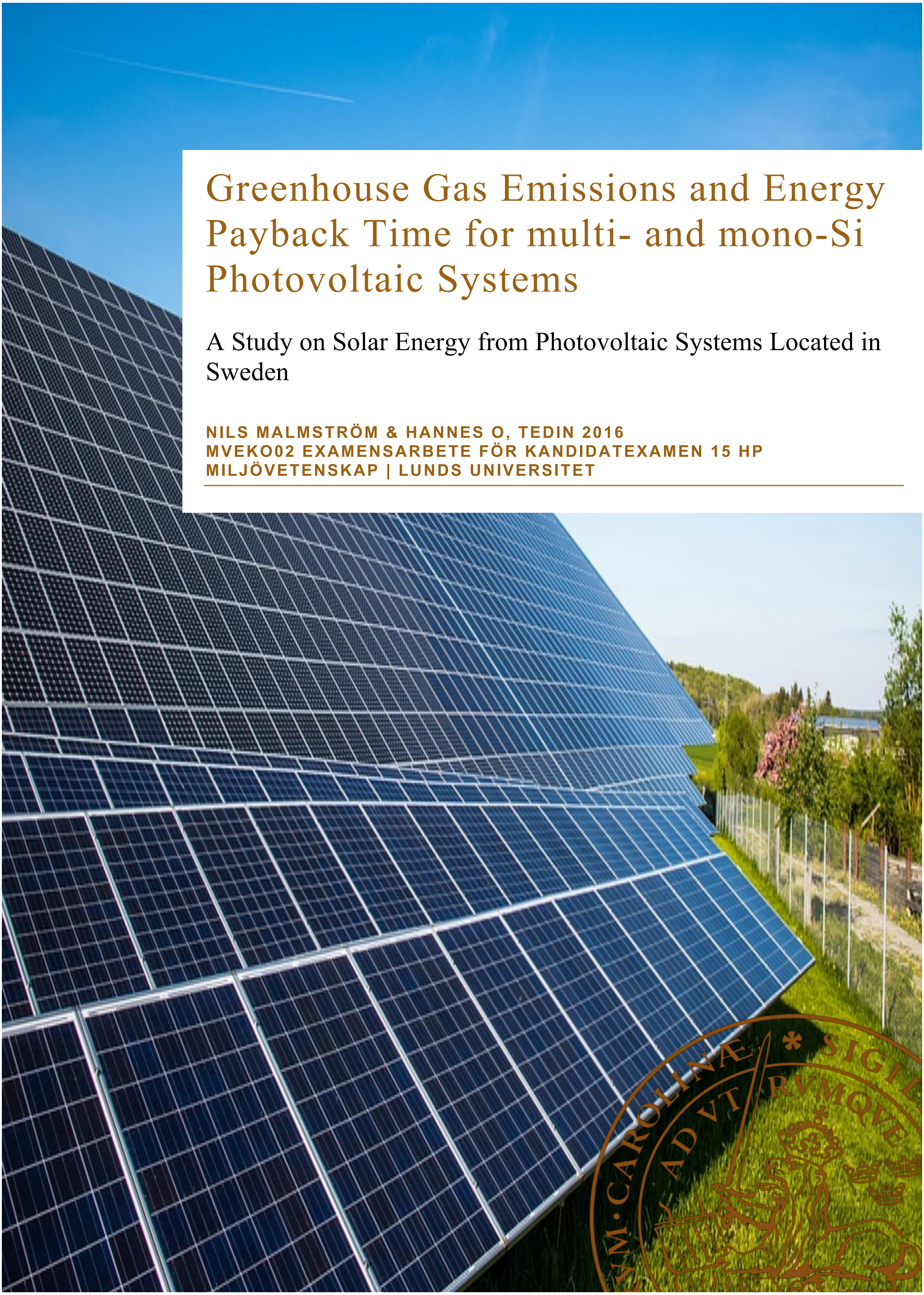

Greenhouse Gas Emissions and Energy Payback Time for multi- and mono-Si Photovoltaic Systems

A Study on Solar Energy from Photovoltaic Systems Located in Sweden

NILS MALMSTRÖM & HANNES O, TEDIN 2016

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Abstract

Climate change is one of the greatest environmental challenges at the present time and is currently an issue affecting the entire global population. Alternative renewable energy sources are vital to be able to deal with this challenge. Solar energy is one of the most promising renewable energy sources and is therefore also one of the fastest growing industries in this field. However, solar energy has its downsides as well. During production of silicon based solar cells a large amount of energy is needed. In China, the world's largest producer of Photovoltaic (PV) cells, this energy is produced mainly through burning of coal and therefore the production of PVs indirectly contributes to greenhouse gas (GHG) emissions.

In this study two different methods were applied to evaluate the GHG emissions (g-CO_2,eq/kWh) and energy payback time (EPBT) for monocrystalline (mono-Si) PV systems and multicrystalline (multi-Si) PV systems in five different places in Sweden; Malmö, Lund, Stockholm, Göteborg and Luleå. The results show that the EPBT range from 2.01 to 3.25 years and that the GHG emissions range from 63.05 to 102.02 g-CO_2,eq/kWh depending on the method applied, which type of PV system that was used, and the solar irradiation.

Based on this study, energy from photovoltaic power could potentially be a part of the solution for Sweden's future energy demands. However, this depends on several different factors. The location of the PV system is of great importance as well as the direction and angle in relation to the sun. Also, the development of the PV cell's efficiency plays a major role in the future EPBT and GHG emissions from solar energy.

This study was based on estimations from previous studies and therefore the results could contain some uncertainties.

Keywords

Solar energy
Greenhouse gas (GHG) emission
Energy payback time (EPBT)
Photovoltaic (PV)
Multi-Si & Mono-Si

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Introduction

Climate change and environmental pollutions are two of mankind's greatest challenges today. The search for solutions has led to rapid development amongst renewable energy sources (Hou et al. 2016) and one of the most promising is Photovoltaic (PV) power (Wang et al. 2014). The sun hits the earth with an incredible amount of energy every second and the ability to harness this energy could prove to be of great importance when readjusting the world's energy demands to renewable sources (Amatya et al. 2015). The energy that strikes the earth from the sun every hour is more than the current energy demand for the entire human population during one year (Amatya et al. 2015). When the PV system is operating the environmental impact is very small but studies show that during the manufacturing of the PV module the impact can be higher than other renewable energy sources (WNA 2011, Hou et al. 2016, Fu et al. 2015, Wong et al. 2016, Peng et al. 2013).

There are many different types of PV cells but the by far most common ones today are the silicon based PV systems (Gerbinet et al. 2014). These can be divided into two main categories - monocrystalline (mono-Si) and multicrystalline (multi-Si) (Gerbinet et al. 2014). One of the world's largest PV producers today is China (IEA. 2014). The manufacture of these PV modules requires large amounts of energy and since China's main energy source is coal (Fu et. al. 2015), this indirectly leads to greenhouse gas (GHG) emissions being released to the atmosphere.

The amount of energy a PV system can produce depends on a lot of different factors. These comprise of irradiation, efficiency of the PV, lifetime of the PV, angle and direction in relation to the sun, the performance ratio, and the area of the PV etc. (Hou et al 2016, Stridh & Hedström 2011). Sweden is located quite far to the north where the irradiation and amount of sun hours are lower than in most part of Europe (Faunhofer Institute 2016). This affects the energy production from the PV systems located in Sweden (Faunhofer Institute 2016).

During the years 1983-2006 the irradiation in Sweden increased almost 8 per cent (SMHI 2016a). The two most important factors that affect the irradiation are the solar altitude and the cloudiness (SMHI 2016a). A theory has been formed about human aerosol emissions affecting the irradiation (Wild 2012). Aerosols can decrease the irradiation directly by scattering and absorbing solar radiation as well as indirectly through their ability to act as cloud condensation nuclei. This means that the irradiation decreases with increasing aerosol levels (Wild 2012).

When referring to PV systems there are usually two types – Large scale (LS) and distributed. The distributed being small-scale systems like PV modules on a rooftop for instance (Hou et al. 2016). The differences are usually that the LS have a better performance ratio, and often are connected to the public electrical grid. Therefore, there is no loss in electricity, apart from the heat that is being emitted during energy transformation (Hou et al. 2016). The distributed systems are usually connected instantly to the houses or buildings and the excess energy that is produced is unfortunately lost if the PV system is not grid-connected (Stridh & Hedström 2011).

During production of PVs, different GHGs are released (Hou et al. 2016). These GHGs have different Global Warming Potentials (GWP), which influence the global climate system. However, they can be expressed trough a common metric, the carbon dioxide equivalent (CO_2-eq). The warming influence is often referred as the raditative forcing (IPCC 2007). The CO_2-eq emissions is the amount of CO_2 emission that would cause the same raditative forcing, during a period of 100 years, as a certain amount of one or many long-lived GHGs. The CO_2-eq emissions in obtained by multiplying the emission of a GHG with its GWP for 100 years (IPCC 2007).

The lifecycle of a PV system is complex and consists of upstream, midstream as well as downstream processes (Figure 1). The upstream processes include quartz mining, upgraded metallurgical-grade silicon (UMG-Si) production, solar grade silicon (SoG-Si) purification, silicon ingot growth and wafer slicing (Figure 1). The midstream processes include solar cell and module production (Figure 1). The downstream processes include PV system integration, which refers to the process of bringing together the different components, and also the construction, operation, and retirement of, PV stations (Figure 1).

GHG emissions are not the only environmental impact during the life cycle of a PV system (Yang et al. 2015). Multi-Si also have abiotic depletion impact, acidification impact, eutrophication impact, human toxicity impact, freshwater aquatic ecotoxicity impact, marine aquatic ecotoxicity impact, terrestrial ecotoxicity impact, ozone depletion impact, and photochemical oxidation potential (Yang et al. 2015).

Currently there exist some other techniques for harnessing energy from the sun (Kim et al. 2012). The most common are PV systems using thin film technique, which have shown good progress in recent years (Dimmler 2011). Of those, copper indium gallium selenide (CIGS) and cadmium telluride (CdTe) are the most widely used (Dimmler 2011). It is suggested that CIGS- as well as CdTe-systems contributes less than Si PV-systems in terms of GHG emissions (Kim et al. 2012). However, these systems contribute to other environmental impacts, like metal depletion, instead (Bergesen et al. 2014).

There are also other techniques that are still in the developmental stage (Collier et al, 2014, Sol Voltaics 2016). For example the company Sol Voltaics, based in Lund, are currently working on developing a PV system using nanowires that, in theory, could increase the conversion efficiency dramatically. Using this technique, only miniscule amounts of nanomaterial would be needed (Sol Voltaics 2016).

There are big differences in GHG emissions between different energy sources (Kim et al. 2012) and it is important to evaluate the actual differences when including the whole life cycle.

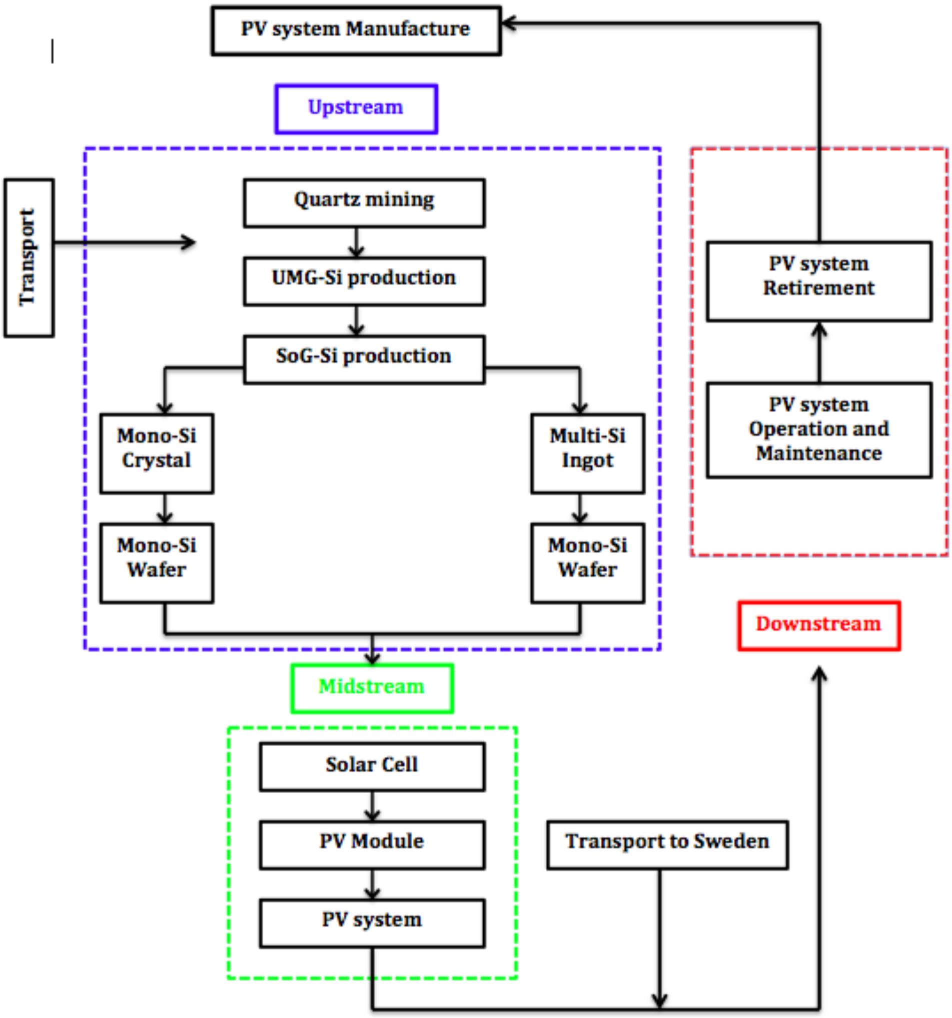


Figure 1. The different stages within the upstream, midstream and downstream processes in a PV's life cycle (Hou et al. 2016)

In this study only mono-Si and multi-Si PVs are accounted for. These are, by far, the most common PVs on the market today in the world as well as in Sweden. These are therefore the most relevant to analyze. Other techniques could become more widespread in the future, and then it would be relevant to investigate the environmental impacts from those. Also only distributed PV systems are considered in this study.

The focus in this study will be the estimated GHG emissions of the PV systems during their lifecycle. To evaluate this the index g-CO_2,eq/kWh, which refers to the amount of GHG emissions released from each kilowatt-hour produced, will be used. The other index that will be accounted for in this study is the energy payback time (EPBT), which refers to the time it takes for a PV system to produce the same amount of energy that was used during production.

Many previous studies are conducted in countries that are leading producers or users of PV systems (Hou et al. 2016, Fu et al. 2015, Peng et al. 2013). This study aims to add knowledge about the EPBT, and the GHG emissions for PV systems that are located in Sweden.

Other environmental impacts, like acidification, eutrophication and abiotic depletion etc. (Yang et al. 2015), from mono-Si and multi-Si PVs, are not taken into account in this study. These environmental impacts are in the same magnitude as GHG emissions (Yang et al. 2015) and are important to bear in mind when reading this study.

The aim of this study is to calculate the GHG emissions, based on estimated values, when mono-Si and multi-Si PV systems are used in different locations in Sweden.

The following questions were formed:

- How long energy payback time (EPBT), in years, does mono-Si and multi-Si PV-systems have in different locations in Sweden?
- How large greenhouse gas (GHG) emissions, in g-CO_2,eq/kWh, does mono-Si and multi-Si PV-systems have in different locations in Sweden?
- How does the method used affect the EPBT and the g-CO_2,eq/kWh?
- Are PV systems a good investment for Sweden based on their environmental impacts, compared to other renewable power sources?

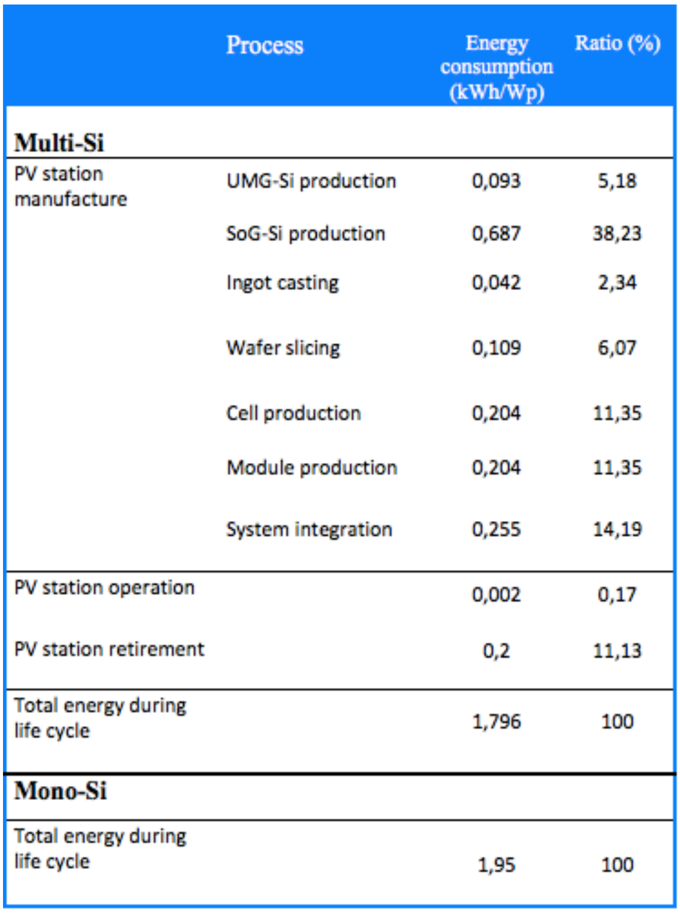
Method

At first scientific articles were obtained and reviewed to collect information and different data from previous life cycle assessments (LCAs). Based on these studies the boundaries for this study, and how its methodology would look like, were determined. In addition to this interviews were made with various people with insights and knowledge of the field.

In this study two methods (see method 1 & 2 below) were used to calculate the EPBT and g-CO_2,eq per functional unit, kWh, for a 1000 W_p PV system. W_p being the watt peak for the system. Five cities were chosen to represent two parameters. The first parameter was the location, and therefore Sweden's most southerly and northerly stations, for irradiation measuring, were chosen. This was determined under the assumption that the annual solar irradiation would be lower the further north the measuring station was located. The second parameter that was taken into consideration when choosing the measuring stations was the size of the city. The size of the city was relevant because of the study's focus on distributed PV systems, which usually are stationed on the roof of buildings. These results were then compared with each other. For both methods the calculations were based on a 1000 W_p PV system.

The calculated value for EPBT and GHG emissions (g-CO_2,eq/kWh) was based on the calculations (1) & (2) for both methods. The total energy consumption during a PV system's life cycle was based on a Chinese study (Hou et al. 2016) that accounted for the different main stages – manufacturing, operation, and station retirement (Table 1). In addition to the comsumed energy from the module, Hou et al. (2016) also accounted for the controllers, inverters, cables etc. in their estimations. The values used from Hou et al. (2016) were based on different factors. One factor was whether the PV system was a multi or mono-crystalline. Mono PVs have a higher efficiency but need more energy during production than multi-Si PVs. Another factor was peak sunshine hours, which was based on solar irradiation.

Table 1. The energy consumption of the main stages during the PV's life cycle for multi-Si and monoi-Si (Hou et al. 2016).



	Process	Energy consumption (kWh/Wp)	Ratio (%)
Multi-Si			
PV station manufacture	UMG-Si production	0,093	5,18
	SoG-Si production	0,687	38,23
	Ingot casting	0,042	2,34
	Wafer slicing	0,109	6,07
	Cell production	0,204	11,35
	Module production	0,204	11,35
	System integration	0,255	14,19
PV station operation		0,002	0,17
PV station retirement		0,2	11,13
Total energy during life cycle		1,796	100
Mono-Si			
Total energy during life cycle		1,95	100

Determining the annual output energy, Q_A, was done in different ways for each method. With the city's values for the annual output energy, this could be multiplied with the lifetime expectancy, T_L, for the PV modules, which in this study was estimated to be 30 years. This was based on recent studies and interviews (Fu et al. 2015). This calculation (3) resulted in the total output energy, Q_T, for a PV system's cradle to grave.

The difference between the two methods was the way the value for annual and total energy output was calculated.

$$\text{EPBT} = \frac{\text{Total energy consumption}}{\text{Annual output energy}} = \text{Years} \qquad (1)$$

The calculation (2) for GHG emissions were based on the total consumption of energy, Q_C, defined as kWh/W_p and the amount of GHG emissions being emitted when using China's national electricity grid, E_G. Lastly the total energy output, Q_T, for the PV system during its life cycle was also used to calculate the g-CO_2,eq/kWh (2).

$$\text{GHG} = \frac{E_G \times Q_C}{Q_T} = \text{g-CO}_2\text{,eq/kWh} \qquad (2)$$

$$Q_T = Q_A \times T_L = \text{ kWh/Wp} \qquad (3)$$

To determine the GHG emissions during the PV system's life cycle using (2) the total consumed energy, Q_C, was again set at 1,796 kWh/W_p for multi-Si and 1,950 kWh/W_p for mono-Si PV systems (Table 1). The value for the average GHG emissions per kWh emitted through the Chinese national electricity grid, E_G, were set to 930 g-CO_2,eq/kWh (Hou et al. 2016).

Since the study's aim is to determine the EPBT and g-CO2,eq/kWh from multi-Si and mono-Si based PV systems in different locations in Sweden one step was added to the life cycle – Transportation from Shanghai to Sweden. The amount of g-CO_2 emissions, E_{transp}, was calculated (4) with an emission factor, E_f, for different means of shipping which was multiplied with the distance, d, expressed in kilometres and the mass, M, in metric tonnes.

$$E_{transp} = E_f \times M \times d \qquad \text{where } E_f = \text{g CO}_2\text{/tonne-km} \qquad (4)$$

The assumption that the PV system would be transported from Shanghai was made based on the company SUNTECH, the manufacturer of Vattenfall's PVs, and its close location to the city of Shanghai.

The distance of the shipping route, for the PV-cell module, from the supplier in China to Sweden was based on the report done by Vattenfall (2016) and was estimated to be 18 000 km overseas and 1 500 km with a heavy truck. Secondly the transportation of the inverters was also based on Vattenfall (2016) where it was estimated to be 1 400 km. The general emission factor for shipping by sea, 10g CO_2/tonne-km, and by road, 62g CO_2/tonne-km, was taken from Jofred & Öster (2011). The weight of the 1000 W_p PV system was based on multi and mono PVs manufactured by SUNTECH, and set to 78 kg.

With these emission values, the g-CO_2,eq/kWh for the transportation could be calculated for the 1000 W_p PV system. The value was added to the life cycle and the total g-CO_2,eq/kWh for the entire life cycle could now be determined.

Method 1

EPBT

Using data from a Swedish report (Stridh & Hedström 2011), where four cities had been chosen and the annual energy output had been estimated, based on the annual solar irradiation of the locations using data from SMHI (Stridh & Hedström, 2011). The interesting parameter for this study was that of the placement of the PV-modules. For each city the module was facing the south and had an optimal angle towards the sun for that location.

The total energy consumption, Q_C, was multiplied with a factor of 1000 to represent a 1000 W_p PV system. This gave the values 1796 kWh and 1950 kWh for multi-Si and mono-Si, respectively (Table 1).

Using (1) the EPBT was then calculated for each city.

GHG

The values for the total output energy, Q_T, for the PV systems in each city was put in (2) and thus the GHG emissions in g-CO_2,eq/kWh was calculated for both multi-Si and mono-Si PV systems for the cities.

The value for GHG emissions from transportation (4) was added to calculate the total GHG emissions to the life cycle of the PV system.

Method 2

To acquire the annual energy output this method used data from SMHI (2016b) on annual solar irradiation in Sweden and choosing almost the same cities as in Stridh & Hedström (2011). This was done due to the lack of a measuring station, and therefore data, in one of the cities – Malmö. Therefore, the city of Lund was chosen, as there was an existing measuring station with data and also because of the city's closeness to Malmö. When using STRÅNG (2016), the parameter was set to "Global irradiation" [Wh/m^2] and the time period was set to 2010-2015. To determine the latitude and longitude for each city, data from SMHI (2016b) was used.

The solar irradiation is an important factor when determining the energy output of the PV systems. This factor depends on where in the world the PV system is stationed, hence an important factor when determining a location's viability and efficiency for the installation of PV systems.

The annual solar irradiation, kWh/m^2, was then converted into peak sunshine hours by dividing it with 1 kW/m^2. This was done using the definition that a peak sunshine hour is the amount of hours the irradiation averages 1 kW/m^2 per year (Fu et al 2015). This was also confirmed by Zareinejad M., Founder of Applied Geomatics Sweden AB, which has developed a tool to calculate how much electricity one can produce with PV systems (Solkollen 2016).

Equation (5) was used from Hou et al. (2016) to determine the annual amount of energy produced per watt, Q_A, from the PV system. Where T_R is the peak sunshine hours, C the capacity of the system defined as 0.001 kW/Wp (Hou et al. 2016) and PR being the performance ratio, which refers to the ratio shown in (6).

$$Q_A = T_R \times C \times PR \ = \text{kWh/Wp} \tag{5}$$

$$PR = \frac{\text{Actual energy output}}{\text{Theoretical possible energy output}} \tag{6}$$

The performance ratio is important since the theoretical output energy is based on conditions such as 25° C within the PV cell at irradiation levels of 1000 W/m^2 (Fu et al. 2015). As the temperature rises the PV cell efficiency decreases and in reality this happens already at 1000 W/m^2 (Stridh & Hedström 2011). Performance ratio, PR, was set to 70% (Hou et al. 2016).

To be able to compare with Stridh & Hedström's (2011) values for a 1000 W_p system the Q_A value was multiplied with 1000 W_p. This was then also multiplied with the PV system's life expectancy, T_L, of 30 years (7).

$$Q_T = Q_A \times 1000 \times T_L = \text{ kWh} \tag{7}$$

EPBT

Energy payback time was calculated using (1) where the annual output energy was calculated from (5) based on the different peak sunshine hours for the different cities.

GHG

To determine the GHG emissions during the PV system's life cycle using (2) the same values for Q_C and E_G was used (Hou et al. 2016). The value for Q_T was based on (7) & (5) and calculated using the average peak sunshine hours for each city during the years 2010 to 2015.

The values for the total output energy, Q_T, for the PV systems in each city was put in (2) and thus the GHG emissions in g-CO_2,eq/kWh was calculated for both multi-Si and mono-Si PV systems for the cities.

The value for GHG emissions from transportation (4) was again added to calculate the total GHG emissions to the life cycle of the PV system.

Results

Transportation emissions

The total transportation emissions were calculated to 22588 g-CO_2,eq for a 1000 W_p system for multi-Si as well as mono-Si PV systems.

Method 1

Using the first method where the total energy output was based on the angle and positioning of the PV-system being optimal, and a value for that annual solar irradiation (Stridh and Hedström 2011), the following results could be calculated.

The EPBT for multi-Si varied between 2.01 and 2.18 years in the four different locations, and for mono-Si the EPBT varied between 2.18 and 2.37 years (Table 1). The values for GHG emissions ranged from 63.05 to 68.65 g-CO_2,eq/kWh and from 68.38 to 74.46 g-CO_2,eq/kWh, respectively, for multi-Si and mono-Si PV-systems (Table 2).

Table 2
The calculated values of EPBT and GHG, for both multi-Si and mono-Si, for the four different cities using their values on total energy output (Stridh and Hedström. 2011).

Factor	Malmö	Göteborg	Stockholm	Luleå
Total energy output, kWh (1000 W_p system)	26850	24660	26670	26400
Multi-Si:				
Energy payback time, y (EPBT)	2.01	2.18	2.02	2.04
Greenhouse gas emissions, g-CO_2,eq/kWh (GHG)	63.05	68.65	63.47	64.12
Mono-Si:				
Energy payback time, y (EPBT)	2.18	2.37	2.19	2.22
Greenhouse gas emissions, g-CO_2,eq/kWh (GHG)	68.38	74.46	68.84	69.55

The shortest EPBT was calculated for PV systems located in Malmö, but with PV systems in Stockholm almost as low. Multi-Si PV systems were shown to have shorter EPBT, than mono Si PV systems, for all locations.

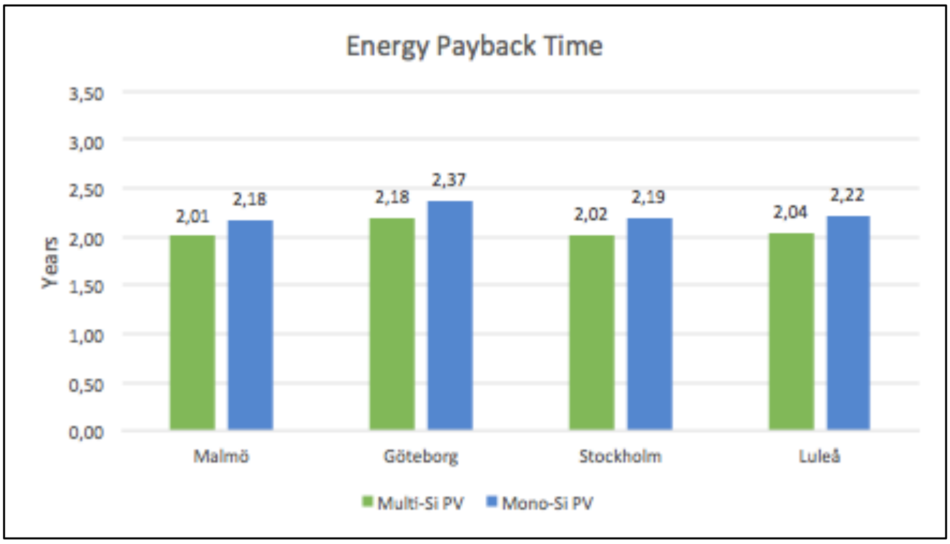


Figure 2. EPBT for each city included in the study using method 1.

The lowest greenhouse gas emissions were calculated for PV systems located in Malmö. Multi-Si PV systems were shown to have lower greenhouse gas emissions, than mono Si PV systems, for all different locations.

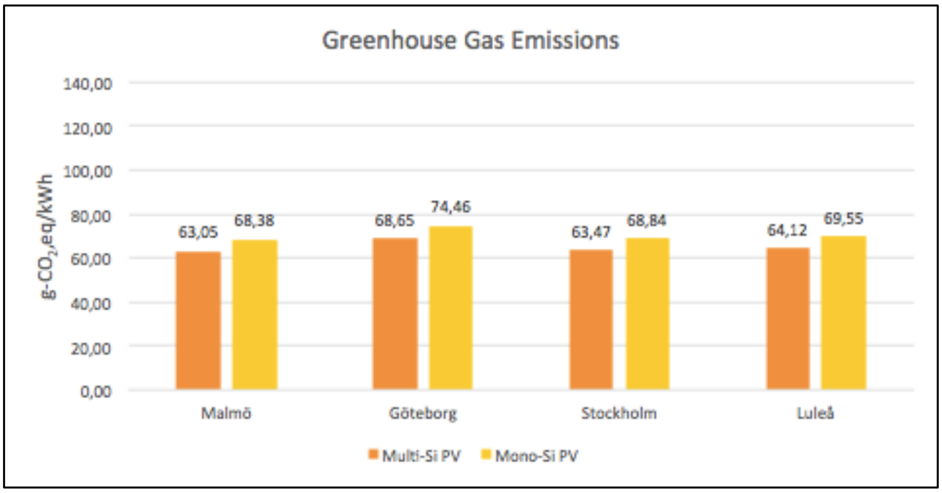


Figure 3. The different values for GHG emissions using method 1.

Method 2

Using this model, the total energy output was calculated using the average peak sunshine hours (Hou et. al. 2016) during the time period 2010-2015, using the solar irradiation for the same time period (STRÅNG. 2016). This gave the following results:

The EPBT for multi-Si varied between 2.60 and 2.99 years in the four different locations, and for mono-Si the EPBT varied between 2.82 and 3.25 years (Table 3). The values for GHG emissions (Table 2) ranged from 81.76 to 94.06 g-CO_2,eq/kWh, and from 88.67 to 102.02 g-CO_2,eq/kWh, respectively, for multi-Si and mono-Si PV-systems.

Table 3
The calculated values of EPBT and GHG, for both multi-Si and mono-Si, for the four different cities using Method 2. The peak sunshine hours were calculated from the average solar irradiation during the same time period.

Factor	Lund	Göteborg	Stockholm	Luleå
Average Peak sunshine hours, h (2010-2015)	961	952	986	857
Multi-Si:				
Energy payback time, y (EPBT)	2.67	2.70	2.60	2.99
Greenhouse gas emissions, g-CO_2,eq/kWh (GHG)	83.88	84.68	81.76	94.06
Mono-Si:				
Energy payback time, y (EPBT)	2.90	2.93	2.82	3.25
Greenhouse gas emissions, g-CO_2,eq/kWh (GHG)	90.98	91.84	88.67	102.02

The shortest EPBT was calculated for PV-systems located in Stockholm and the longest for PV-systems located in Luleå. Multi-Si PV-systems was shown to have shorter EPBT, than mono-Si PV-systems, for all locations.

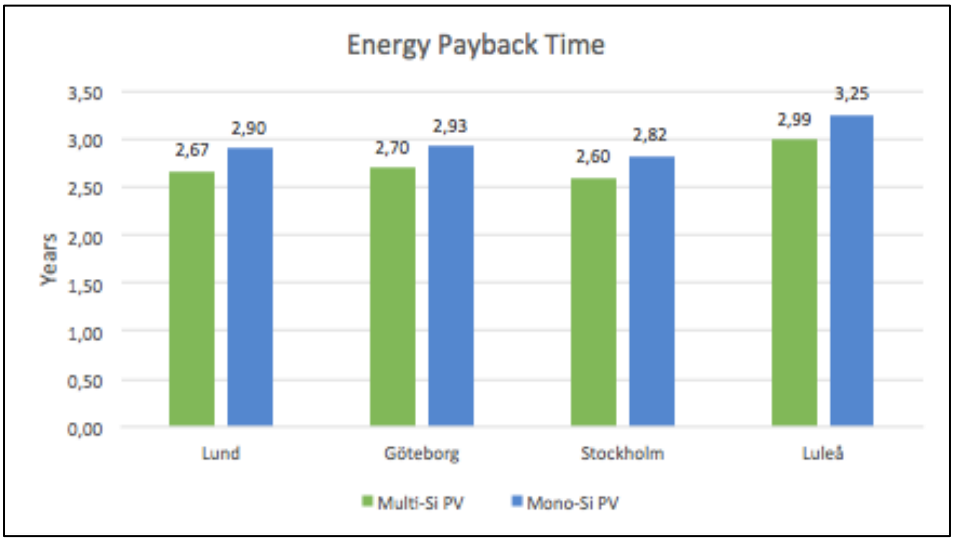


Figure 4. EPBT for each city included in the study using method 2.

The lowest greenhouse gas emissions were calculated for PV-systems located in Stockholm, and the highest for PV-systems located in Luleå. Multi-Si PV-systems were shown to have lower greenhouse gas emissions, than mono-Si PV-systems, for all different locations.

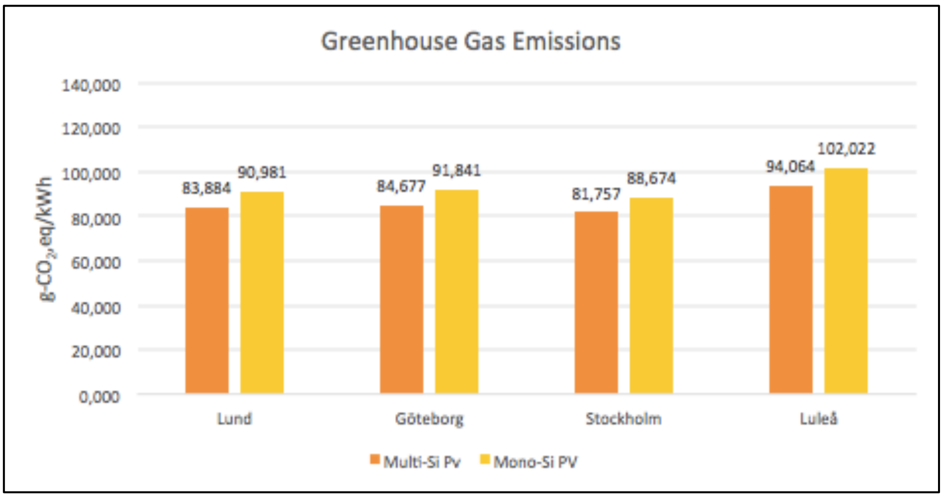


Figure 5. The different values for GHG emissions using method 2

Discussion

The results from this study show that the EPBT varies from 2.01 to 3.25 years. The first method indicated that the location did not matter, concerning the EPBT. Göteborg had longer EPBT than Luleå even though Luleå is located much further north. This could be due to local variations, such as shadowing, during that year.

The second method, on the other hand, indicates that the location mattered slightly. However, Stockholm had the shortest EPBT even though it was not stationed furthest to the south. The results indicate that the method used is crucial, which means that the choice of method is important for determining the outcome of the study.

The results from this study showed that the GHG emissions varied from 63.05 to 102.02 g-CO_2,eq/kWh. Also here the first method indicated that the GHG emissions depended on the location of the PV system, while the second method showed no such indications. Thus, according to the results in this study, the method used is an important factor when calculating the GHG emissions.

The lowest EPBT for the mono-Si in this study was 2.18 while the highest was 3.25 years and with a mean value of 2.61 years. For multi-Si the lowest EPBT was 2.01 years while the highest was 2.99 years, and with a mean value of 2.40 years. Concerning the GHG emissions the highest value for the mono-Si was 102.02 and the lowest was 68.38 g-CO_2,eq/kWh and with a mean value of 81.84 g-CO_2,eq/kWh. For multi-Si the highest value was 94.06 and the lowest was 63.05 with a mean value of 75.46. According to these results the mono-Si PV systems has greater environmental impacts, in terms of GHG emissions, than multi-Si PV systems, and also have a longer EPBT in general.

The SoG-Si production is the process that demands the most energy in the life cycle of a silicon based PV system (Hou et. al 2016). Since China is the world's largest PV producer (IEA 2014), and a majority of the energy produced in China comes from coal-fired power plants (Fu et al. 2015), this indirectly leads to large amounts of GHG emissions during this stage of the production.

If the energy used for the SoG-Si production was generated from renewable energy sources instead, the GHG emissions could be reduced significantly. This could be achieved either by China increasing their renewable energy production, or by the production being transferred to a location using renewable energy sources to a higher degree.

When the production is stationed in China the PV modules has to be transported long distances to be installed in Sweden. However, this study indicates that the transport, when shipped overseas, is a quite insignificant factor in the perspective to the entire life cycle.

The most important factors, in terms of CO_2 emissions, are the SoG-Si production, the cell production, the module production, and the system integration (Hou et al. 2016, Fu et al. 2015). To reduce the GHG emissions in the life cycle of a Si PV system these are therefore the recommended processes to imply the most focus on improving.

Comparison with other power sources and PV cells

When comparing the GHG emissions from PV-systems to other energy sources, through a life cycle perspective, you can observe that the environmental impact is far less than for fossil fueled power sources (figure 6). However, compared to other power sources such as biomass, nuclear, hydroelectric and wind the PV systems actually have higher CO_2 emissions (figure 6).

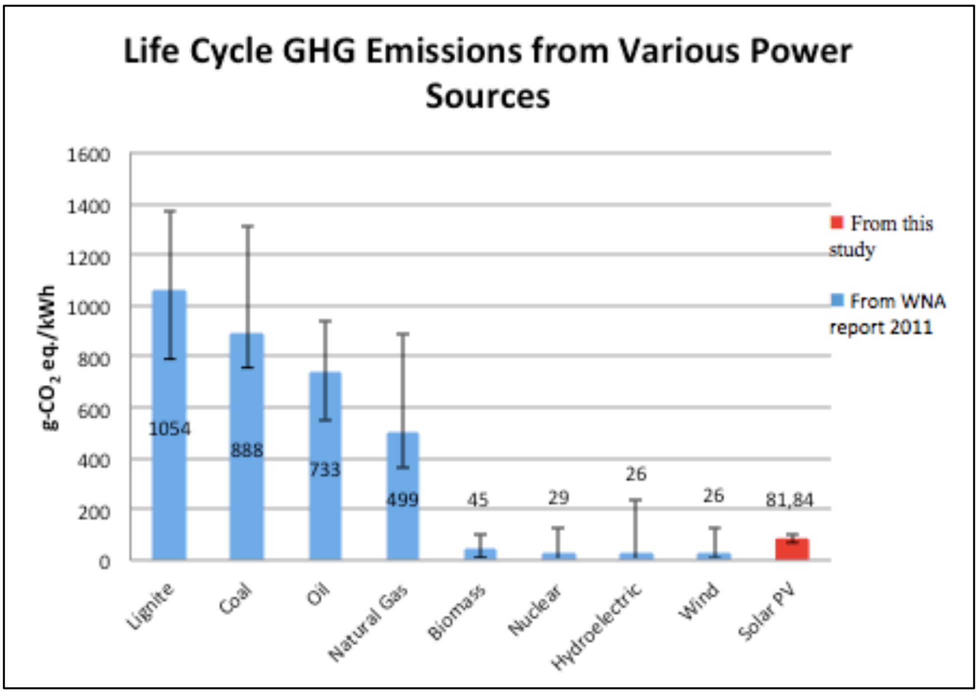


Figure 6. The comparison with various power sources and their GHG emissions during their life cycles. The data values for each bar represents the mean values.

How big the GHG emissions, in g-CO_2,eq/kWh, are depends on a lot of different factors (equation 2 & 4). One important factor is the efficiency of the PV-system. This is a factor that many companies in the world currently are working to improve (Sol Voltaics 2016).

One example of this is Sol Voltaics, a company stationed in Lund, Sweden. Their aim is to increase the efficiency of PV systems by more than 50 %, using nano wire technology, and put these cells on top of existing Silicon based panels. This is called tandem technology and occurs using two types of PV cell models on top of each other to create higher efficiency.

According to Niklas Mårtensson, engineer at Sol Voltaics, the company does not know when the product could be introduced as a commercial product on the market but says that, over all, the progress is going forward. Although Mårtensson says that using this nano technology will reduce the amount of materials needed, and therefore reduce the indirect GHG emissions, there are other issues like the use of more expensive materials.

In this study other impacts, from silicon based PV systems, than GHG emissions are not accounted for but these are of course also important to take into account when evaluating the total environmental impact of the whole life cycle. Examples of these are abiotic depletion impact, acidification impact and eutrophication impact (Yang et al. 2015), as well as land use and carcinogens (Bergesen et al. 2014). However, to weigh different environmental aspects against each other is always difficult. For example, an environmental aspect can induce a local impact while another induces a global impact. GHG emissions induce global impacts and therefore do affect Sweden as well as the location where the pollutants are emitted.

Other life cycle assessments (LCAs) have been conducted to try to evaluate the environmental impacts from Si PV systems in Sweden (Vattenfall 2016). Ulla-Karin Wendt, from Vattenfall's environmental department, is one of the people responsible for Vattenfall's report (Vattenfall 2016). She points out about the problem of getting information from Chinese producers, which makes it a difficult task to conduct a reliable LCA.

Jörgen Eriksson, Product Manager Vattenfall AB, says that the life cycle perspective is important in their choice of products, but that they need a reliable producer when they evaluate options.

In this study two different methods were applied to estimate what the environmental impacts are, in terms of GHG emissions, from mono-Si and multi-Si PV systems. The data for the GHG emissions were collected from one source (Hou et al. 2016), and it is therefore hard to evaluate the reliability of this data. The data is also based on a lot of assumptions, which of course influence the result as well.

The results of this study should therefore be seen as indications and not as stated facts. More data with reliable measurement is needed for future studies. More studies on the subject are recommended, for mono-Si and multi-Si PV systems as well as for other PV systems.

Future PV generations and energy solutions

Even if PV systems are more common in countries with higher annual solar irradiation then Sweden there is still a lot of investments in research and usage of solar powered technology.

In addition to Sol Voltaics there is another Swedish company, Epishine, which have made a cost efficient technology with the goal to make the PV cells completely organic, meaning they will be manufactured without any metals (Entreprenör 2016). This will, according to Epishine, make the PV system a lot easier to recycle and lower the EPBT significantly to a month. However, the plastic that is used for the production of the PV cells is expensive and is something that needs to be solved before the production can be taken to a larger scale (Entreprenör 2016).

In Sweden the most common types of PV systems are the distributed. Due to the climate and irradiation in Sweden the energy production is a lot higher during the summer but at the same time the energy consumption is also lower during this period (Eon 2016), which means there is a lot of excess energy, unless the PV system is connected to the electrical grid. A future solution according to Mårtensson is to develop some kind of storage battery to fill with this excess energy and use it later when it is needed.

So if the large scale PV systems are better then why is a large country like Sweden, with leading edge companies and scientists, not investing in these LS PV systems? The dilemma is that in the north where there is a lot of space for these projects there is also little annual irradiation. In the southern parts, especially Skåne, where the irradiation is higher there are other conflicts. The region mainly consists of cultivated lands with nutrient rich soil (Länsstyrelsen 2016), and is therefore of great value for the Swedish agriculture.

This conflict of interest is very important and the farmers are likely unwilling to give up pieces of land, and parts of their livelihood, for LS PV systems when these only are efficient during the summer period. A compensation would probably be demanded and then the cost benefit of installing these PV systems could be questioned. However, since the farmers in Skåne usually have large buildings such as storage for seeds, machines and animals etc. a combination might be a solution where the installation of larger distributed PV systems on these buildings' roofs. Since the farmer and PV system are both active during the same period (summer) the usage of solar power could maybe lead to tractors being powered by electricity. As a result, the tractors would probably be lighter and have a smaller negative impact on the soil and its ground water (Cambi et al. 2015)

Recently one of the property holders in the city of Lund, LKF, announced that they will install PV systems on the roof tops of one of their properties. The total area being 5 500 m^2 large and is according to the CEO the biggest roof-mounted PV system north of Hamburg (Sydsvenskan 2016). With flat roofs and without shading these are good conditions for the installation of PVs. They have more instalments under way.

Another approach to the conflict of land use is that of the “PV cell tower” which is an efficient way of land usage, putting the PV cells on the walls of the building (Egen el 2015). The advantages with this tower are that the system can harness the solar energy during a longer time period during the day, compared to a fixed horizontal PV system. Another benefit is that during the snowy periods in Sweden the snow reflects the light, which bounces onto the PV system (Egen el 2015). This might be a solution for other areas where there is a conflict in land usage.

Recently an article was published by researchers at Lund University where they presented a new iron (Fe) based dye. One of the major advantages are the harnessing efficiency of the solar power which is much better than previous elements, an example of previous dyes is the Ruthenium (Ru) based, this element is not nearly as abundant as Fe (Fredin et al. 2016).

Conclusions

The results from this study indicate that the method that is used to estimate the EPBT and GHG emissions is important for the outcome of the result. Thus, when evaluating results from future studies in the field, this should be considered.

It is clear that the angles and positioning of the PV system have significant importance. The method based on peak sunshine hours indicated that this was a relevant factor. However, the difference in peak sunshine hours between the four cities was not that large and did therefore not show a large difference between the results.

At the moment the investment in PV systems for Sweden might not be the most environmentally friendly of the renewable resources because of the indirect impact of GHG emissions. This might change in the future if the Chinese electrical grid mix consists of more renewable energy sources. Another possibility is the manufacturing of PVs in Sweden where the grid mix already has a smaller carbon footprint.

Finally future studies are recommended since this study base its results on estimations from two different methods and a more unified method might give a better estimation.

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