 Background

The climate is changing, with consequences for both humans and wildlife. Melting ice covers, rising sea levels and warmer temperatures in the atmosphere and in the oceans are being observed. The anthropogenic emissions of greenhouse gases are higher than ever and the human impact on the climate change is no longer questionable (IPCC, 2014). To mitigate this climate change and to keep the global warming below 2°C, cost effective solar energy will be an important source of electricity in our future energy system (Pietzcker et al., 2014).

Photovoltaic (PV) power systems were one of the two most installed power systems in Europe 2013, together with wind power. The same year electricity produced from PV met 3 % of the total electricity demand in Europe (EPIA, 2014). In Sweden the cumulative PV capacity doubled for the fourth year in a row in 2014, but still only covers 0.06 % of the electricity demand in Sweden (Lindahl, 2015a). Most of the PV power systems in Sweden are put on roof tops, on both residential and commercial buildings, while in other European countries the mix between different market segments shows a great variation (EPIA, 2014). For instance, the PV markets in countries like Romania and Spain are dominated by ground mounted systems whereas Belgium and Denmark mainly have residential PV systems.

In Sweden there has been research looking at the potential of roof top PV (Kjellsson, 2000) and solar maps illustrating the irradiance on buildings have been created (Hedén, 2013). The same attention has seemingly not been put on ground mounted systems. Even if the market share of ground mounted systems in Sweden is small there are examples of solar parks that has been installed (Dahlström, 2015c; Jönsson, 2015; Rönning, 2015), utilizing different land types such as agricultural land and landfills. There are plans to build new and larger parks in Sweden in the next couple of years (Sveriges Radio, 2014; Öresundskraft, 2015).

The increasing PV capacity in Sweden makes it interesting to discuss where to install PV power systems in our future Swedish society. The same PV module can be placed on a roof top or on the ground, but might experience different conditions for producing electricity depending on tilt, azimuth angle and shading of the PV modules. Larger PV systems might benefit from economy of scale compared to smaller systems. A roof could be considered a free and available space for PV, and if PV is installed on the ground the solar park will be more or less expensive depending on land type and geographical region.

Depending on where a PV system is installed it is affected in different ways by capital subsidies, tax reductions and feed-in tariffs. By removing these aspects from an economical analyze the cost for producing one kWh can be compared between different systems, before other economical systems evens out the difference. Then it can be evaluated how to produce electricity from PV for as low costs as possible.

1.2 Aim & objectives

The aim of the project is to compare centralized ground mounted PV systems with distributed residential PV systems.

The main objective is to calculate a comparative cost per produced kWh for distributed residential PV systems and ground mounted PV systems for three different regions in Sweden. The objective is not to make a full economic analysis but to calculate a comparative cost including installation costs, land costs and produced electricity. The land use change and the potential environmental impacts from having PV on the ground will also be briefly discussed.

1.3 General methodology

This study was performed in two parts. The first part, covered in chapter 3. *System parameters*, included finding different parameters and system costs regarding residential PV systems and ground mounted PV systems. The gathering of information was performed by analyzing scientific literature and consulting researchers at universities, administrative authorities and PV companies in Sweden. Study visits to two ground mounted PV systems in different part of the country were made during the time of the project to see examples of ground mounted systems in Sweden.

The second part, covered in chapter 4. *Energy simulations and cost calculations*, consisted of simulating the energy output from the different PV systems in the program System Advisor Model (NREL, 2015) followed by calculations of cost per produced kWh. Both the simulations and calculations were based on parameters found in the first part of the study. More detailed descriptions of the methods used in the simulations and calculations are made in chapter 3.

To include the difference in weather and cost of land depending on where in Sweden a PV system is placed the energy and cost calculations have been performed for three different parts of Sweden; the southern, central and northern part of the country.

1.4 Limitations

There are several types of PV systems but to make a comparison of two different systems the focus of the project is to compare distributed residential PV systems with centralized ground mounted PV systems. These systems are assumed to represent the endpoints of a broad range of grid connected PV applications.

The study will not include off-grid systems connected to batteries, only grid connected PV systems. The study is made for Swedish climate conditions and PV system prices. To compare the systems the only economical parameters included in this study are the cost of installing the PV systems, cost of land and maintaining the PV systems during its lifetime. Further limitations that have been made are:

- Profits for selling the produced electricity or cost reductions such as capital subsidies and tax reductions are not included.
- Interest rates and inflation are not included.
- Cultural and social aspects considering the placement of different PV systems are not included.
- Differences in transmission losses in the grid depending on the location of a PV system are not included.
- Potential differences in the costs of removing a ground mounted PV system versus a residential PV system and recycle the components are not included.
- Costs of insurances and surveillance systems depending on PV system are not included.
- Any legal regulations of using land for PV will not be included in the study.
- Differences in availability due to component failures are not included.

2. Photovoltaics

2.1 A global perspective

Photovoltaic systems are rapidly increasing in capacity around the world. Between 2009 and 2013 PV had the highest growth rates among all energy systems (REN21, 2014). The installed PV capacity reached 139 gigawatts in the end of 2013 and produced 0.7 % of the total global electricity production the same year.

More than half of the installed PV capacity around the world is found in Europe (EPIA, 2014). In the end of 2013 PV covered 3 % of the total electricity demand in Europe.

The share of PV market segments varies greatly from one country to another (EPIA, 2014). Romania has 10 % of the installed PV capacity in Europe and almost all installations are ground mounted whereas the market in Denmark, with 3 % of the European capacity, is completely dominated by residential PV systems. Germany, the country with as much as 30 % of the PV capacity in Europe, has a mix of ground mounted, commercial, industrial and residential PV systems.

2.2 PV in Sweden

The energy produced from PV in Sweden covered 0.06 % of the total electricity consumption in the end of 2014 (Lindahl, 2015a). The technology has had a rapid growth in Sweden with a doubling in capacity for four years in a row. In the end of 2014 the cumulative capacity was 79.4 MW, a capacity that produces approximately 75 GWh in a year. Most systems are connected to the distribution grid on residential and commercial buildings. Only a small fraction of the PV systems in Sweden are off-grid systems or centralized ground mounted systems (Lindahl, 2015a).

2.3 Definitions of PV Systems

There are many different types of PV systems; the modules can be installed on the ground or top of a roof, the energy can be used directly or stored in a battery or the system can be connected to the electricity grid.

Grid-connected systems are divided into two main groups of systems: distributed and centralized PV power systems. A distributed system is a system built to produce electricity to a grid-connected costumer and to deliver electricity to the distribution grid when the electricity is not directly needed. A centralized PV power system works like a power plant and is not linked to a specific costumer. Centralized systems are often ground mounted (Lindahl, 2014).

Distributed systems can be further divided into residential, commercial and industrial systems (Lindahl, 2014). Residential systems are usually up to 20 kWp and installed on roof tops by private house owners typically on one family buildings. Commercial systems are put on buildings such as schools and other public buildings and are often larger than residential systems, approximately between 20 and 250 kWp. Industrial systems are the largest roof top systems often with sizes above 250 kWp, put on industrial buildings (Lindahl, 2014).

PV systems on buildings can be either building integrated PV or building applied PV (van Noord, 2010). Building applied PV, BAPV, are PV systems put on top of an existing building with the only purpose of producing electricity. Building integrated PV, BIPV, are photovoltaics integrated into the built environment and besides generating electricity the modules also has another function, for example being a roof, a wall or used as a shading device.

The different grid connected PV systems are summarized in Figure 2-1. The two systems compared in this study are indicated with a black border.

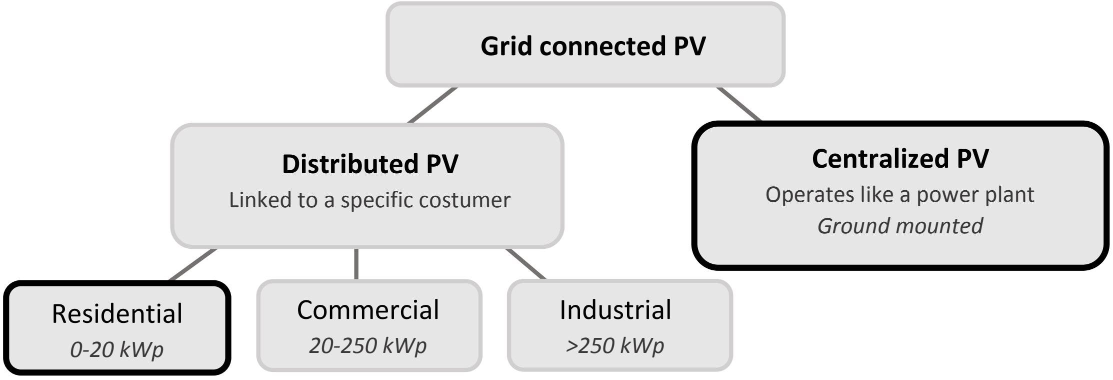


Figure 2-1. The different types of grid connected PV power systems (Lindahl, 2014). The sizes given are only an approximation the systems are not classified according to size. The two types PV systems compared in this study are indicated with a black border.

2.4 Photovoltaics in theory

2.4.1 The solar cell

Solar energy can be directly converted into electricity by the use of solar cells - a technique called photovoltaics. A solar cell is a thin plate made from semiconducting materials; the most commonly used semiconducting material in solar cells is silicon (Wenham et al., 2007). There are different types of solar cells based on silicon: crystalline silicon and thin film silicon solar cells. This study will focus on crystalline silicon since this is the most commercial used technique today (IEA, 2014).

Crystalline silicon can be either monocrystalline or polycrystalline. Monocrystalline silicon solar cells have the atoms arranged in perfect crystals without irregularities (Wenham et al., 2007). They are dark and have a uniform look. Polycrystalline silicon solar cells have grain boundaries between the crystals (Wenham et al., 2007) and have a non-uniform look with different tints of blue.

Silicon has four valence electrons and atoms are bound to each other by covalent bonds, forming a crystalline structure. If light shines on a silicon crystal, electrons in the valence band can absorb the energy and be excited to the next energy level - the conduction band. The electron then leaves an empty positive space behind, which is referred to as a hole. An electron-hole pair is formed. The difference in energy between the valence band and the conduction band is called the band gap and varies in energy depending on the material used, for silicon the band gap is 1.1 eV (Wenham et al., 2007).

In order to generate a current the silicon is doped with two other materials. On top of the solar cell a material with one more valence electron than silicon is incorporated. This is called the n-side. In the rest of the cell a material with one less valence electron than silicon is introduced, this is called the p-side. The junction between the two doped sides is called a p-n junction. The extra electrons introduced in the n-side will diffuse towards the p-side, and the holes will diffuse towards the n-side. This creates an electric field across the p-n junction - a built-in potential. When an electron is excited it will diffuse towards the positive n-side and the hole will diffuse towards the negative p-side of the cell. On top of the cell, on the n-side, there are contacts that collects the electrons. In a photovoltaic module several cells are connected in series. When the light shines on a module the electrons will be exited and move from the front of one cell to the rear contacts on the back of the next cell in a module to recombine with a hole. A direct current is generated (Wenham et al., 2007). A cross section of a solar cell is seen in Figure 2-2.

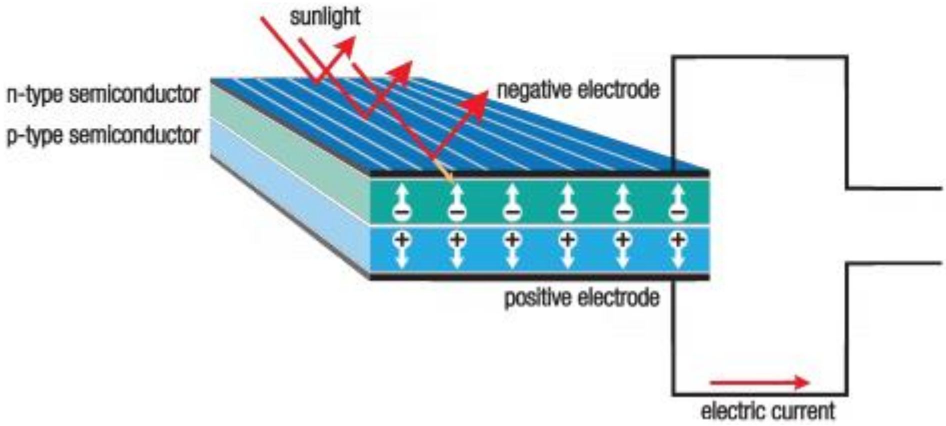


Figure 2-2. Cross section of a solar cell (Redarc, 2015). With permission to publish.

In the PV module the cells are put in strings with bypass diodes between the strings to allow the current to pass if cells in one string produces less current (Wenham et al., 2007). In a standard module there are often 60 cells connected in series in three strings with by-pass diodes between the strings on the short edge of the module (Yingli, 2015).

When the cells produce different levels of current it is called mismatch. There are several explanations to why this mismatch can occur: cells can be shaded, cracked or unevenly dirty due to for example bird droppings. If one cell produces less current it limits the whole string output due to the serial connection; higher produced current from “good” cells cannot flow through a lower producing “bad” cell (Wenham et al., 2007). The reason for not having by pass diodes across each cell is that it would be too expensive (PVeducation, 2015).

Besides the modules a PV system also include other components to function. A grid connected PV system includes modules, mounting systems, cables, DC-AC inverters and meters (Wenham et al., 2007).

2.4.2 Orientation

The electricity produced from a solar cell is determined by the amount of light that reaches the surface (Wenham et al., 2007). The orientation of a PV module is therefore an important parameter. The energy output from a PV module will vary with both tilt and azimuth angle. In this study the tilt of the module is defined as ranging from 0° to 90°, where 0° represents a horizontal surface and 90° represents a vertical surface. The azimuth angle is defined as 0° in the north and 180° in the south, which is the same as when looking at a compass. East is 90° and west is 270°.

2.4.3 Shading

If a cell is shaded the power output from the cell is reduced. The reduction is proportional to the part of the cell being shaded if the shading object is opaque, which means that if half of the cell area is shaded the power out is reduced by 50 % (PVeducation, 2015). But the shading of one cell reduces the output in the entire string as described previously.

Shading can occur from objects in the surroundings such as trees, chimneys or other buildings. If the modules are installed tilted on a flat surface one row of modules can shade the row behind depending on the distance between the modules. This type of shading is called mutual shading (Kanters, 2013).

2.4.4 Temperature effect

The temperature of a solar cell is affected by the incoming irradiation, cooling effects from the wind, temperature of the surrounding air and the characteristics of the module. When the cell becomes warm the energy difference in the band gap is decreased which lowers the built in potential in the cell. A lower voltage gives a reduced power output and consequently a lower efficiency of the cell (Wenham et al., 2007). If air can circulate around the module this will have a cooling effect. If a module is integrated into a roof and the back of the module has no air gap the operating temperature could become higher than a module mounted with an air gap (PVeducation, 2015). A module can be applied on top of a roof without being integrated into the structure as described in section 2.3. This will result in an air gap between the modules and the roof.

2.4.5 Standard Test Conditions

The electrical parameters of a system, such as the efficiency and system power, are received from testing the cells at Standard Test Conditions. These conditions are determined as an operating temperature of 25°C, incoming solar radiation of 1000 W/m2 and an Air Mass of 1.5. Air mass 1.5 means that the light travels through the atmosphere 1.5 times the shortest distance through the atmosphere. The tests are standardized to be able to compare cells made of different types of material or similar cells from different manufacturers (PVeducation, 2015). The power of a PV system is given in watt peak.

2.4.6 Performance

Polycrystalline silicon solar cells have a commercial efficiency of 14-18 %, which is slightly lower than the efficiency of 16-24 % for monocrystalline solar cells (IEA, 2014). In many studies the lifetime of a PV system has been assumed to be around 30 years (Hsu et al., 2012). The degradation of the PV modules can be assumed to be estimated as an annual loss of 0.5 % per year (Jordan et al., 2010).

The inverters are not lasting as long as the modules. In economical calculations they can be assumed to last 15 years before they need to be replaced (Solkompaniet, 2013a). An inverter has an efficiency of between 95-97 % (IEA, 2014).

These parameters of performance will be used when determining the input values in the simulations and calculations in chapter 4.

3. System parameters

Potential of integrating more PV in Sweden

Before looking at the two different system it is interesting to study the possibility of integrating more PV capacity in our electricity mix. PV is an intermittent source of energy, meaning that the production is fluctuating. According to Söder (2013) 55 TWh of intermittent renewable energy sources are possible to integrate into the grid and still retain a balance in the power system. Such integration of renewable intermittent energy will not be without challenges but still not impossible. The study was made having 45 TWh energy produced from wind power and 10 TWh from PV.

Another study made by Carlstedt (2006) states that without any further measurements it is theoretically possible to install 5 TWh of solar electricity in Sweden. This means that 5 TWh of solar could be integrated in the energy system with the present energy production mix and without improving storage or export possibilities. In a third study made by Rönnelid (2008) looking at the impact of PV in the grid, it was concluded that when PV power has a share of 9 % or more of the annual electricity demand in Sweden there will be complications in the grid. The total electricity consumption in Sweden is roughly 140 TWh annually (EnergyAgency, 2014), which gives a potential of 12.6 TWh of PV power systems. The most conservative value of 5 TWh is later used as an example when comparing the difference in cost per kWh for the two systems.

3.1 Residential PV

More than one fourth of the PV installed in Sweden are residential PV systems (Lindahl, 2015a). As described previously these are grid-connected systems with sizes up to around 20 kW and typically installed on roof tops on one family houses.

3.1.1 BAPV or BIPV

When PV is building integrated conventional building material can be replaced by different BIPV solutions potentially making it a cost effective alternative. The PV modules could also be integrated in a more aesthetic way than Building Applied PV and provide different design opportunities. In a recent market analysis made by Verberne (2014) in the Netherlands the BIPV proved to be price competitive with BAPV if a full roof is made of a BIPV instead of a full roof made of concrete tiles and then adding PV modules. Since these solutions are only in the same price range when building a new roof and for full roof solutions BIPV is not included in this study. The cost per kWh is assumed not to be lower than building applied PV. BAPV will then represent the low cost alternative on residential buildings to be compared with centralized ground mounted PV. But as stated in the study (Verberne, 2014) building integrated solutions give the impression of being a promising cost effective alternative in the future.

Since Building Applied PV has been less expensive to install than Building Integrated PV (Verberne, 2014) most of the residential systems can be expected to be Building Applied PV.

3.1.2 PV in the built environment

One obvious advantage with installing PV in the built environment is that the area required is already used for something else so no new land has to be exploited (Hernandez et al., 2014). In this study a roof is considered a free space, since a roof would exist regardless of a PV installation.

The roof used for a PV installation will eventually need reconditioning. The lifetime of a roof with roofing felt and roofing-tiles is 40-60 years and for tin roofs around 30-40 years (omBoende, 2015). The lifetime of a PV module is assumed to be around 30 years (Hsu et al., 2012). If a PV system is put on a roof that is new or recently reconditioned it seems likely that the system can stay on the roof during the entire lifetime of the modules. If the roof needs reconditioning within 30 years after the installation of the PV system the modules might have to be taken down and put up again resulting in a more expensive roof renovation. Since most of the PV systems in Sweden are installed during the last decade this has probably not caused many problems yet. In this study it is assumed that the installment of a PV system on a roof top is made on a roof that will last at least 30 years.

There is a great potential of installing PV on roofs. If all roofs in Sweden receiving more than 75 % of the incoming solar radiation would be covered with a PV system with a 10 % system efficiency more than 25 TWh per year could be produced (Kjellsson, 2000). This can be put in relation to the total electricity consumption in Sweden, which is roughly 140 TWh annually (EnergyAgency, 2014).

3.1.3 An average residential PV system

A PV module can be put on any roof top in any angle, but will produce a different amount of energy depending on the azimuth angle and tilt.

No study or statistics covering the average performance for PV systems in Sweden has been found. According to Adsten (2015) there were attempts to gather information regarding installed systems when there were only a few PV systems in Sweden, but the number of private installations grew and became hard to review. At the moment there is no administrative authority that gathers data of PV system performance in Sweden.

In a study reviewing 933 of the installed PV systems in Belgium (Leloux et al., 2012) the performance of the PV systems were evaluated. The 993 systems were considered a representative sample of the installed PV systems in Belgium. The evaluation showed that the systems had a 6 % lower energy output compared to a high quality reference system due to the orientation of the modules. The reduction of 6 % was stated as “the price to pay” for installing residential PV systems instead of installing them in solar parks (Leloux et al., 2012). That is, if the orientation of modules is the only difference in energy output between a residential system and a solar park. It was not possible to estimate the effect of shading on the energy output, but it was estimated that a reduction in energy output of 2 % due to shading was a good assumption for residential systems in Belgium (Leloux et al., 2012).

In the review of the Belgium PV systems it was stated that the results can be used to approximate the energy production from residential PV systems not only in Belgium but also in the rest of Europe (Leloux et al., 2012). Since no equivalent study for Swedish residential systems were found the assumptions for the simulations in this study will partly be based on the results from the Belgium review. A total reduction of 8 % was due to the orientation and shading of the modules, and this number will be used as a reference number when evaluating the simulations.

For the city of Lund in the southern part of Sweden there is a solar map showing the potential of PV systems on roof tops (Kraftringen, 2015a). The roofs are classified according to the incoming radiation in the sections excellent, good, poor and not advisable (Hedén, 2013), see Table 3-1. The incoming radiation has been determined by scanning the area with laser from the air. The irradiation on a surface depends on the tilt, azimuth angle and shading of the surface.

Table 3-1. Definitions used in Lund solar map (Hedén, 2013). The roofs labelled "Good" and "Excellent" are used in the calculations.

Category	Lower limit (percentage of maximum solar irradiation)	Irradiation / (kWh/m^2, year)
Not advisable	0 %	< 800
Poor	68 %	800 – 900
Good	77 %	900.1 – 1020
Excellent	87 %	1020.1 <

The roofs classified as "good" and "excellent" are assumed to be used for PV system installations in Sweden. Due to shortage of statistics the systems are assumed to be equally distributed on all the roofs. This means that the possibility that "excellent" roofs are subject to more PV installations than "good" roofs is not included. The orientations classified as "good" and "excellent" for Lund will be assumed to be subject to installations of PV systems in all three locations in Sweden.

In the solar map it is possible to look at the potential in a chosen area of Lund. To illustrate an example a residential area in the north of Lund can be seen in Figure 3-1.

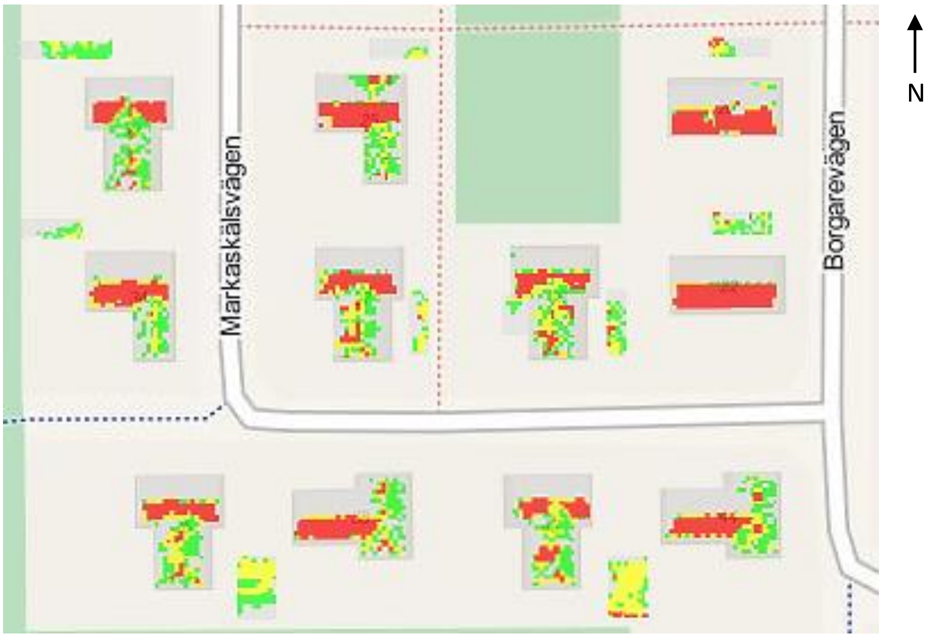


Figure 3-1. Solar map for a residential area in the northern part of Lund (Kraftringen, 2015a). The definitions of the colors are seen in Table 3-1. With permission to publish.

According to Lindahl (2015b) there are no statistics covering the distribution of PV system sizes in Sweden. One attempt to gather this information was made by Stridh (2015) by evaluating the systems that had been approved capital subsidies between 2009 and 2012 in Sweden, which corresponded to 582 systems. The mean power of these systems was 11.6 kWp and the median value 4.2 kWp. In the review of the systems in Belgium described in the previous section (Leloux et al., 2012) around three fourths of the PV power in Belgium came from installations of sizes between 3 and 5 kWp. Solkompaniet, a PV company in Sweden, offers PV packages through Vattenfall seen in Figure 3-2. Their most frequently sold package size is the 3.3 kW PV system (Åkerström, 2015b). Based on this information it will be assumed in this study that a system size of 4 kWp is the most common residential PV system size. A system of 4 kWp covers a roof area of around 30 m^2.

3.1.4 Cost of residential PV systems

An average residential PV system is assumed to be around 4 kWp as described in section 3.1.3. All costs used in the calculations has been chosen as close as possible to a system size of 4 kWp.

Several companies offer package prices for standard residential PV systems. The package prices from three large energy companies in Sweden are illustrated in Figure 3-2.

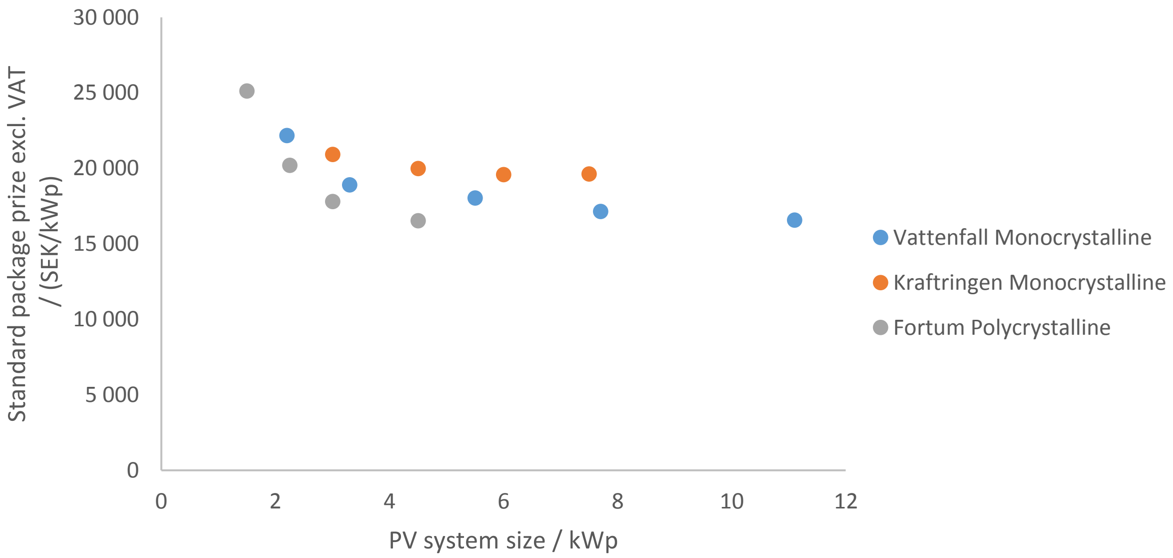


Figure 3-2. Standard package prices in SEK/kWp from three Swedish energy companies excluding VAT. (Vattenfall, 2015; Kraftringen, 2015b; Fortum, 2015)

The system prices are lower for larger installations, since initial costs like project planning and administration for a PV project are almost the same regardless of the size (Larsson, 2015).

Two of the companies, Vattenfall and Kraftringen, include monocrystalline modules in their package prices whereas Fortum has based its prices on polycrystalline modules. It can be assumed that the higher costs for the package prices from Vattenfall and Kraftringen are partly explained by the fact that monocrystalline solar cells are more expensive than polycrystalline - around 7 % according to Dahlström (2015a). Therefore the package prices from Fortum were used in the calculations to keep the prices comparable to the system prices for a large centralized system, which can be assumed to often be installed using the less expensive polycrystalline modules. The package price for PV systems from Fortum in the range of 3-5 kWp was estimated as 16 500 SEK/kWp from Figure 3-2, which was the number used in the calculations.

A package price is set for a standard installation. Looking at the conditions for a standard installation listed in the Vattenfall PV product sheet (Vattenfall, 2015), which was not found on the web page for Fortum or Kraftringen (they only stated that the package price was a starting price), there are some aspects that could lead to additional costs. For a package price the base of the roof should not be more than 3 meters high, the material of the roof should be either brick or sheet, the area subject to the installation should be consistent, inverters should be possible to install close to the modules and a distribution box should be available in the house. On top of this the ground in front of the house should be flat to ease the installation and the tilt of the roof should not be higher than 30 degrees. According to Åkerström (2015b) at Solkompaniet, the PV corporation partner to Vattenfall, around one third of the PV packages sold are standard packages. Around one third is subject to one or two cost additions and the rest three or four cost additions. In this study it is assumed that all the conditions above are met except for the tilt of the roof. The extra costs for roof tilts above 30 degrees are listed in Table 3-2 below.

Table 3-2. Additional costs as percentage of package price depending on the tilt of the roof as they are added when installing systems from Vattenfall. (Åkerström, 2015a)

System size	**2.2 kWp**	**3.3 kWp**	**5.5 kWp**	**7.7 kWp**	**11.1 kWp**
Tilt 0-30 degrees	-	-	-	-	-
Tilt 31-35 degrees	2.9 %	3.4 %	3.5 %	3.7 %	3.8 %
Tilt 36-45 degrees	4.6 %	5.4 %	5.6 %	5.9 %	6.1 %
Tilt > 45 degrees	5.5 %	6.5 %	6.8 %	7.1 %	7.3 %

The price additions for a 3.3 kWp system (the size closest to 4 kWp) in Table 3-2 is included in the cost calculations.

Since 2010 a residential PV system put on top of a roof is free to connect to the grid if the household do not produce more energy than they consume annually, so called micro producers. The existing connection to the grid has to have enough capacity to handle the PV capacity, but this is generally the case for normal households in Sweden. The system installed also has to have a capacity below 43.5 kW and need a maximum fuse size of 63 A (E.on, 2015; Lindahl, 2013). No cost for grid connection is therefore included for residential PV systems.

Operation & Maintenance

As mentioned in section 2.4.6 the inverters are assumed to have a lifetime of 15 years and therefore has to be replaced once during the life time of the system. This is assumed to be a cost of 0.5 % of the investment cost (Solkompaniet, 2013).

PV modules are exposed to the surroundings and will therefore to some extent be covered by dust and dirt. In an experiment carried out by Appels et al. (2013) in Belgium it was seen that soiling has constant reduction of the energy output of around 3-4 % for modules with a tilt of 35 degrees. In the same study it was seen that an annual cleaning of the modules had no effect since small dust particles quickly covers the modules again and larger particles are simply washed off with rain fall (Appels et al., 2013). No cost for cleaning the modules will therefore be included. A value of 3 % energy reduction due to soiling will be used as an input parameter in the energy simulations in SAM.

In Sweden there is an ongoing study looking at the effects of snow on the power output from PV systems in Sweden (SolElprogrammet, 2014). The study is estimated to be finished in 2017. In this study it is assumed that no snow removal is necessary since no other information was found. Snow would cover the modules during the winter months when the solar radiation on the northern hemisphere is reduced nonetheless. No cost for snow removal is therefore included.

3.2 Ground mounted PV

The centralized ground mounted systems in Sweden constitutes only a small fraction of the total PV systems installed. The ground mounted systems that exist are all quite new and the first ones started producing energy in 2009 (Lindahl, 2014). Ground mounted PV systems will also be referred to as solar parks.

3.2.1 Land use

In general a solar park requires around 25 000 m^2 to 35 000 m^2 of land per MWp installed capacity according to a study performed in the USA (Turney and Fthenakis, 2011). In the same study the energy production from ground mounted PV were compared to conventional energy sources looking at a number of impacts from energy production, such as land use, climate change and animal and plant life. Compared to conventional energy sources there were no impacts from ground mounted PV that were found negative, instead most of the impacts were found positive (Turney and Fthenakis, 2011). In a life cycle analysis of different energy technologies by Fthenakis and Kim (2008) it was found that ground mounted PV have a smaller land footprint than the other renewable energy sources included in the study; biomass, wind and hydropower.

In this study however, ground mounted PV are not to be compared with other energy sources but with roof mounted PV. Since the roofs would exist regardless of a PV installation the impact on the land needed for the installation of ground mounted PV is therefore to be compared with the alternative that no land use is necessary.

There are a couple of definitions frequently used when discussing land use. *Direct land use* means the land covered by the PV modules, the space in between the modules, the space required to the surroundings to avoid shading and the area required to access the park for maintenance. *Indirect land use* is the area required for all the other steps involved, such as raw material extraction, manufacturing of products and decommissioning of the system (Fthenakis and Kim, 2008). The indirect land use from a solar park can be considered negligible compared to the direct land use from the park (Fthenakis and Kim, 2008). The indirect land can also be assumed to be similar for residential and ground mounted PV systems, whereas the direct land use is the main difference between the two. The direct land use from ground mounted PV is therefore discussed further in this section.

Depending on the land type chosen for a PV system the ground might have to be prepared prior to the installation. This is referred to as land-cover change and depending on the original state of the land this change has different impact on the environment (Hernandez et al., 2014). The land is also transferred from one field of application to another, which is called land-use change. Carbon is stored in the soil to different extent depending on the type of ecosystem and might be released when land-cover and land-use change take place (Hernandez et al., 2014). If the site chosen for a solar park is covered by forest the land-cover change causes CO_2 emissions equal to around 36 g CO_2-eq per kWh produced from the PV system (Turney and Fthenakis, 2011). In a study reviewing 129 life cycle analyses of crystalline silicon PV systems (Hsu et al., 2012) the greenhouse gas emissions for residential PV have a median value of 44 g CO2-eq per kWh and ground mounted systems emissions median values of 48 CO2-eq per kWh. The ground mounted systems have probably been installed on land which during the land-cover change carbon has not been released to a large extent. By removing forest it would mean almost a doubling of the greenhouse gas emissions allocated to ground mounted PV. By installing PV on agricultural land it requires little or no land cover change (Solkompaniet, 2013a; Jönsson, 2015).

Apart from releasing carbon to the atmosphere by changing the land cover the biodiversity in the chosen area might also be affected. According to (Hernandez et al., 2014) PV systems that are installed on already existing buildings and constructions such as roof top systems can be expected to have a minor or no negative impact on the biodiversity. Even though there are quite few studies made on the subject it is seen that utility scale PV using previously undisturbed land can affect the biodiversity on the specific site due to the clearing of vegetation. The solar park might also become an obstacle on a regional scale since the landscape becomes more fragmented. Even though some species might be able to simply move around the fence of the solar park it could become a barrier for other species, negatively affecting the gene flow among populations. The physical transformation of land and the landscape fragmentation are seen as the major threat to biodiversity from large scale PV plants (Hernandez et al., 2014).

How to minimize the environmental impact

In the study by Hernandez et al. (2014) some measures to minimize the impact of large scale PV are suggested. The importance of choosing an appropriate site for the solar park to produce as much energy as possible without disturbing the environment is addressed together with a suggestions to put a price on ecosystem services.

To avoid greenhouse gas emission due to land-cover change a ground mounted PV system could be installed on already disturbed land such as landfills. Using these types of land instead of productive land types such as agricultural land or forest could prevent unnecessary land-use change (Hernandez et al., 2014).

To avoid the negative impacts on wildlife it is important to find sites for solar parks with no endangered species or sensitive vegetation. The siting is also important in an ecological point of view when it comes to transmission lines. As with preparing the area of the solar park the construction of new transmission corridors could also enhance the fragmentation of the landscape resulting in loss in biodiversity. On the other hand, wide corridors could create new habitats and increase the edge effect (increased biodiversity in the borders between two biotopes) and instead increase the biodiversity (Hernandez et al., 2014).

There are several possibilities to gain co-benefits from large scale PV systems. Integrating PV into agricultural land could be one possibility, by creating a combination of energy and food production called agrivoltaics (Dupraz et al., 2011). One example is to allow livestock to graze the area around the modules to avoid vegetation that otherwise must be cleared to prevent shading of the modules. The land would then be used to produce energy and food at the same time (Hernandez et al., 2014).

Land types for ground mounted PV

More than two thirds of Sweden are covered by forest and 8 % by agricultural land (SCB, 2013). Ground mounted PV can be installed on many types of land; the solar parks in Sweden are found on old landfills (Bernhardsen, 2015), agricultural land (Jönsson, 2015; Karwonen, 2015) and land originally consisting of stones and brushwood (Kraftpojkarna, 2015). The costs for ground mounted PV systems in this study were calculated using prices for forest and agricultural land. There were two reasons for choosing these land types: the large fraction of land consisting of these two types of land and the available price statistics.

3.2.2 Ground mounted systems in Sweden

There are a few solar parks installed in Sweden today, and the number of parks are likely to increase in the next couple of years. For example a park that is said to become the largest solar park in Sweden is planned to be built between Örebro and Kumla in the near future (Sveriges Radio, 2014). The exact location of the park has not yet been determined. In Helsingborg another large park is being planned, also stating that it will become the largest park in Sweden (Öresundskraft, 2015). The park is planned to be built on old landfills. Both of the parks are said to be built in a size of approximately 2 MW.

A few larger ground mounted solar parks have been built in Sweden. One is found outside Västerås with an installed capacity of 1 MW (Kraftpojkarna, 2015), which is a solar park built using solar tracking modules to increase the output of power. Looking at fixed ground mounted modules there are parks in Simris (Jönsson, 2015), Arnebo (Karwonen, 2015), Skedala (Bernhardsen, 2015) and in Arvika (Rönning, 2015), see Table 3-3.

Table 3-3. Examples of four ground mounted centralized PV systems in Sweden. (Jönsson, 2015; Karwonen, 2015; Bernhardsen, 2015; Rönning, 2015)

Location of park	**Land type**	**Size**	**Production start**
Simris, Scania	Agricultural land	442 kWp	2013-12-18
Arnebo, Uppland	Agricultural land	312 kWp	2013-09-16
Skedala, Halland	Land fill	500 kWp	2014-10-05
Arvika, Värmland	Land fill	1040 kWp	2015-02-08

The four solar parks presented in Table 3-3 together with the park in Västerås add up to a capacity of approximately 3.3 MWp. These solar parks seem to represent a large fraction of the total capacity installed as centralized systems in Sweden, which was approximately 4 MWp in the end of 2014 (Lindahl, 2015a).

When working on this study two solar parks were visited to see examples of installations in Sweden. The first park visited is located in Simris in the southeastern part of Scania, a park that started producing electricity on 2013. The park is owned by Österlenvind AB and has 1804 polycrystalline modules with a total installed capacity of 442 kWp (Jönsson, 2015). The land type used is agricultural land and the PV modules were installed without any need of ground preparation. The modules cover an area of around 10 000 m^2 and the park is surrounded by flat agricultural land. The park is maintained by cutting the grass annually, cleaning the modules is not considered necessary since rain removes the majority of the dirt. A picture of a part of the park is seen in Figure 3-3.

Figure 3-3. The solar park in Simris with a capacity of 442 kW. In the background, north of the park, a wind turbine also owned by Österlenvind AB is seen. To the left is Henrik Davidsson together with the CEO of Österlenvind, Ola Jönsson. Picture taken by the author.

The second park that was visited is the largest park in Sweden at the moment and is located outside Västerås just next to the highway E18. The park is owned by Kraftpojkarna and the installation of the park was finished in the beginning of 2014 (Kraftpojkarna, 2015). Instead of having fixed ground mounted modules the park consists of 92 solar trackers that follows the sun. On each solar tracker there are 36 monocrystalline modules. The park has an installed capacity of 1 MWp and covers an area of 40 000 m^2. A picture of a part of the park and the highway can be seen in Figure 3-4.

Figure 3-4. The solar park outside Västerås with modules on solar trackers. Picture taken by the author.

The land used was claimed to be unworkable and consisted of stone and brushwood. Even though it was practically possible to install the park on the ground after just clearing the vegetation the owner decided to make the ground completely even and remove large stones. The reason for this was to make the area look neat and to be easily accessible for visitors. If machines are to be used for maintaining the vegetation in the future this will also be easier without the presence of large stones. The preparation of the ground resulted in an extra cost of 2 million SEK and will be used in this study as an example of a high cost for ground preparation, due to the removal of large stones, compared to not preparing the ground.

As with the solar park in Simris the modules are not cleaned other than by rainfall. During a period of time there were road works carried out on the highway next to the park and the modules could therefore have been subject to a higher amount of dust in the air. The energy production was studied during the period of road works and no difference in energy production could be seen between the modules closest to the roads and the modules furthest away from the road (Kraftpojkarna, 2015).

The vegetation in the park had not recovered from the ground preparations at the time of writing. Therefore no maintenance of the ground has been needed, and if machines or grazing livestock will be used to perform this maintenance in the future has still not been decided (Kraftpojkarna, 2015).

3.2.3 Cost of ground mounted PV systems

When it comes to larger systems there are no standardized package prices. The costs of the four solar parks mentioned previously in section 3.2.2 (Jönsson, 2015; Karwonen, 2015; Bernhardsen, 2015; Rönning, 2015) can be seen in Table 3-4.

Table 3-4. System costs of four different solar parks in Sweden (Jönsson, 2015; Karwonen, 2015; Bernhardsen, 2015; Rönning, 2015).

Location of park	**Size**	**Production start**	**Total cost excluding VAT and cost of land**	**Cost per installed power, excluding VAT and cost of land**
Simris, Scania	442 kWp	2013-12-18	7 900 000 SEK	17 900 SEK/kWp
Arnebo, Uppland	312 kWp	2013-09-16	3 588 000 SEK	11 500 SEK/kWp
Skedala, Halland	500 kWp	2014-10-05	7 040 000 SEK	14 000 SEK/kWp
Arvika, Värmland	1040 kWp	2015-02-08	14 200 000 SEK	13 700 SEK/kWp

In a case study made by Solkompaniet (2013) the cost of a solar park with different system sizes outside Örebro was calculated. The study was performed for a specific area but was made with general assumptions to be applicable for other solar park projects in Sweden. The cost of the solar park was calculated using poly-crystalline modules and the ground mounting technique was stated to be cost effective since the same technique is used as when building crash barriers on roads (Solkompaniet, 2013). The system prices from the case study is illustrated in Figure 3-5, VAT is not included.

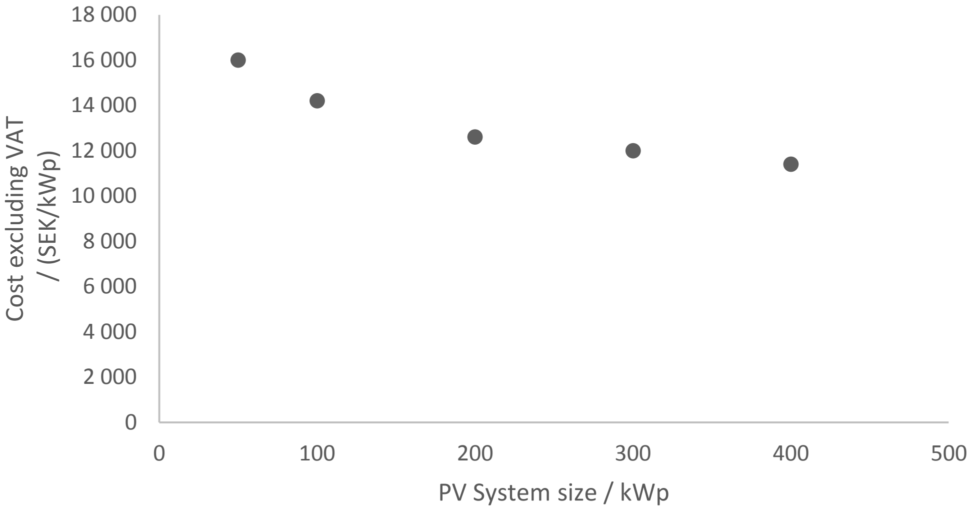


Figure 3-5. PV The calculated cost per kWp of ground mounted PV systems of different sizes calculated in the case study made by Solkompaniet (2013). VAT is not included.

As for the residential system initial costs such as project planning and administration are almost the same regardless of the size of the solar park (Larsson, 2015). Also, when building a larger solar park a lower sales margin for the components can be accepted from the contractor since more modules, inverters and other components are ordered at the same time. If ordering a great quantity of material the contractor might also get a quantity discount from the producer, pushing the prices even lower (Larsson, 2015).

Cost of land and preparation of land are not included in the prices from the case study. To connect the park to the grid it was assumed in the case study that for park sizes around 400 kWp would cost approximately 150 000 SEK since the existing transformer station would have to be rebuilt. These costs are included in the prices illustrated in Figure 3-5. In the cost calculation in this study the price for a 400 kWp will be used which is 11 400 SEK/kWp.

An even larger park – potential system costs

For the comparison it would have been interesting to see what the cost is for larger solar parks than 400 kWp. No estimated cost for larger parks were found, but looking at the costs of ground mounted PV systems in Figure 3-5 it could be expected than the system cost would stabilize around a certain value for PV systems larger than 400 kWp. According to Larsson (2015) the price might become as low as 10 000 SEK per kWp for parks above 1 MWp. The main difference when building a larger park is the cost of connecting it to the grid. A larger capacity means that the transformer station and cables have to be designed to handle the output power from the park. An increased cost of a transformer station and cables have to be balanced with other benefits due to economy of scale mentioned previously for the price per kWp to stabilize for larger parks (Larsson, 2015). Since the price for a larger solar park is mainly speculative the size of 400 kWp is the largest size found with information regarding the system costs.

Operation & Maintenance

The inverters are assumed to last 15 years, same as for the residential PV system, and the costs for replacing them are also assumed to be 0.5 % of the investment cost. Maintenance regarding dirt or snow removal is assumed not to be necessary on ground mounted PV either and will therefore result in no additional costs. Another aspect concerning ground mounted PV is the growth of vegetation around the PV modules. However, the removal of vegetation is assumed to be a negligible cost. It could be possible to use grazing cattle to handle the problem with upcoming vegetation which could become an income for the park owner.

3.2.4 Cost of land

The price of agricultural land is a mean price of arable and grazing land taken from statistics put together by the Swedish Board of Agriculture (2013). The southern part is represented by “the southern flat country of Götaland”, the central part by “the flat country of Svealand” and the northern part by “the upper northern Sweden” as defined in the statistics from the Swedish Board of Agriculture (2013).

The price of forest is found in the Swedish Statistical Yearbook of Forestry from the Swedish Forest Agency (2014). The prices for productive forest were found for each region, where the southern part is represented by prices from “Götaland”, the central part from “Svealand” and the northern part from “the upper northern Sweden”. Since these prices are including trees the value of the trees and the cost of removing them has to be included before a final price is obtained. Information on how to do this in a reasonable way was given by Christiansen (2015). The profit from tree felling was calculated by dividing the total net conversion value by the total net felling. This gave an approximate income per m^3 and could then be multiplied by the approximate volume of forest in each geographical region. This income was then subtracted from the prices for productive forest to get an approximation of the cost of a clear cut forest.

The price for buying one square meter of agricultural land together with the price for one square meter of forest with the trees removed is summarized in Figure 3-6. All prices are excluding VAT.

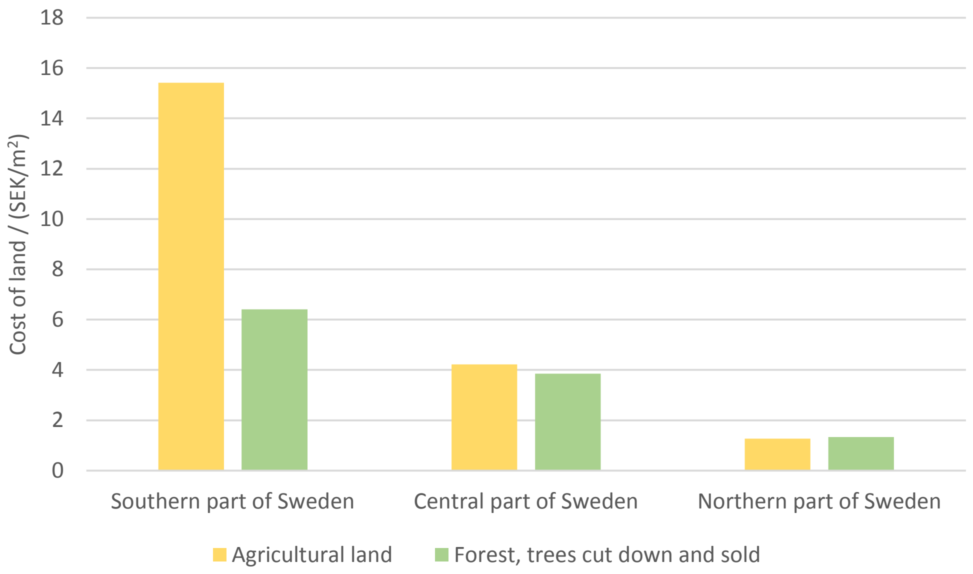


Figure 3-6. Cost of one m² of agricultural land and forest in the three different regions using statistics from the Swedish Board of Agriculture (2013) and the Swedish Forest Agency (2014). VAT is not included.

Ground preparations

If a park is to be put on agricultural land it could be assumed that the land is ready for the installation without any further preparations. This was the case with the solar park in Simris (Jönsson, 2015), and also the assumption in the case study by Solkompaniet (2013) described previously. If forest land is to be used the ground is probably not as flat as with agricultural land types. Since each solar park project will have its own specific requirements it is difficult to know the extent of the need for land preparation.

For this study a low cost scenario and a high cost scenario are assumed as alternatives to see the difference in price and a possible price range depending on to what extent the land has to be prepared. These assumptions were discussed with Dahlström (2015b). The first assumption is that no ground preparation is needed except for removing the trees. The modules can then be put directly on the clear-felled area. This might not look neat and tidy and it could be hard to remove vegetation using machines after the park has been installed. It might also be necessary to have cables above ground if it is hard to bury them in the ground due to stubs and roots. The other assumption is made using Västerås solar park as an example. The park was put on a type of land containing brushwood with large stones and the ground was completely evened before installing the park (Dahlström, 2015b). This was done because they wanted an easily accessible solar park for visitors, the park to look tidy for people passing by on the highway and making the removal of upcoming vegetation easier if this is to be done with machines in the future. The cost for preparing the ground was 500 000 SEK per hectare (10 000 m^2) and this number is used in the calculations as a relatively high cost for land preparation.

3.3 Summary of parameters and costs

The parameters found and assumptions made in this first part of the study are summarized in Table 3-5. All costs presented are excluding VAT (Value Added Tax).

Table 3-5. The parameters from chapter 3 needed for the simulations and calculations in chapter 4.

	Residential PV	**Ground mounted PV**
System size	4 kWp	400 kWp
Costs		
System cost	16 500 SEK/kWp	11 400 SEK/kWp
Connecting to the grid	0 SEK /year	Included in System cost
Changing inverters	0.5 % of investment /year	0.5 % of investment /year
Removing vegetation	-	0 SEK /year
Cleaning modules	0 SEK /year (instead 3 % constant energy reduction due to soiling)	0 SEK /year (instead 3 % constant energy reduction due to soiling)
Clearing snow	0 SEK /year	0 SEK /year
Roof tilt 40°	+ 5.4 % of system cost	-
Roof tilt 50-90°	+ 6.5 % of system cost	-
Agricultural land, southern part	-	15 SEK/ m^2
Agricultural land, central part	-	4 SEK/ m^2
Agricultural land, northern part	-	1 SEK/ m^2
Forest, southern part	-	6 SEK/ m^2
Forest, central part	-	4 SEK/ m^2
Forest, northern part	-	1 SEK/ m^2
No land preparation cost	-	0 SEK/ m^2
High costs for land prep.	-	50 SEK/ m^2

4. Energy simulations and cost calculations

The energy simulations have not been made for the exact systems sizes of 4 kWp and 400 kWp since the chosen modules and inverters in the simulation needed to be matched without limiting the energy output. However, the energy output from the simulations is given in kWh/kWp and all the calculations has been rescaled to the sizes of 4 kWp for residential systems and 400 kWp for ground mounted systems. To simulate the energy output from a residential PV system and a ground mounted PV system the program SAM, System Advisor Model (NREL, 2015), was used. The performance model *Photovoltaic (detailed)* was chosen. This model calculates the electrical output of a grid connected system and includes a simple tool to calculate the effect of mutual shading, which was needed for the solar park. The alternative *No financial model* was chosen since only the energy production was wanted from the simulations. The *No financial model* requires no input of costs, and the cost calculations were instead made manually after performing the energy simulations.

4.1 Input parameters in SAM

4.1.1 Location and Resource

In SAM there are available weather files containing weather data during one year. Three weather files were used in the simulations. For the southern part of Sweden it was assumed that the Copenhagen weather file was representative since there were none available from the southern part Sweden. The central part was simulated using a weather file from Stockholm and the northern part by the Kiruna weather file. The coordinates for the location of each weather file are found in Table 4-1.

Table 4-1. The weather files and the coordinates of each location used in the energy simulations in SAM.

Weather file	Latitude	Longitude
Denmark DNK Copenhagen	55.63 °N	12.67 °E
Sweden SWE Stockholm Arlanda	59.65 °N	17.95 °E
Sweden SWE Kiruna	67.82 °N	20.33 °E

4.1.2 Module

Parameters from a standard poly crystalline module were used for both the residential and ground mounted PV system. In SAM the option *Simple Efficiency Module Model* was chosen and the efficiency of the module was set to 16 % for all irradiance levels, which was assumed to be a realistic efficiency for polycrystalline modules based on values described in section 2.4.6. The mounting option was set to *open rack* which means that air is allowed to circulate around the module to exclude any influence from temperature differences. The residential PV systems in Sweden are assumed to be building applied as described in section 3.1.1, which means that there is usually an air gap between the module and the roof.

The rest of the module characteristics were set as a standard 260 Watt module (Yingli, 2015). A specific module was required for measurements needed in the shading and area calculations. The specific module was chosen based on the argument from the producer that it is sized to fit on both smaller and larger roofs and still economical enough to be used in larger parks. The length of the module is 1.64 meters and the width is 0.99 meters.

4.1.3 Inverter

The efficiency of the inverters were set to 96 % since the expected efficiency is between 95-97 % as described in section 2.4.6.

4.1.4 System Design

The tilts of the residential roof were set to vary between 0 degrees and 90 degrees to include all tilts from a horizontal roof to a vertical facade. Azimuth angles were set to vary between east and west which is a range in degrees between 90 and 270 degrees, when south is defined as 180 degrees. The interval was set to 10 degrees for both tilt and azimuth angles. For the ground mounted system the tilt and azimuth of the PV modules were chosen as the optimum orientation received from the energy simulations of the residential roofs.

4.1.5 Shading

The effect of mutual shading between the rows of modules is taken into consideration in this part of the model. Mutual shading is only simulated for the solar park and is not included in the calculations for the residential system since the modules are designed to be put flat on the roof.

The number of rows and modules per row have to be specified in SAM. Since this study is to be kept as general as possible the aim was to model a fairly square park, in reality the design would be adapted to the specific site. The number of rows and modules per row were kept fixed, making the design a bit more rectangular for some row distances. The modules were mounted with the long side of the module parallel to the ground. The reason for doing this is that the strings with bypass diodes are oriented along the long side of the module. In a park the modules can be expected to be shaded on the bottom of the module from the row in front. If the modules would be installed with the short side parallel to the ground and the row in front would shade the bottom of a module, it could limit the energy output from all the cells in the module as described in section 2.4.3. The rows were kept one module high.

The parameter Ground Coverage Ratio (GCR) also has to be defined in SAM. The ground coverage ratio is defined as:

$$GCR = \frac{Total\ module\ area}{Total\ land\ area} \qquad \textit{(Equation 4-1)}$$

Since it might be easier to relate to the distance between rows of modules instead of a ground coverage ratio the desired row distances were determined and from this the corresponding GCR’s were calculated and entered in SAM. In this study the row distance is defined as the distance between the back of one row to the front of the next one. The shading angles were also calculated since this was needed to determine the distance between the park and a forest edge. The row distance and the shading angle are illustrated in Figure 4-1.

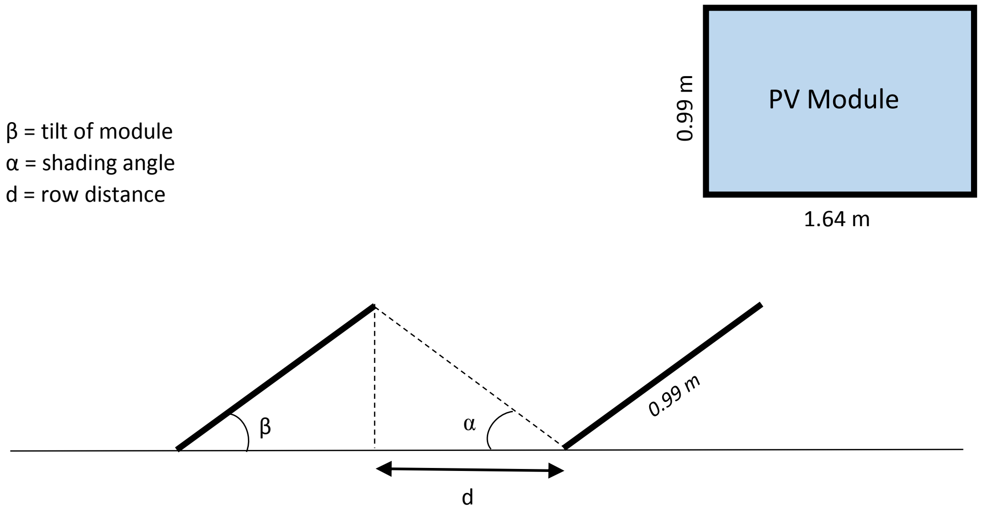


Figure 4-1. Sketch of two rows of PV modules seen from the side.

For each row distance the GCR is calculated by dividing the length of the side of the row, the short side of the module which is 0.99 meters, by the length from the front of one row to the front of the next. For example, a GCR equal to 1 means that the front to front distance is 0.99 meters. The front to front distance is calculated by adding the length beneath the module to the row distance. The length beneath the module depend on the tilt of the module and the equation for GCR becomes:

$$GCR = \frac{0.99}{d + 0.99 \cdot \cos\beta} \qquad \text{(Equation 4-2)}$$

Where *d* is the row distance and *β* is the tilt of the module.
The shading angle, α, is then calculated as:

$$\alpha = \tan^{-1}\left(\frac{0.99 \cdot \sin\beta}{d}\right) \qquad \text{(Equation 4-3)}$$

For a tilt of 40 degrees the relationship between the row distance, GCR, shading angle, length and width of the park and the total area for the modules and space in between are found in appendix A.1.

4.1.6 Other losses

To exclude parameters not included in this study the rest of the system losses were kept the same for both the residential system and the ground mounted system. The alternative was to put these losses to zero to neglect them, but since the annual energy losses in a PV system are usually estimated to be approximately 10 % (Leloux et al., 2012) losses were included to aim for a more realistic energy output from the simulations.

For mismatch, diodes and connections, and for DC - and AC wiring the losses were kept as the default values in SAM. Reduction due to soiling was put to a constant loss of 3 % as described in section 3.1.4.

4.1.7 Summary of parameters

The input parameters in SAM described in section 4.1.1- 4.1.6 are summarized in Table 4-2. These parameters are the same when simulating the residential PV system and the ground mounted PV system.

Table 4-2. Summary of the system parameters and assumptions used as input in SAM and the following calculations.

Performance parameters	
Module efficiency	16 %
Degradation in module efficiency	0.5 % per year
Inverter efficiency	96 %
Losses	
Soiling	3 %
Mismatch	2 %
Diodes and connections	0.5 %
DC wiring	2 %
AC wiring	1 %

4.2 Residential PV

4.2.1 Energy simulations

The first simulation performed in SAM was the irradiance for different orientations to illustrate how different azimuth angles and tilts are classified using the definitions in Lund solar map. The irradiation on tilts between 0-90 degrees and azimuth angles from west to east using Copenhagen weather file were simulated. The color definitions from Table 3-1 were applied to the levels of irradiation to illustrate the difference in irradiance on a surface depending on orientation and tilt. The roofs classified as "excellent" and "good" were then selected. Then energy output in kWh/kWp for all three regions were simulated.

4.2.2 Cost calculations

To calculate the cost per energy for a PV system the total system cost and cost of operation and maintenance are divided by the number of kWh produced by the system during an assumed lifetime of 30 years. The assumptions found in Table 3-5 are used to calculate the cost per energy for a system in the size of 4 kWp.

$$\frac{Cost}{Electricity} = \frac{C_{roof} \cdot n_{tilt \leq 30°} + C_{roof} \cdot 1.054 \cdot n_{30° > tilt \leq 40°} + C_{roof} \cdot 1.065 \cdot n_{tilt > 40°} + O\&M}{\sum E_{roof,1st\ year} \cdot LT \cdot (1-\varphi)} \qquad \text{(Equation 4-4)}$$

$$O\&M = C_{roof} \cdot 0.05 \cdot LT \qquad \text{(Equation 4-5)}$$

$$\varphi = \frac{(1-(1-0.005)^{LT})}{2} = 0.07 \qquad \text{(Equation 4-6)}$$

where C_{roof} is the package price of a residential PV system, n is the number of roofs, $E_{roof,1st\ year}$ is the energy production from the residential PV system in kWh/kWp, $O\&M$ is the cost for Operation and Maintenance, φ is the mean reduction in module efficiency during its lifetime and LT is the life time of the system.

4.3 Ground mounted PV

4.3.1 Energy simulations

The optimum orientation from the energy simulations of the residential systems were used when simulating the energy output from the park.

4.3.2 Total area of the solar park

Before the cost of produced electricity for the ground mounted PV could be calculated the total area of the park needed to be determined.

Depending on the surroundings the solar park could be subject to shading which would cause a reduction in energy output from the system. In this study it is assumed that if agricultural land is used the surroundings also consists of agricultural land which does not shade the park. It is assumed that a distance of ten meters is used between the park and a surrounding fence to avoid shading from the fence and to be able to pass with machines used to cut vegetation, see Figure 4-2. As an example the park in Simris have a distance of between 5 and 20 meters to the fence (Jönsson, 2015).

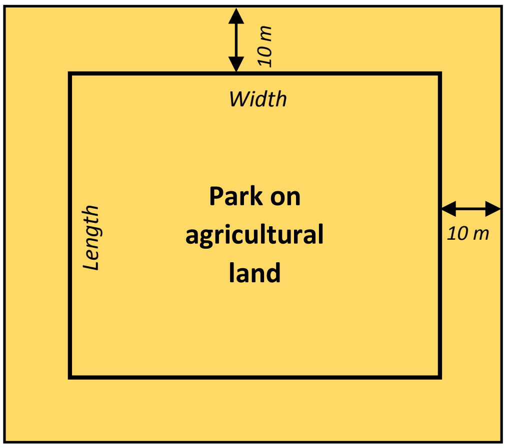


Figure 4-2. Sketch of the area assumed to be needed when putting the park on agricultural land.

If the park is put in a forest it is assumed that the closest surroundings also consists of forest. Extra land therefore has to be bought and cleared to avoid shading from trees. A tree is assumed to reach a maximum height of 30 meters before it is being felled (Martinsson, 2015; KunskapDirekt, 2015).

The extra land needed is calculated by assuming the same shading angle between the tree and the first row of modules as the angle between two rows of modules, see Figure 4-3.

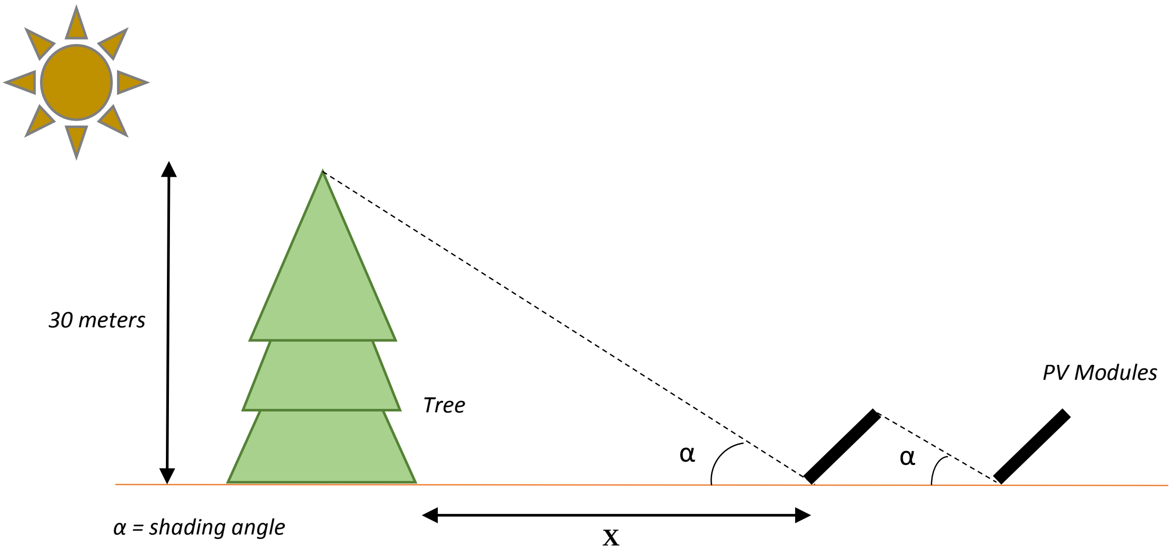


Figure 4-3. Sketch of the first two rows of the solar park seen from the side. The distance X depends on the shading angle, α.

The distance *X* south of the park and an area from south-east to south-west are assumed to be enough to clear from trees. On top of that the ten extra meters around the park assumed above in the agricultural land case is added to the north, east and west side. It is not studied how well this assumption prevents the park from being shaded, instead it is included to address the issue and to illustrate how this affects the costs of produced energy. The assumptions are illustrated in Figure 4-4. The calculations of the area are found in Appendix A.1. The area required for the modules and the row distance is given by SAM and described further in the section 4.1.5.

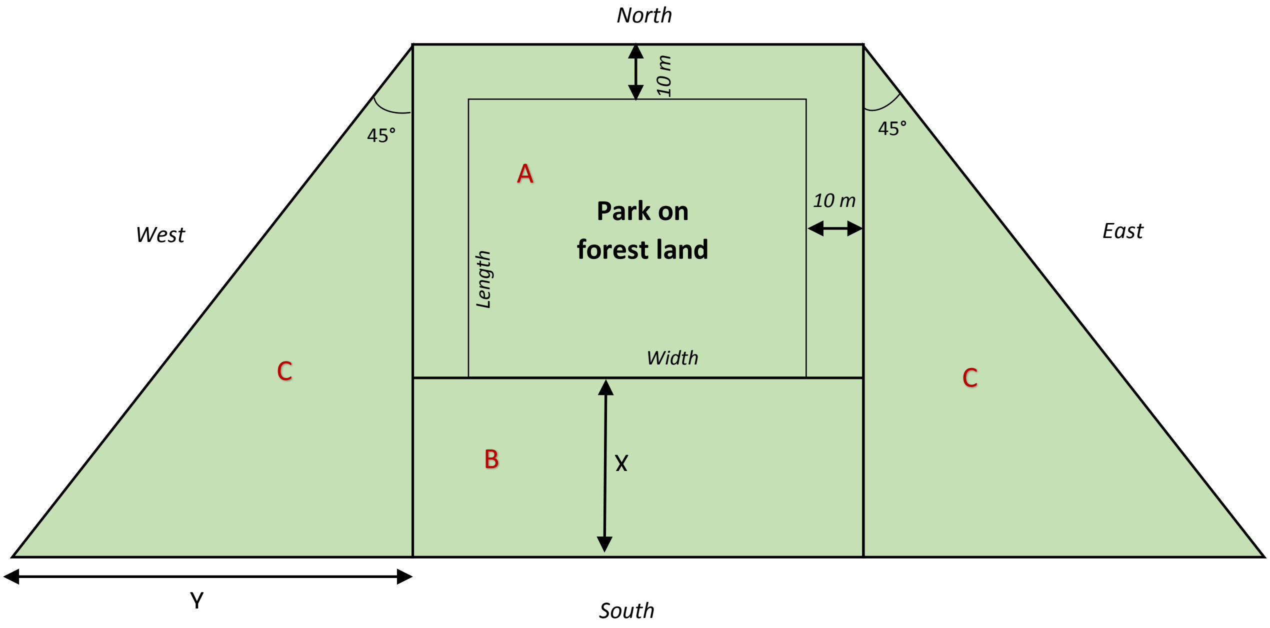


Figure 4-4. Sketch of the area assumed to be needed when putting the park in a forest.

The total land area needed for a park on agricultural land and in a forest is found in Table A-2 in Appendix A.1.

4.3.3 Cost calculations

The costs of produced electricity are calculated similar to the residential PV systems but with the cost of land included.

$$\frac{Cost}{Electricity} = \frac{(C_{park}+O\&M)\cdot System\ size + A_{tot\ (land\ type)}\cdot C_{land\ type} + A_{(park+fence)}\cdot C_{ground\ prep.}}{E_{park,1st\ year}\cdot LT\cdot(1-\varphi)\cdot System\ size}$$

(Equation 4-7)

$$O\&M = C_{park}\cdot 0.05\cdot LT$$

(Equation 4-8)

$$\varphi = \frac{(1-(1-0.005)^{LT})}{2} = 0.07$$

(Equation 4-9)

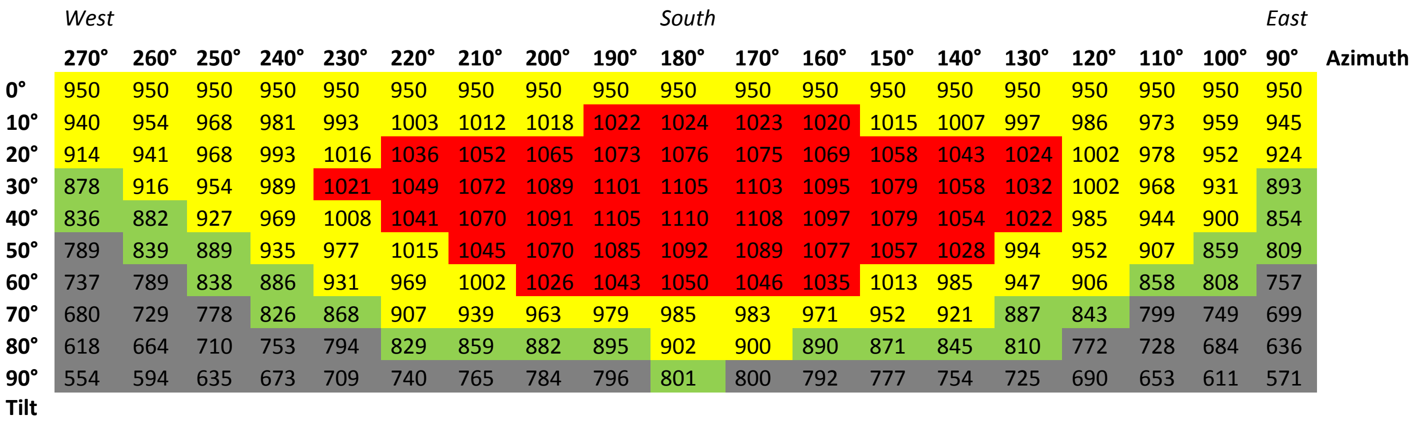
Where C_{park} is the cost of a ground mounted PV system, *O&M* is the cost for operation and maintenance, $E_{park,1st\ year}$ is the energy production from the solar park in kWh/kWp, *LT* is the life time of the system and φ is the mean reduction in module efficiency during its lifetime. $A_{tot(park+fence)}$ is the area of the solar park including modules, row distance and distance to the fence. $A_{tot(land\ type)}$ is the area of the solar park plus the additional area needed to avoid shading from the surroundings. For area calculations see equation A-1 to A-7 in Appendix A.1. $C_{land\ type}$ is the cost of land depending on land type and geographic area, see Figure 3-6. $C_{ground\ prep.}$ is the cost for preparing the area needed for the modules after tree felling, see Table 3-5.

5. Results

5.1 Residential PV

The irradiance on a roof vary with different tilts and azimuth angles. The irradiance for the southern part of Sweden is seen in Table 5-1. The roofs classified as “excellent” are colored with red and the roofs classified as “good” are colored with yellow according to Lund solar map. Green symbolizes “poor” and grey “not advisable”, see Table 3-1 for the different classifications.

Table 5-1. The irradiance on different surface tilts and azimuth angles per square meter and year for the southern part of Sweden (Copenhagen weather file), colored using the definitions from the Lund solar map. The unit is in kWh/m² annually, which is not written in the table due to space limitations.



	West									*South*									*East*	
	270°	**260°**	**250°**	**240°**	**230°**	**220°**	**210°**	**200°**	**190°**	**180°**	**170°**	**160°**	**150°**	**140°**	**130°**	**120°**	**110°**	**100°**	**90°**	**Azimuth**
0°	950	950	950	950	950	950	950	950	950	950	950	950	950	950	950	950	950	950	950	
10°	940	954	968	981	993	1003	1012	1018	1022	1024	1023	1020	1015	1007	997	986	973	959	945	
20°	914	941	968	993	1016	1036	1052	1065	1073	1076	1075	1069	1058	1043	1024	1002	978	952	924	
30°	878	916	954	989	1021	1049	1072	1089	1101	1105	1103	1095	1079	1058	1032	1002	968	931	893	
40°	836	882	927	969	1008	1041	1070	1091	1105	1110	1108	1097	1079	1054	1022	985	944	900	854	
50°	789	839	889	935	977	1015	1045	1070	1085	1092	1089	1077	1057	1028	994	952	907	859	809	
60°	737	789	838	886	931	969	1002	1026	1043	1050	1046	1035	1013	985	947	906	858	808	757	
70°	680	729	778	826	868	907	939	963	979	985	983	971	952	921	887	843	799	749	699	
80°	618	664	710	753	794	829	859	882	895	902	900	890	871	845	810	772	728	684	636	
90°	554	594	635	673	709	740	765	784	796	801	800	792	777	754	725	690	653	611	571	
Tilt																				

Since roofs with a tilt of more than 30 degrees will be subject to an additional installation cost the roofs were divided into sections depending on tilt, see Table 5-2.

Table 5-2. The roofs defined as ”Good” and ”Excellent” using the solar map for Lund, divided by tilt for cost calculations.

Tilt	**Number of roofs**
0-30 degrees	74
40 degrees	15
50-90 degrees	37
Total	126

The same roofs were chosen to represent an average roof for a residential PV system for all three locations.

The first year energy production for a PV system in the southern part of Sweden (Copenhagen weather file) in kWh per installed kWp is illustrated in Table 5-3.

Table 5-3. First year energy production from a system located in the southern part of Sweden (Copenhagen weather file). The background is colored using the solar map definition. The unit is in kWh/kWp, which is not written in the table due to space limitations.

	West									*South*									*East*	
	270°	**260°**	**250°**	**240°**	**230°**	**220°**	**210°**	**200°**	**190°**	**180°**	**170°**	**160°**	**150°**	**140°**	**130°**	**120°**	**110°**	**100°**	**90°**	**Azimuth**
0°	867	867	867	867	867	867	867	867	867	867	867	867	867	867	867	867	867	867	867	
10°	857	869	881	893	903	912	920	926	929	931	930	928	923	916	907	897	886	874	862	
20°	832	857	880	902	922	940	955	966	973	976	975	969	960	947	930	911	890	867	843	
30°	800	834	867	898	926	950	971	986	996	1001	999	991	978	959	936	910	880	848	814	
40°	763	803	843	880	914	943	969	987	1000	**1005**	1003	993	977	955	927	894	859	820	780	
50°	720	765	808	849	886	921	947	969	982	989	986	976	958	933	902	866	826	784	740	
60°	674	720	764	806	846	880	910	931	946	952	950	940	920	895	861	825	783	739	694	
70°	624	667	711	753	792	827	855	877	891	897	895	885	867	840	809	770	731	686	642	
80°	568	610	651	690	726	759	785	806	819	825	823	814	797	773	742	708	668	629	586	
90°	512	548	584	619	651	680	703	721	732	737	736	728	715	694	667	635	602	564	527	
Tilt																				

The highest energy output is reached when having a tilt of 40 degrees and an azimuth angle of 180 degrees. This was also the optimum when simulating with Stockholm and Kiruna weather files, these values can be found in the Appendix A.2.

The energy produced by a PV system put on these roofs is compared to an optimum roof with a tilt of 40 degrees and an azimuth angle of 180 degrees (south). These values are seen in Table 5-4.

Table 5-4. The first year energy production on a roof with the highest energy production compared to an average roof.

	Southern part of Sweden (Copenhagen weather file) / (kWh/kWp)	**Central part of Sweden** (Stockholm weather file) / (kWh/kWp)	**Northern part of Sweden** (Kiruna weather file) / (kWh/kWp)
1st year energy production from optimum residential PV systems	1005	989	840
1st year energy production from average residential PV systems	908	878	744
Ratio between average and optimum PV system	90 %	89 %	89 %

The energy ouput from an average residential system, systems on roofs classified as “good” and “excellent” in Lund solar map, is 10-11 % lower than from a residential system with optimum tilt and azimuth angle. This can be compared to the 8 % reduction from different orientations and shading in the Belgium review of PV systems (Leloux et al., 2012). The average roof in this study has a slightly higher reduction in energy output than the Belgium study. The assumption that PV systems are evenly distributed on these variations in azimuth angles and tilt might explain the difference, roofs with a more optimized tilt and azimuth angle might represent a larger fraction of the total installations in reality. But due to shortage of further information the assumption made regarding roof tilt and azimuth angle will be used in the calculations to illustrate an average residential PV system. This will give a range in cost per produced kWh between systems from optimally oriented residential PV systems and residential PV systems with 10-11 % less energy production. The first year energy production for the three locations are illustrated in Figure 5-1.

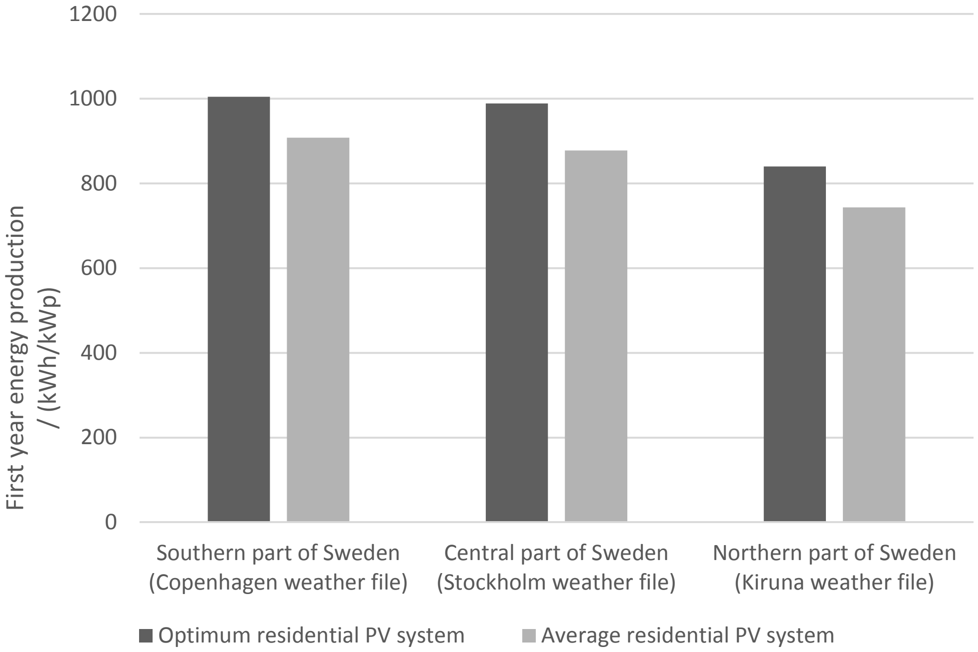


Figure 5-1. First year energy production at the different locations from an optimum residential PV system and an average residential PV system.

A system installed in the southern part of Sweden produces slightly more energy than a system installed in the central part. In the far north of Sweden the energy produced is noticeably reduced compared to the other two regions.

The costs per kWh for residential PV systems are seen in Figure 5-2.

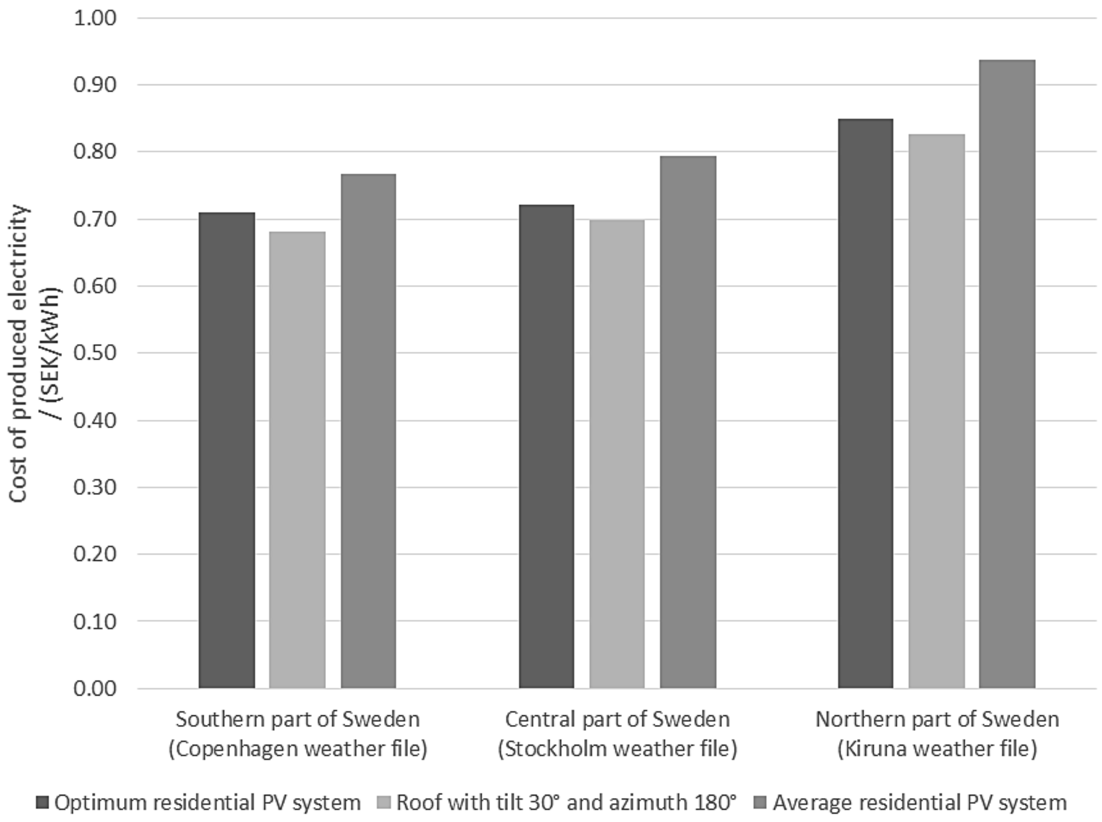


Figure 5-2. Cost of energy for three different cases; an optimum residential PV system, a roof with lower installation cost due to a tilt of 30 degrees and an average residential PV system.

The reason for including a system with a tilt of 30 degrees is that the installation costs are lower than for the optimum tilt of 40 degrees. Even though a tilt of 40 degrees gives a higher energy production the cost addition for the tilt higher than 30 degrees results in a higher cost per kWh. The cost per produced kWh is highest for an average residential system. The difference between the regions have the same proportions as the energy production in Figure 5-1.

5.2 Ground mounted PV

The energy output from the solar park for the southern, central and northern part of Sweden with a tilt of 40 degrees and azimuth angle of 180 degrees varies with row distance, see in Figure 5-3.

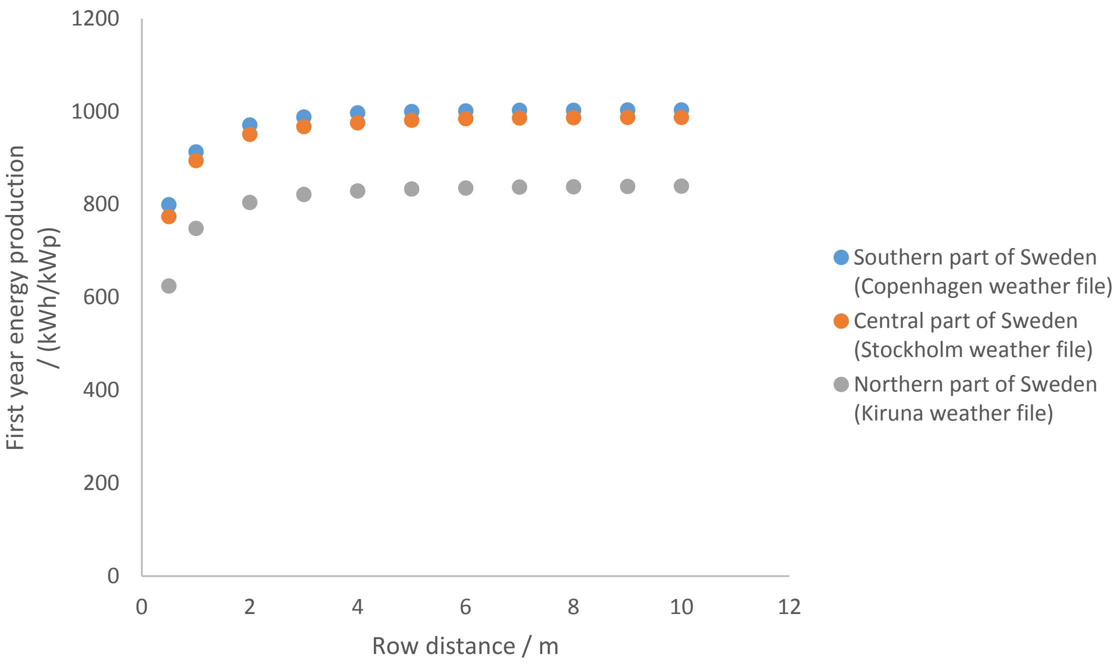


Figure 5-3. The energy production during the first operating year versus row distance for the tree regions.

The energy produced by a solar park in the different regions differ mostly from the southern and central part to the northern part, which has a significantly lower energy production. The impact from the mutual shading due to the row distance is visible; the energy output is clearly reduced for row distances below three meters.

The cost per produced electricity differs with land type and also varies depending on row distance. For agricultural land see Figure 5-4 and for forest see Figure 5-5. The calculations for a park in a forest are based on the assumption that the cost for ground preparation is zero.

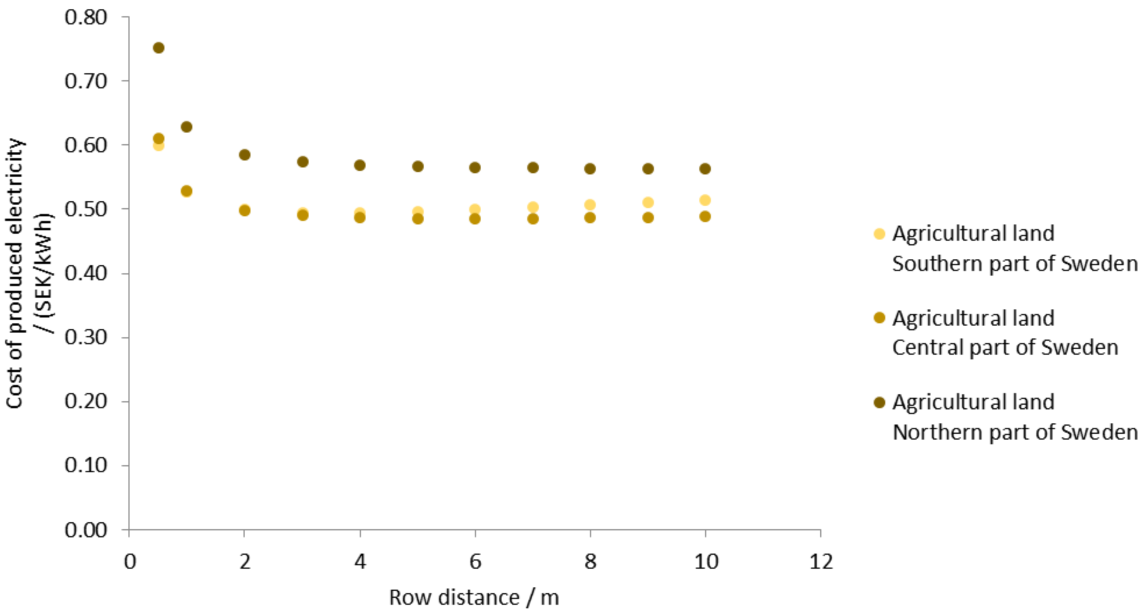


Figure 5-4. The cost of produced electricity for a solar park installed on agricultural land. .

A solar park placed on agricultural land has the highest cost per produced kWh for the northern part of Sweden. The pattern is similar to the energy production illustrated in Figure 5-3, after a row distance of around three meters the values stabilizes. Looking at the cost of produced electricity for a park put in a forest the relationship with the row distance is different. The cost per kWh do decrease up to a row distance between two and three meters but instead of stabilizing the costs are then increasing with longer row distances. The difference between agricultural land and forest is the extra land included to avoid shading from the forest edge when the solar park is installed in a forest. See Figure 5-5.

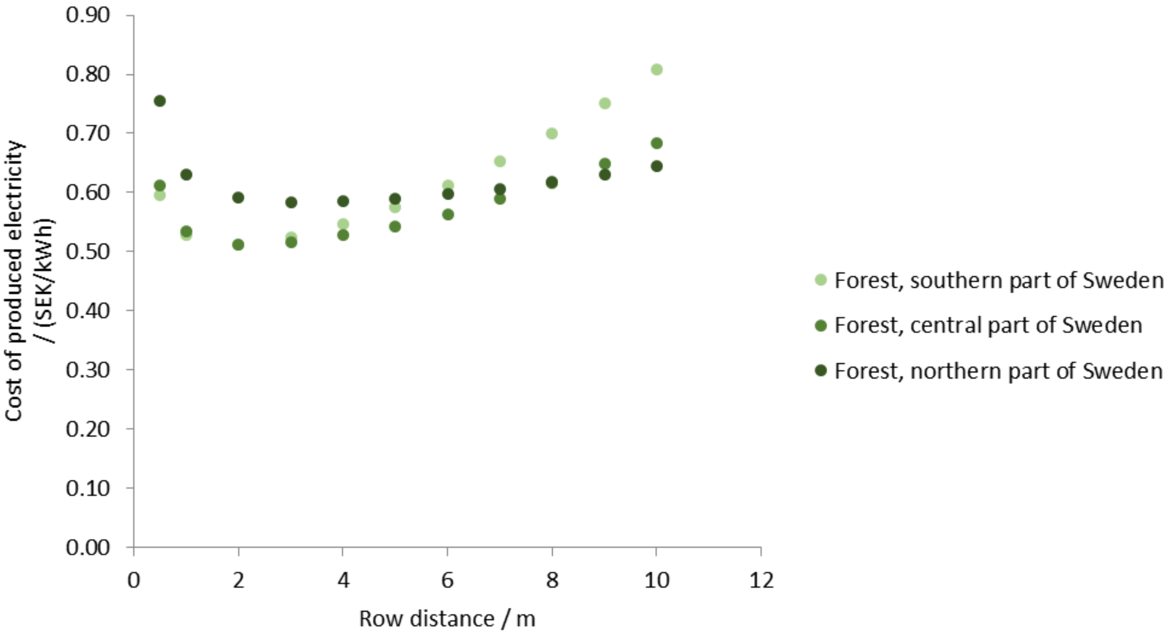


Figure 5-5. The cost of produced electricity for a solar park installed in a forest. The calculations do not include the cost for preparing the ground after tree felling.

In the simulations the park has an installed capacity of 400 kWp. The same calculations are made for a park that is four times larger which doubles the length and width of the park, and the ratio between the extra area needed for a park in a forest to the area of the park changes. This change has an impact on cost of produced electricity, see Figure 5-6.

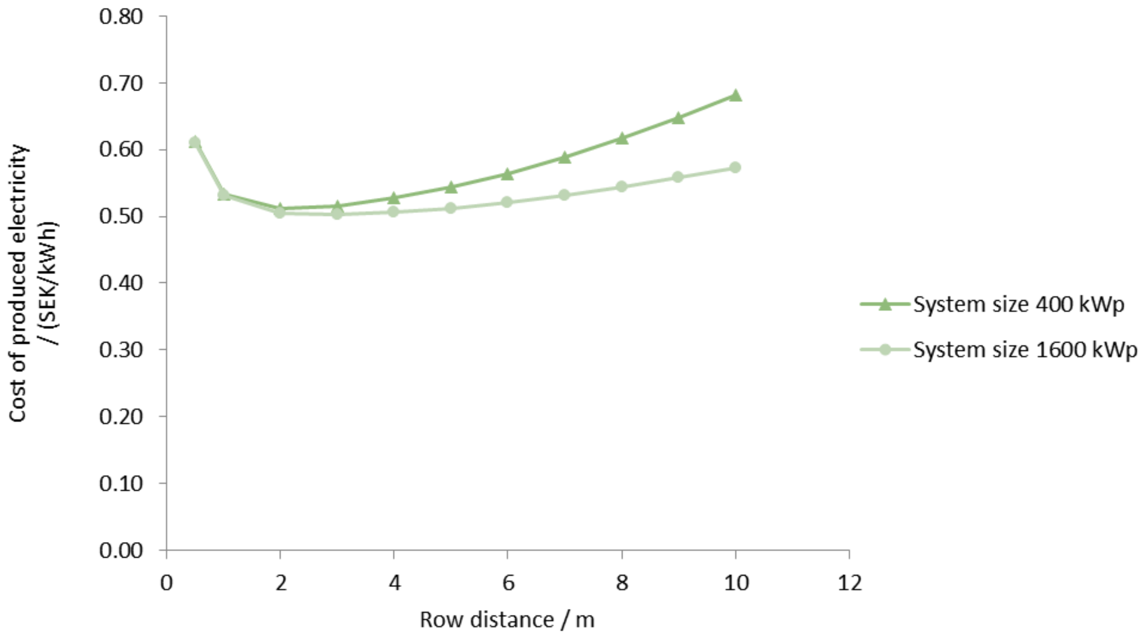


Figure 5-6. Cost of produced electricity for a 400 kWp park and a four times larger park with forest costs and weather for the central part of Sweden. No cost for ground preparation is included.

A clear difference can be seen between the two park sizes. Up to a row distance of around three meters the cost per produced kWh is similar but for longer row distances the smaller park has a significantly higher cost per kWh than the four times larger park.

5.3 Comparing cost of produced electricity

The energy produced in the solar park reaches a plateau after a row distance of around 3 meters, as seen in Figure 5-3. Looking at the cost of the produced electricity in Figure 5-4 for agricultural land and Figure 5-5 for forest a row distance of three meters gives low costs in both cases. The row distance of three meters is therefore used when comparing the cost of energy produced in the park with the cost of energy produced by the residential systems. The area needed for a park on agricultural land with a row distance of 3 meters and ten meters extra to the fence is 13 681 m^2. For a park installed in a forest with the extra land needed to avoid shading the area for a row distance of 3 meters is 83 772 m^2, which is more than six times the area needed for a park on agricultural land. Area needed for other row distances are found in Appendix A.1 in Table A-2.

The lowest cost per kWh on a residential PV system and the cost per kWh on an average residential system are compared to the cost of energy produced from a ground mounted PV system on different land types. The forest land is divided into the two scenarios described section 3.2.4, one with no extra cost for preparing the ground after tree felling and the other with an assumable high cost of 50 SEK per square meter. See Figure 5-7.

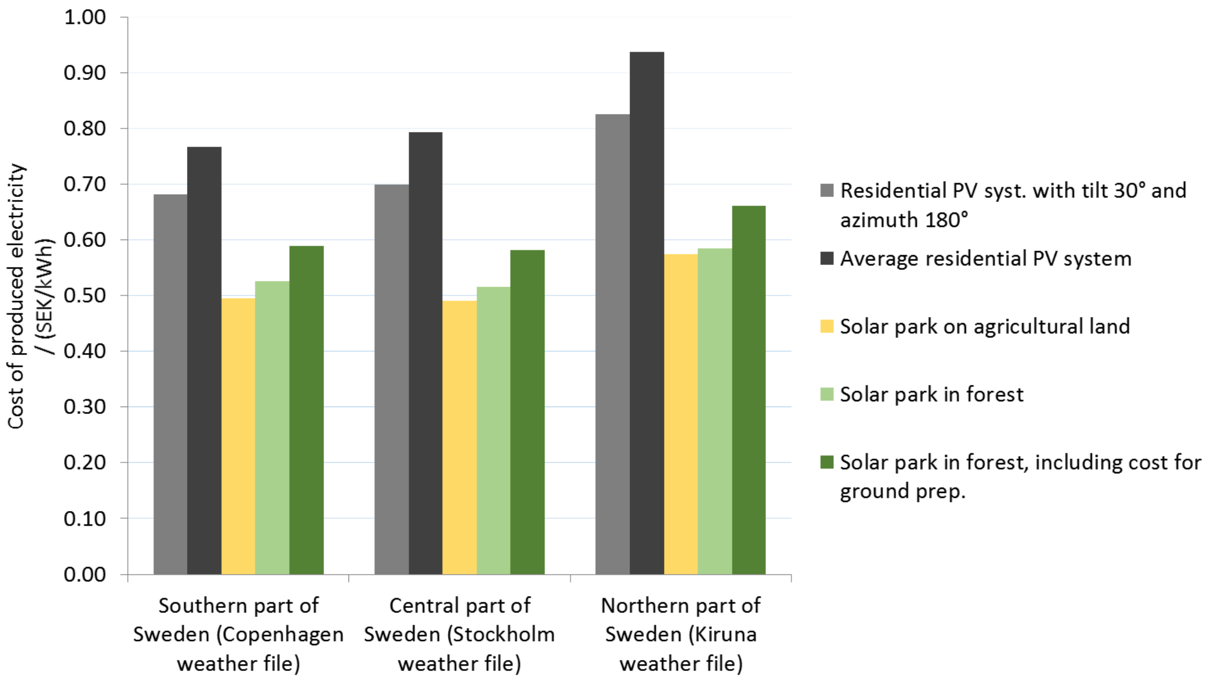


Figure 5-7. Cost of produced electricity for residential PV systems and a ground mounted PV system on different land types with a row distance of three meters between the modules.

The average residential system has the highest cost per produced kWh while a park put on agricultural land has the lowest for all three regions. Regardless of land type, ground mounted PV systems have a lower cost per kWh than a residential PV system. A solar park installed in a forest, without including the cost of ground preparation, has a higher cost of around 0.04 SEK in the south to 0.01 SEK in the north compared to a park on agricultural land. Comparing the three regions, the southern and central part of Sweden have similar costs per produced kWh for all PV systems whereas in the north the costs of the energy produced from the ground mounted PV system are around 0.10 SEK higher and for residential PV systems 0.10 to 0.15 SEK/kWh higher.

To put these number in a context the difference in installing ground mounted parks instead of as residential PV systems were calculated for a PV capacity corresponding to an annual production of 5 TWh, as stated to be possible in the study made by Carlstedt (2006), See Table 5-5. These are not the real costs differences since the calculations in this study do not include interest rates, inflation etc. But it illustrates that a difference in costs per produced kWh could result in large differences in terms of TWh.

Table 5-5. Annual difference in cost between installing 5 TWh on the ground instead of as residential PV systems together with the area of land these 5 TWh of solar parks would occupy on each land type.

	Annual difference in cost by producing 5 TWh from average residential syst. compared to 5 TWh on agricultural land / Million SEK	Area covered with solar parks with 3 meters row dist. on agricultural land to prod. 5 TWh annually / km^2	Annual difference in cost by producing 5 TWh from average residential syst. compared to 5 TWh in forests / Million SEK	Area covered with solar parks with 3 meters row dist. in forests to prod. 5 TWh annually / km^2
Southern part of Sweden	1 360	180	1 210	1 090
Central part of Sweden	1 510	180	1 390	1 110
Northern part of Sweden	1 810	210	1 760	1 310

If installing ground mounted PV capacity corresponding to 5 TWh it would result in land use of around 200 km^2 if putting the parks on agricultural land and an area of more than 1000 km^2 in forests. The area of around 200 km^2 for agricultural land and 1000 km^2 for forest can be compared to, for example, the area of around 4600 km^2 covered by roads in Sweden today (SCB, 2013). Once again, this is just to put the results in a larger perspective.

6. Discussion

Looking at the capacity installed in Sweden compared to the rest of Europe it can be expected that Sweden is in the very beginning of its solar revolution. If the development will continue in the same rate as it has been during the last four years, doubling in capacity each year, it is interesting to discuss how the share of the different market segments for PV systems will be divided in the future.

The residential systems existing today might perform better than the estimated average system in this study with a 10-11% lower energy production than an optimally oriented residential PV system. On the other hand, the residential systems could also be performing worse in reality, if many installations exists on surfaces with orientations receiving less irradiation than the surfaces used in the study. By only choosing roofs classified as “excellent” and “good” it might exclude tilts and azimuth angles that are represented by PV systems in reality. However, it could probably be assumed that the “better” oriented roofs are subject to more PV system installations in reality than roofs receiving less irradiation.

The actual price for a residential system might be higher than the cost used in this study if the average costumer has to pay higher additional costs than assumed in the study. The assumption that all package price conditions were met except for the tilt of the roof tops might result in a lower system cost than in reality. In the study it was also assumed that a PV system placed on a flat roof has the same package costs as a roof with a tilt. In reality, if installing a PV system on a horizontal roof the modules might be installed similar to a ground mounted system with a tilt and a distance between the modules to avoid mutual shading. How this would affect the costs for horizontal roofs has not been studied.

Calculations of the extra land needed to avoid shading from trees when putting a park in the forest are very rough, and it leads to an area six times larger than area needed on agricultural land. If PV systems are installed in forests the trees have to be cut down which results in a net release of carbon dioxide to the atmosphere, since no trees are replanted. Apart from the land needed for modules and the distance between the rows extra land has to be cleared to avoid shading from the forest edge. The land use and land cover change therefore affects a much larger area than just the park area if forest land is used. However, the impact of the extra land decreases when building a larger park as was seen in Figure 5-6.

7. Conclusions

The conclusion from this study is that PV systems should be placed on the ground to produce the most electricity per invested Swedish crown. Agricultural land is the least expensive land type option when compared with forest, since the ground is already flat and no shading forest edge has to be taken into consideration. The irradiation has a larger impact on the cost per produced kWh than the cost of land, making PV in the far north more expensive. The environmental impact from installing PV on the ground is not well known but an installation will result in land use – and land cover change to some extent. This study can be used as a base for further discussions and research on where to install PV systems in the future.

8. Future research

Even though PV requires a small land use compared to other energy sources there is still the alternative to use existing structures to further minimize the land use change. The environmental impacts have to be further studied and implemented on the specific land types that might be chosen for an installation. Including costs of both negative and positive environmental impacts in an economical calculation might be one way to ensure that the environment benefits from PV and not the opposite. There are examples of parks on landfills today and the potential of utilizing such land would be interesting to follow up.

In future studies it would also be interesting to study what the incentives are to install PV in Sweden. Perhaps there are more possible investors among private households and these people only find a value in having their own system on the roof. Or there might be great potential in selling shares of a solar park for private people.

When performing this study the shortage of performance evaluations for existing Swedish PV installations were noted. Many owners make their own evaluations but no national statistics has been gathered. A national register of the tilt, azimuth angle and size distribution of installed PV systems were also not possible to find for Swedish systems. The main suggestion for further studies is to gather more comprehensive data for the Swedish PV systems. Then it is possible to review the performance of the cumulative capacity of today and how it can be optimized in a cost-effective way in the future.

References

ADSTEN, M. 2015. 08-677 27 35 (phone call). Elforsk. *Statistics of PV system performance.* 2015-03-25.

APPELS, R., LEFEVRE, B., HERTELEER, B., GOVERDE, H., BEERTEN, A., PAESEN, R., DE MEDTS, K., DRIESEN, J. & POORTMANS, J. 2013. Effect of soiling on photovoltaic modules. *Solar Energy,* 96**,** 283-291.

BERNHARDSEN, L. 2015. lars.bernhardsen@hem.se (email). Halmstads Energi och Miljö AB. *Solar park in Skedala*. 2015-04-30.

CARLSTEDT, N.-E. K., BJÖRN; KJELLSSON, ELISABETH; NEIJ, LENA; SAMUELSSON, OLOF 2006. *Konkurrenskraft för nätansluten solel i Sverige -sett ur kraftföretagens och nätägarnas perspektiv* (Elforsk report 07:17).

CHRISTIANSEN, L. 2015. linn.christiansen@skogsstyrelsen.se (email). Skogsstyrelsen. *Average price for forest in Sweden*. 2015-04-08.

D.C. JORDAN, R. M. S., C.R. OSTERWALD, & E. GELAK, A. S. R. K. 2010. Outdoor PV Degradation. In *35th IEEE Photovoltaic Specialists Conference (PVSC '10).* Honolulu, Hawaii. June 20-25, 2010.

DAHLSTRÖM, T. 2015a. tommy@kraftpojkarna.se (email). Kraftpojkarna AB. *Difference in price between mono- and polycristalline modules*. 2015-04-22.

DAHLSTRÖM, T. 2015b. 021-277 92 (phone call). Kraftpojkarna AB. *Ground preparation.* 2015-04-29.

DAHLSTRÖM, T. 2015c. 021-277 92 (phone call). Kraftpojkarna AB. *The Megawatt park, operation and maintenance.* 2015-03-11.

DUPRAZ, C., MARROU, H., TALBOT, G., DUFOUR, L., NOGIER, A. & FERARD, Y. 2011. Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes. *Renewable Energy,* 36**,** 2725-2732.

E.ON. 2015. *Producera din egen el - så här gör du.* https://www.eon.se/privatkund/Produkter-och-priser/Elnat/Producera-din-egen-el/Sa-har-gor-du/ [2015-05-15]

EPIA 2014. *Global Market Outlook For Photovoltaics 2014-2018.* http://www.epia.org/uploads/tx_epiapublications/Market_Report_2013_02.pdf [2015-01-29]

FORTUM. 2015. *Paket och priser.* http://www.fortum.com/countries/se/privat/energismart-hemma/sol/priser/pages/default.aspx [2015-04-22]

FTHENAKIS, V. & KIM, H. C. 2008. Land use and electricity generation: A life-cycle analysis. *Renewable and Sustainable Energy Reviews,* 13**,** 1465-1474.

HEDÉN, P. 2013. *Solelpotentialbedömning - framställning av solelpotentialkarta för Lund och utvärdering av laserdata.* Master's Thesis, LTH, Lund University. Lund.

HERNANDEZ, R. R., EASTER, S. B., MURPHY-MARISCAL, M. L., MAESTRE, F. T., TAVASSOLI, M., ALLEN, E. B., BARROWS, C. W., BELNAP, J., OCHOA-HUESO, R., RAVI, S. & ALLEN, M. F. 2014. Environmental impacts of utility-scale solar energy. *Renewable and Sustainable Energy Reviews,* 29**,** 766-779.

HSU, D. D., O'DONOUGHUE, P., FTHENAKIS, V., HEATH, G. A., KIM, H. C., SAWYER, P., CHOI, J.-K. & TURNEY, D. E. 2012. Life Cycle Greenhouse Gas Emissions of Crystalline Silicon Photovoltaic Electricity Generation. *Journal of Industrial Ecology,* 16**,** S122-S135.

IEA 2014. *Trends 2014 in Photovoltaic Applications, Survey Report of Selected IEA Countries between 1992 and 2013* (Report IEA-PVPS T1-25:2014).

IPCC 2014. *Climate Change 2014 Synthesis Report Summary for Policymakers*. http://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf [2015-05-20]

JÖNSSON, O. 2015. 0414-131 53 (phone call). Österlenvind AB. *Solar park in Simris.* (2015-03-10)

KANTERS, J. D., HENRIK 2013. Mutual shading of PV modules on flat roofs: a parametric study. In *2013 ISES Solar World Congress*. Cancun, Mexico. 3-7 November 2013.

KARWONEN, M. 2015. maria.karwonen@sheab.se (email). Sala-Heby Energi AB. *Solar park in Arnebo.* 2015-02-27.

KJELLSSON, E. 2000. *Potentialstudie för byggnadsintegrerade solceller i Sverige, Rapport 2. Analys av instrålningsnivåer på byggnadsytor* (Rapport TVBH-7216).

KRAFTPOJKARNA. 2015. *Megawattparken.* http://www.kraftpojkarna.se/index.php/blog/cat/projekt/post/solparken/ [2015-05-08]

KRAFTRINGEN. 2015a. *Solkartan Lund* http://www.kraftringen.se/Privat/Solceller/Solkartan [2015-05-21]

KRAFTRINGEN. 2015b. *Våra solcellspaket.* http://kraftringen.se/Privat/Solceller/Vara-solcellspaket/ [2015-04-22]

KUNSKAPDIREKT. 2015. *Ståndortsindex - gran & tall.* http://www.kunskapdirekt.se/sv/KunskapDirekt/Alla-Verktyg/Standortsindex---gran-och-tall/ [2015-04-08]

LARSSON, D. 2015. david.larsson@solkompaniet.se (email). Solkompaniet AB. *PV and economy of scale.* 2015-05-11.

LELOUX, J., NARVARTE, L. & TREBOSC, D. 2012. Review of the performance of residential PV systems in Belgium. *Renewable and Sustainable Energy Reviews,* 16**,** 178-184.

LINDAHL, J. 2013. *National Survey Report of PV Power Applications in Sweden 2012.* (IEA-PVPS Task 1). Uppsala University, Uppsala. Swedish Energy Agency.

LINDAHL, J. 2014. *National Survey Report of PV Power Applications in SWEDEN 2013.* (IEA-PVPS Task 1). Uppsala University, Uppsala. Swedish Energy Agency.

LINDAHL, J. 2015a. *IEA-PVPS National Survey Report of PV power applications in Sweden 2014.* (IEA-PVPS Task 1). Uppsala University, Uppsala. Swedish Energy Agency. [Pre publishing]

LINDAHL, J. 2015b. Johan.Lindahl@angstrom.uu.se (email). Uppsala University. *Size distribution.* 2015-03-25.

MARTINSSON, B. 2015. bjorn.53@live.se (email). Forest owner. Average height of trees. 2015-04-14.

NREL. 2015. *System Advisor Model*. https://sam.nrel.gov/ [2015-03-19]

OMBOENDE. 2015. *Gör medvetna val för rätt underhåll.* http://www.omboende.se/sv/Aga1/Hus/Drift-och-underhall-/ [2015-05-14]

PIETZCKER, R. C., STETTER, D., MANGER, S. & LUDERER, G. 2014. Using the sun to decarbonize the power sector: The economic potential of photovoltaics and concentrating solar power. *Applied Energy,* 135**,** 704-720.

PVEDUCATION. 2015. *PV Modules and Bypass diodes.* http://pveducation.org/pvcdrom/modules/bypass-diodes [2015-05-19]

REDARC. 2015. *How do solar panels work?* http://www.redarc.com.au/solar/about/solarpanels/ [2015-05-19]

REN21 2014. *Rewables 2014 Global Status Report.* http://www.ren21.net/REN21Activities/GlobalStatusReport.aspx [2015-02-28]

RÖNNELID, M. E., NICOLÁS. 2008. Potential of solar electricity in the Swedish electricity grid. In *Eurosun 2008,* Lisbon, Portugal 7-10 October 2008.

RÖNNING, L. 2015. 070-209 78 08 (phone call) Arvika Kraft AB. *Solar park in Arvika.* 2015-05-07

SCB 2013. *Markanvändningen sektorsvis.* http://www.scb.se/Statistik/_Publikationer/MI0803_2010A01B_BR_05_MI03BR1301.pdf [2015-02-23]

SOLKOMPANIET 2013. *Fallstudie solceller - Markplacerad anläggning i Gräve, Örebro.* [Case Study]

STRIDH, B. 2015. *Statistik över solcells-installationer i Sverige – 1. Effekt.* http://bengtsvillablogg.info/2012/10/30/statistik-over-solcells-installationer-i-sverige-1-effekt/ [2015-03-25]

SWEDISH BOARD OF AGRICULTURE 2013. *Agricultural land prices 2013.* http://www.jordbruksverket.se/webdav/files/SJV/Amnesomraden/Statistik,%20fakta/Priser%20och%20prisindex/JO38/JO38SM1401/JO38SM1401_ikortadrag.htm [2015-03-18]

SWEDISH ENERGY AGENCY. 2014. *Energiläget i siffror.* https://www.energimyndigheten.se/Statistik/Energilaget1/ [2015-05-14]

SWEDISH FOREST AGENCY 2014. *Swedish Statistical Yearbook of Forestry.* Sweden: Swedish Forest Agency.

SVERIGES RADIO. 2014. *Sveriges Radio - Solelpark sätter Örebroregionen på kartan* http://sverigesradio.se/sida/artikel.aspx?programid=159&artikel=6056840 [2015-03-12]

SÖDER, L. 2013. *På väg mot en elförsörjning baserad på enbart förnybar el i Sverige, En studie om kraftsystemets balansering.* Stockholm: KTH.

TURNEY, D. & FTHENAKIS, V. 2011. Environmental impacts from the installation and operation of large-scale solar power plants. *Renewable and Sustainable Energy Reviews,* 15**,** 3261-3270.

VAN NOORD, M. 2010. *Byggnadsintegrerade solcellsanläggningar - Europeisk Best-Practice.* (Elforsk rapport 10:41).

VATTENFALL. 2015. *Installera solceller och spara pengar och miljö* http://www.vattenfall.se/sv/solceller.htm [2015-04-22]

WENHAM, S. R., GREEN, M. A., WATT, M. E. & R., C. 2007. *Applied Photovoltaics,* London: Earthscan.

VERBERNE, G. B., P; FRONTINI, F; VAN DEN DONKER, M.N; CHATZIPANAGI, A; SINAPIS, K; FOLKERTS, W 2014. BIPV products for facades and roofs: A market analysis. In *the 29th EU-PVSEC*, Amsterdam, The Netherlands, 22-26 September 2014.

YINGLI. 2015. *Multicrystalline Solar Panels* http://www.yinglisolar.com/en/products/multicrystalline/ [2015-03-23]

ÅKERSTRÖM, C. 2015a. christian.akerstrom@solkompaniet.se (email). Solkompaniet AB. *Cost addition depending on roof tilt.* 2015-04-15

ÅKERSTRÖM, C. 2015b. christian.akerstrom@solkompaniet.se (email). *Most frequently sold PV package.* 2015-04-17

ÖRESUNDSKRAFT. 2015. *Project Solar Park.* http://www.oresundskraft.se/privat/produkter-tjaenster/producera-din-egen-el/solar-park-helsingborg/om-projektet/ [2015-03-11]

A. Appendices

A.1 Design of park

Table A-1. The relationship between the row distance, ground coverage ratio, shading angle and the size of the solar park.

Row distance d / m	GCR	Shading angle / °	Width of park / m	Length of park / m	Area for modules and row distance / m^2
0.5	0.79	52	123	26	3238
1	0.56	33	123	36	4452
2	0.36	18	123	56	6880
3	0.26	12	123	76	9308
4	0.21	9	123	95	11736
5	0.17	7	123	115	14164
6	0.15	6	123	135	16592
7	0.13	5	123	155	19020
8	0.11	5	123	174	21449
9	0.10	4	123	194	23877
10	0.09	4	123	214	26305
20	0.05	2	123	415	50991

The total area needed for agricultural land is calculated as:

$$\mathrm{A}_{\mathrm{tot\,(park+fence)}} = A_{tot(agricultural)} = (\mathrm{Width} + 20\ \mathrm{m}) \cdot (\mathrm{Length} + 20\ \mathrm{m}) \qquad \textit{(Equation A-1)}$$

The total area needed for forest land is assumed to be:

$$\mathrm{A}_{\mathrm{tot\,(park+fence+shading)}} = A_{tot(forest)} = \mathrm{Area\ A} + \mathrm{Area\ B} + \mathrm{Area\ C} \qquad \textit{(Equation A-2)}$$

$$\mathrm{Area\ A} = (\mathrm{Width} + 20\ \mathrm{m}) \cdot (\mathrm{Length} + 10\ \mathrm{m}) \qquad \textit{(Equation A-3)}$$

$$\mathrm{Area\ B} = (\mathrm{Width} + 20\ \mathrm{m}) \cdot \mathrm{X} \qquad \textit{(Equation A-4)}$$

$$\mathrm{Area\ C} = \mathrm{Y} \cdot (\mathrm{X} + \mathrm{Length} + 10\ \mathrm{m}) \qquad \textit{(Equation A-5)}$$

$$\mathrm{X} = \frac{30}{\tan\alpha} \qquad \textit{(Equation A-6)}$$

$$\mathrm{Y} = \tan 45 \cdot (\mathrm{Width} + 10\ \mathrm{m} + \mathrm{X}) \qquad \textit{(Equation A-7)}$$

where α is the shading angle depending on row distance. For Area A, Area B and Area C see Figure 4-4. The total area for putting a park on agricultural land or in a forest is found in Table A-2.

Table A-2. Total area needed for each row distance for a park put on agricultural and a park put in a forest.

Row distance / m	Area for park on agricultural land / m^2	Area for park in a forest / m^2
0.5	6 624	12 317
1	8 035	22 170
2	10 858	48 533
3	13 681	83 772
4	16 504	127 886
5	19 327	180 875
6	22 150	242 740
7	24 973	313 480
8	27 796	393 096
9	30 619	481 586
10	33 442	578 953

A.2 Energy simulations

Table A-3. First year energy production from a system located in the south of Sweden (Copenhagen weather file). The unit is in kWh/kWp which is not written in the table due to space limitations.

	West									*South*									*East*	
	270°	**260°**	**250°**	**240°**	**230°**	**220°**	**210°**	**200°**	**190°**	**180°**	**170°**	**160°**	**150°**	**140°**	**130°**	**120°**	**110°**	**100°**	**90°**	**Azimuth**
0°	867	867	867	867	867	867	867	867	867	867	867	867	867	867	867	867	867	867	867	
10°	857	869	881	893	903	912	920	926	929	931	930	928	923	916	907	897	886	874	862	
20°	832	857	880	902	922	940	955	966	973	976	975	969	960	947	930	911	890	867	843	
30°	800	834	867	898	926	950	971	986	996	1001	999	991	978	959	936	910	880	848	814	
40°	763	803	843	880	914	943	969	987	1000	**1005**	1003	993	977	955	927	894	859	820	780	
50°	720	765	808	849	886	921	947	969	982	989	986	976	958	933	902	866	826	784	740	
60°	674	720	764	806	846	880	910	931	946	952	950	940	920	895	861	825	783	739	694	
70°	624	667	711	753	792	827	855	877	891	897	895	885	867	840	809	770	731	686	642	
80°	568	610	651	690	726	759	785	806	819	825	823	814	797	773	742	708	668	629	586	
90°	512	548	584	619	651	680	703	721	732	737	736	728	715	694	667	635	602	564	527	
Tilt																				

Table A-4. First year energy production from a system located in the central part of Sweden (Stockholm weather file). . The unit is in kWh/kWp, which is not written in the table due to space limitations.

	West									*South*									*East*	
	270°	**260°**	**250°**	**240°**	**230°**	**220°**	**210°**	**200°**	**190°**	**180°**	**170°**	**160°**	**150°**	**140°**	**130°**	**120°**	**110°**	**100°**	**90°**	**Azimuth**
0°	813	813	813	813	813	813	813	813	813	813	813	813	813	813	813	813	813	813	813	
10°	809	823	836	849	860	869	877	883	886	887	885	881	875	866	856	844	832	818	804	
20°	792	819	844	868	890	908	923	933	940	941	938	930	918	902	882	860	835	809	783	
30°	767	804	840	874	904	929	950	965	973	975	971	960	943	920	893	862	828	792	755	
40°	737	782	826	866	902	933	958	976	987	**989**	983	970	949	922	889	852	811	768	724	
50°	702	752	800	844	885	919	948	968	979	982	975	961	937	907	870	828	783	736	688	
60°	663	714	763	811	852	890	918	940	951	954	948	931	907	875	837	793	746	697	648	
70°	618	667	718	763	807	842	872	893	905	907	900	884	860	828	789	746	699	651	603	
80°	567	615	661	706	746	781	809	828	839	841	834	820	796	766	729	689	644	599	553	
90°	514	556	599	639	676	706	731	748	757	759	753	739	719	692	659	621	582	540	500	
Tilt																				

Table A-5. First year energy production from a system located in the north of Sweden (Kiruna weather file). The unit is in kWh/kWp, which is not written in the table due to space limitations.

	West									*South*									*East*	
	270°	**260°**	**250°**	**240°**	**230°**	**220°**	**210°**	**200°**	**190°**	**180°**	**170°**	**160°**	**150°**	**140°**	**130°**	**120°**	**110°**	**100°**	**90°**	**Azimuth**
0°	683	683	683	683	683	683	683	683	683	683	683	683	683	683	683	683	683	683	683	
10°	680	692	703	714	724	732	738	743	745	746	744	740	735	727	718	708	697	685	673	
20°	668	690	713	733	751	767	779	788	793	793	790	783	772	758	740	721	699	677	654	
30°	650	682	712	741	766	788	805	817	824	825	820	810	795	775	751	723	694	663	632	
40°	629	666	703	737	769	795	816	831	839	**840**	834	821	803	778	749	716	681	644	607	
50°	603	644	684	723	757	787	811	828	837	838	831	817	795	768	735	699	660	619	579	
60°	571	614	657	697	733	765	791	809	818	819	812	796	774	744	710	671	630	588	547	
70°	534	577	619	660	697	730	755	774	783	784	777	760	738	708	672	634	592	552	510	
80°	492	533	574	613	650	680	706	724	733	734	726	711	688	659	624	587	548	508	470	
90°	446	484	520	558	591	621	644	660	669	670	662	648	627	599	568	533	497	461	425	
Tilt																				