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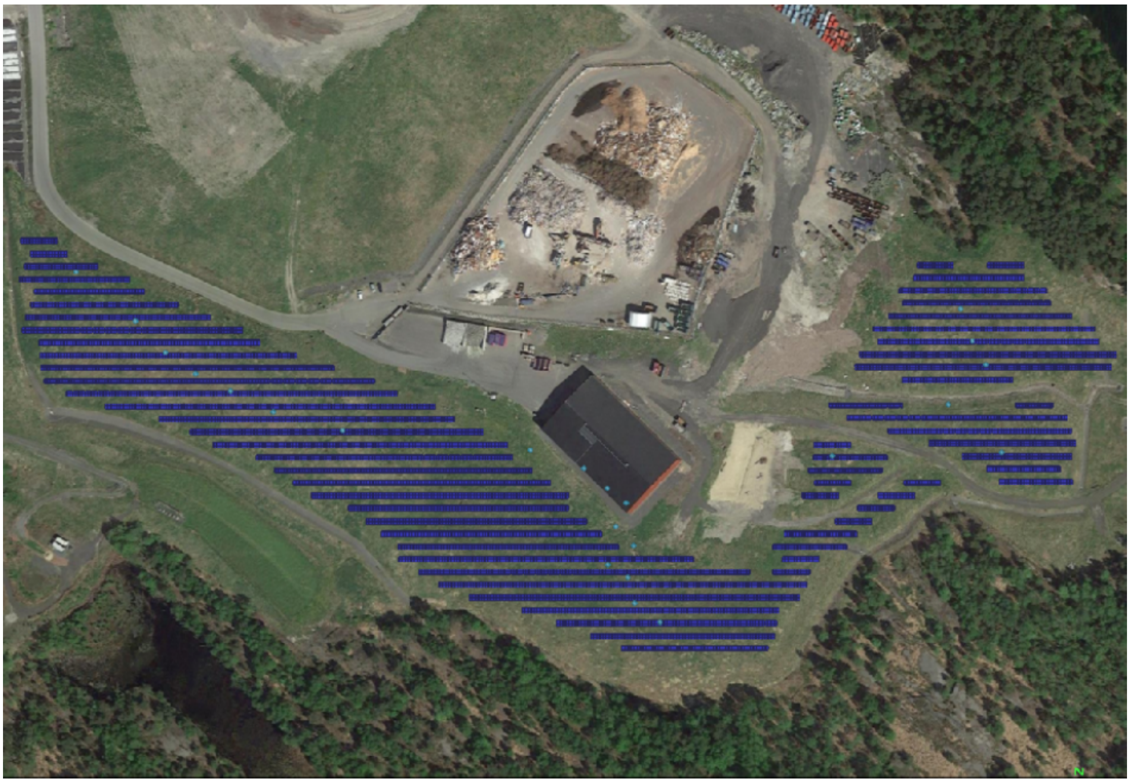

Technical, Environmental and Economic Feasibility study of installing a Photovoltaic Power Plant on a Landfill in South Western Sweden

Master's thesis in Sustainable Energy Systems

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: Initial layout of the Photovoltaic Plant installation.

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Abstract

The increasing global energy demand, which is today mainly supplied by energy sources that are of fossil origin has a severe impact on the environment. Renewable energy sources have the potential to mitigate emissions and are being promoted globally as well as nationally in Sweden. Solar power production has been increasing in the past decade due to increased deployment in countries such as the USA, China, India, and the rest of the world driven by climate targets. But the land requirement will put a constraint on how much PV can be deployed. Hence, there is a need to explore the possibility of establishing a photovoltaic plant on land spaces that have limited applications such as closed landfill sites. This study explored such possibility by researching technical challenges and solutions and conducting a Life Cycle Assessment and an economic feasibility analysis on establishing the solar photovoltaic plant on a closed landfill at kikås, Mölndal.

The research on technical challenges revealed that several challenges could arise during the installation phase depending on the condition of the landfill site. A major challenge lies with the mounting system (a type of anchoring used to erect the mounting system) due to limitations placed by ground penetration restrictions and risks of damaging the settlement. Hence, possible solutions have been identified and described in this study. A cradle to grave life cycle assessment has been made using OpenLCA software empowered by the ecoinvent database. The results from this study show that the GWP of 75.16 gCO_2- eq./kWh for a PV system is situated in the area with irradiation around 1000 KWh/yr. A major portion of that arises from production and transportation of solar modules which is equal to 56.7 gCO_2-eq./kWh which is 75.48% of the total GWP arising from the PV plant. Besides the GWP, the acidification potential was found to be 0.401 gSO_2 eq./kWh. Economic feasibility is assessed by modeling the electricity prices based on two different (2015 and 2018) historical electricity price profiles which are used for revenue calculation. Based on the four scenarios with different electricity profiles it was observed that the revenue will be higher in the case when the electricity price profile follows a similar trend of 2018.

Keywords: Photovoltaic, Life Cycle Assessment (LCA), landfill, landfill cap, Environmental impact, landfill settlements, Mounting techniques.

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1
Introduction

Due to the ever-growing population, the demand for comfort, mobility, and energy consumption has been increasing from year to year [30]. A major percent of the energy demand has been satisfied has fossil fuel origin. The problem with the huge use of fossil fuel to satisfy the energy demand is the environmental pollution [30]. Most of the current energy generation technologies that exist in the world are fossil fuel based technologies. This poses a threat to the energy supply since fossil fuel resources are finite. At the same time, the emissions of greenhouse gases need to be brought under control. Hence there is a need for an increase in renewable energy generation in the energy mix. By 2020, Sweden aimed to achieve a very ambitious target which is to have 50% renewable energy in the energy mix [25]. In addition, the European Union has set a standard on greenhouse gas emission that needs to be achieved by all the members [20]. According to it, the member states needs to reduce emissions by 80% to 95% by the year 2050 [20].

In order to achieve such standards and finally reduce the share of fossil fuel-based energy generation, renewable energy generation technologies play a key role. Among them, solar energy is an important one. Solar energy is the most promising and reliable energy sources in most of the counties [30]. In order to convert solar energy into usable form i.e electricity and heat by utilising solar energy conversion technologies such as concentrated solar power and photovoltaic technologies respectively.

Solar Photovoltaic (PV) technology plays a vital role in reaching the climate targets and reduces fossil fuel origin energy in the energy mix. In the last decade, solar PV technology has seen huge development and it has been deployed on large scale in many counties since it is both commercial and a mature renewable energy technology [30]. In addition, solar PV technology is silent, has less moving parts, and requires fewer maintenance [25]. And a most important drive for the deployment of solar PV is that there will be no greenhouse gas emissions during its operation stage. Nevertheless, the fact remains that emissions will occur during the production stage [26] and takes years to offset them.

Photovoltaic plants need a significant amount of area to be established on a large scale. The land requirement on this scale is one of the disadvantages. The land is used to install the solar plant will not be available for any other purpose for the next few decades. Now, that land could have been used for agriculture if it was fertile. And also it could lead to both direct and indirect land-use changes. Since the large area of land is a requirement, then utilising the land which can no longer to be used for example agriculture or building construction due to the environmental concerns.

Such land can be found at closed landfill sites, where the available land area has limited application for further use. Combining renewable energy generation along with the efficient use of land resources (closed landfill site) has a bright future since the electricity production from solar PV is becoming more competitive with the electricity production from conventional electricity generation [5] [25].

The landfill is situated at Kikås, Mölndal, and is owned by the municipality of Mölndal. The landfill was operational from 1936 until 2008 [14]. The waste deposited at Kikås is characterised by low carbon content since the household waste was not accepted after 1972 [14]. An investigation of gas production and potential for the gas recovery was carried out as recently as in 2014 [14]. The results from the investigation showed that the gas recovery potential was low. But still, further investigation was done in 2014 to assess the gas recovery potential [14]. Since the gas generation is too low, then the site is much more suitable for PV plants since it poses less threat to the environment. A 6 ha of Kikås landfill area has been investigated to be utilised as a land resource to establish a photovoltaic plant by Mölndal Energi. This investigation focuses on the technical challenges, Life cycle assessment, and economic aspects involved in establishing the solar plant at Kikås.

2
Literature Review

There have been several studies focusing on the technical and economic feasibility of installing the photovoltaic plant on the landfill site. In a series of studies conducted by NREL (National Renewable Energy Laboratory), they have investigated the suitability of the landfill site to establish the solar plant [27]. Feasibility studies dedicated for establishing the photovoltaic plant at several landfill sites such as Vincent Mullins Landfill in Tucson [27] by Matthew Steen, Kolthoff Landfill in Cleveland in Ohio by James Salasovich [22], Price Landfill Site in Pleasantville in New Jersey by James Salasovich [23] and Refuse Hideaway Landfill in Middleton, Wisconsin by James Salasovich [21]. These feasibility studies utilized the System Advisor Model (SAM) to conduct performance and financial analysis for the photovoltaic plant. And such modeling approach is not used in this study but the key takeaways from those studies are the importance given to technical aspects of landfill cap stability of the site that needs to be considered while installing the PV plant on the landfill and utilization of weather data, system specs, costs, incentives and also included losses as inputs to perform the economic analysis. And other factors were on-site electricity consumption, shadow effects, and distance to the grid. Similar studies have been made by NREL for different landfill sites across the United States.

The study titled "Solar Landfill" by Cecilia et al. [25] emphasis legal, technical, and financial aspects concerning the installation of PV plant on the closed landfill. They describe the technical challenges that lie with the different types of mounting systems such as weight, landfill cap stability, and sensitivity of settlement. The emphasis on risks involved in damaging or penetrating the landfill cap and risk of settlement. The study conducted by Jonas Larsson [14] dedicated to estimating the landfill gas (LFG) potential at Kikås Landfill and assessing the environmental impacts.

According to a study conducted by Laleman R et al. [13] It was found that the EPBT (Energy Payback Time) of six different PV-technologies were all less than 5 years under irradiation of 900 to 1000kWh/m_2/yr and the GHG emission rate was about 80 $gCO_2 - eq.$/kWh with a lifetime of 30years and if the lifetime was lowered then the GHG emission rate will increase. Ito et al.[10] conducted a study on six different PV modules viz. mono-Si, multi-Si, thin-film Si, a-Si, CIS, and CdTe. Among them, multi-Si cells generated the least amount of CO_2 emissions rate of 43gCO_2-eq./kWh because of the relatively higher conversion efficiency. Alesma et al. [1] estimated that for multi-Si PV system irradiation under 1700kWh/m2/yr Energy payback time (EPBT) will be 3 to 8 years which depends on whether it is the rooftop system or large ground-mounted system and was expected to be 1.2 to

2.4 years in future. Alesma and Wild-Scholten [32] measured the data from multi-Si PV manufacturers and estimated that EBPT and the life-cycle CO_2 emission rates to be 2.2 years and 37 gco_2/KWh for the latest multi-Si PV module status in 2004 and 2005 during its production.

Pacca et al. [19] estimated the EPBT considering the conversion efficiency of 0.3 and GHG emission for a multi-Si PV system to be 2.2 years and 72.4 gCO_2/KWh respectively based on US electricity mix using process-based LCA. Sumper et al. [28], conducted a life cycle assessment for a rooftop PV system, and the difference in result for EPBT and GHG emission rate in comparison to that of previous studies were found be 1.7 to 9 years for EPBT, while the GHG emission rate ranged from 22 to 180 $gCO_2 - eq./kW\ h$. The authors describe that such a big difference in values may attribute to the different boundary settings in each analysis, different electricity mix structure for manufacturing PV modules, and the type production processes and technologies. Based on this it can be concluded that the environmental impact will greatly depend on the country's electricity mix and transportation where the PV system components are manufactured. Meijer et al.[15] reported that energy demand of 4900 MJ/m^2 is required to produce multi-Si module assuming that wafer is produced from electronic-grade silicon to a With 14.5% cell efficiency and the corresponding EPBT estimated was 3.5 years under the solar irradiation in the Netherlands (1000 $kWh/m^2/yr$) which clearly indicates that the EPBT is highly dependent on solar insolation and depends on the configuration of PV systems.

3
Theory

3.1 Life cycle Assessment

Life Cycle Assessment is both a structured and comprehensive method that is used for quantifying material and energy flows and their environmental impact during the life cycle of a product (goods and service) [8]. In other words LCA is a analysis tool for assessing the potential environmental impact associated throughout the product's life cycle or a service, i.e. acquisition of raw material, manufacturing, use and disposal of the product [4]. In the last decade the the deployment of solar power (i.e solar photovoltaic technology) has been huge due to increased investment from both governments and private sector [8]. Such investments only happened due to decrease in production costs which was contributed by improved material utilisation and module efficiency and also to decrease the environmental (carbon) footprint of the energy generation [8]. In order to know how much of a environmental impact is caused by installing a solar PV plant of certain capacity is necessary to justify whether establishing the solar plant is good for the environment and how long will it take to offset the emissions that occurs during the entire life stages of the solar PV plant.

The methodology of LCA is carried out in 4 stages which are as follows,

1. **Goal and Scope definition:** In goal and scope definition,, the intended application of the study, reason behind the conduction of the study and the audience to whom the result is going to be communicated. As mentioned earlier, the purpose is to assess the environmental impact of establishing a Solar photovoltaic plant of 3MW capacity throughout its life cycle. It further defines the functional unit of the system under study, system boundaries, type of environmental impact to consider and how detail the analysis is going to be.

2. **Inventory analysis:** It is the most time consuming step. It involves data and information gathering necessary for the LCA and building a model that represents the system according to the requirements defined in the goal and definition. It is also referred to as Life Cycle Inventory Analysis (LCI). The activities in this stage includes data collection, model construction according to the system boundaries and calculation of resource use and environmental impact during the PV plant's life cycle [4]. The results from the LCI represents information regarding the emissions and resource use throughout the product's life cycle [4].

3. **Impact assessment:** Impact assessment also known as Life Cycle Impact Assessment (LCIA). In LCIA, the inventory results are characterised into more relevant information ,i.e. information on impact on the environment (ex: Global warming potential rather than CO_2 emission) [4]

4. **Interpretation:** During the interpretation phase, a check must be made in order to confirm the conclusions are well-substantiated. The ISO 14044 standard describes a number of checks to test whether conclusions are adequately supported by the data and by the procedures used. This way, the results can be shared and improvement on those results can be achieved in the world without any surprises.

3.1.1 Life Cycle Assessment overview of Solar PV

The beginning stage of the Life Cycle of the solar PV starts for extraction of the material i.e cradle and ends with the waste disposal or recycling and recovery of the material at the end of life of the solar plant i.e grave. The extraction of raw material includes the material required for the solar panel production, for example, silica sand, encapsulation and balance of system components, for example, silica for glass, copper for wiring and iron and concrete for mounting structure [9]. Figure 3.1 shows the framework of the life cycle assessment.

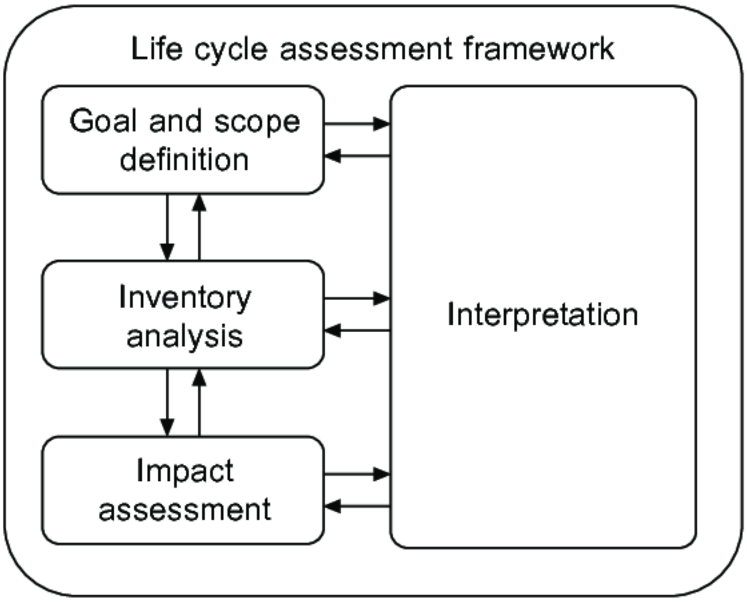

Figure 3.1: LCA framework [18]

After the extraction of the raw material, the material is processed and used in the manufacturing of the required components. Among them a large amount of energy consumption is seen in the extraction of silica sand and purifying it to obtain the solar grade silicon through Siemens process [9]. The solar grade silicon is then used in the production of crystalline silicon for the solar panel production. The solar panel production can be characterised by 3 important stage, 1) wafer production, 2) solar cell production and 3) finally module production. In wafer production stage, the solar grade poly or mono crystalline silicon is cut into thin layers of around 0.2 mm of thickness [9]. Then a p-n junction is formed on those thin layers by dopant diffusion and electricity circuits are created by applying and sintering metalization pastes during the solar cell production stage. Finally, in the module production stage, the solar cells are connected both physically and electronically and are covered by glass and other protection layers such glass and aluminium frame [9]. The solar modules or panels are transported to the installation site. During the installation the mounting systems are built on the landfill cap and the module, cable (wiring), inverters and a connection to the grid are integrated. Then at the End of Life of solar PV plant, the PV systems are decommissioned and are sent for recycle and recovery of the material and finally disposal of material that are unable to be recovered.

3.2 Technical challenges involved in Establishing Photovoltaic Plant on a Landfill

Installing a solar PV system on a closed landfill comes with various technical aspects or challenges which need to be taken into consideration and dealt with. The policies linked Landfilling of waste have been a lot stricter in Sweden compared to rest of the EU countries and US due to the increased awareness of environmental and health risks.

The primary objectives of a landfill cap system are to:

1. **Minimise leachate**: A fundamental function of the cap is to limit leachate production, which is accomplished by limiting the infiltration of rainwater. Leachate from landfills may migrate to the groundwater or recipient, which might lead to severe contamination.
2. **Prevent air intrusion and control migration of landfill gas**: The cap is designed as an impermeable layer. This prevents air intrusion and uncontrolled gas migration. However, in order to avoid potential risk of gas explosion, gas migration pathways should be assured.
3. **Create an aesthetic landscape and allow vegetation on the site**: As a part of the closure of landfills effort is made to restore the landscape.

After the final coverage of the landfill, large areas will be available for new limited applications. One of such application is building a solar PV plant on the landfill cap. Along with the increasing number of closed and final covered landfills there is growing need for renewable energy production. The motivation for establishing the solar PV plant on a final covered landfill is that electricity generation from solar power has drastically increased both in Sweden and the rest of the world.The utilisation of land which has limited applications would be good for the society, energy companies and government.

The large area that is available together with the growing demand for solar power, has made the Solar PV installation on landfill cap has been a prominent solution. Since it addresses both the ecological and economical issues. Using the large areas of landfill cap for solar installation will address the land use issues which in turn addresses the economic and ecological issues direct or indirect land usages.

As mentioned in the literature review there has been several studies made in conjunction with Solar PV and landfill. Here, a feasibility study has been conducted for Kikås landfill to assess the economic feasibility and environmental impact of installing a PV plant. The landfill site was operational between 1936 and 2008, although household waste was not accepted after 1972. Since the waste deposited at Kikås is characterised by low carbon content there has been a rather low interest in measures that can mitigate methane emissions. The landfill has been closed since 2008 and remains nonoperational to this day. The landfill has been closed for several years with help of sealing layers as shown in figure 1.

The solar PV plant is going to be established on the landfill, the need to conduct a research on technical challenges that lies during the installation of the plant and maintenance during the operation phase since they pose the threat to emit emissions of landfill gas (LFG). LFG is formed in landfills during anaerobic degradation of organic matter and consists of roughly 50 % methane (CH_4) and 50 % carbon dioxide (CO_2) which are greenhouse gases.

The risk of releasing the gases lies during the installation of mountings that is required to install the solar panels. In any landfill that is no longer active some safety measures are taken to avoid the emissions (landfill gas) from the landfill. In order to ensure that a protection layer called the landfill cap is used to seal the landfill area. They are sealed in a way that the gases generated due to anaerobic degradation of organic matter are prevented from affecting the environment and risks such as gas explosions to occur. The figure 3.2 shows the different layers of landfill cap at Kikås [14].

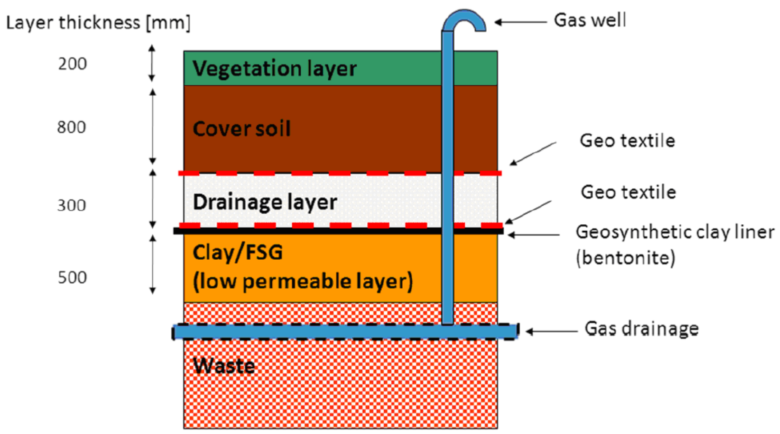

Figure 3.2: layers of landfill [14]

3.3 Solar PV Plant Components

The crystalline PV module has been the proven and dominant solar technology that exist today. The solar technologies are under constant development with the improvement in efficiency of conversion of solar energy to electricity. The following describes the components that are required to build a photovoltaic plant.

3.3.1 Solar Photovoltaic Module

The solar module technologies are under constant development and they are differentiated by the type of PV material used during the production of the module. This results in a range of conversion efficiencies from light energy to electrical energy [1]. The two technologies that are in use are crystalline and thin film technologies.

1. **Crystalline Silicon Technologies:** The crystalline silicon (c-Si) based solar modules are the most abundantly used due to the availability of silicon and their efficiency. Silicon based modules can have a life time in the range of 25 to 30 years [27]. The c-Si solar panels has demonstrated the consistency and high efficient performance in the field for more than 30 years in the field [17]. The performance of the c-Si solar modules will reduce due to degradation over their life time and it is usually under 1% [27].

   The c-Si technologies are divided into mono crystalline and multi crystalline silicon technologies, which represents the presence of multiple crystals. The efficiency of c-Si solar modules vary among 12% to 18% [27] [17].

2. **Thin film Technology:** Thin-film photovoltaic cells are made from amorphous silicon (a-Si) or other materials such as cadmium telluride (CdTe). Thin film cells are made up of layers of semiconductor materials which are a few micrometers in thickness. Thin film photovoltaic cell are sometimes constructed into flexible modules, which can be used as a cover on the land fill cap surface and they are referred to as geomembrane surface [22]. But they can be mounted on the fixed tilt or tracking system configuration if they are manufactured into rigid structures. The efficiency of thin-film solar cells is lower in comparison with the crystalline cells. The overall efficiency of a thin-film panel is between 6% and 8% for a-Si and 11%–12% for CdTe. But recently a study found that CdTe technologies have the efficiency of 15.8% [22][27].

3.3.2 Mounting

The solar panel array needs to be mounted, secured and oriented at an certain angle to obtain efficient output. In order to establish the solar plant the mounting system needs to withstand stronger wind loads and ice and snow loads. The mounting system are usually anchored to the ground using screw or ballast or using concrete foundation.

The mounting system used in the utility scale solar power plant are usually known as Ground mounted Systems. Generally, the ground mounted systems are characterised into fixed tilt and tracking type of system. Fixed tilt mounting system are preferred

[1] The module efficiency is a measure of the percentage of solar energy converted into electricity

over the tracking type when it comes to installing the PV plant on a landfill because the mechanical drive components in the tracking system will be affected by the settlement[2] in the site [23].

3.3.3 Inverters

Inverters are the devices that convert the DC solar output into AC. There are two types of inverters for grid-connected systems or utility solar power plant: string and micro-inverters. String type inverters have higher efficiency and has low operation and maintenance costs. String inverters are available in various sizes (1.5 kW to 1,000 kW) [22] and capacities to handle a large range of voltage output. The expected life time of inverter is typically 10 years but the larger units have lifetime up to 20 years. The efficiency of the inverter is higher than 98.5% [27].

3.3.4 Electric Installation

The electric installation involves connection of arrays to inverters. Generally, the wiring to connect the arrays and the inverter will be done underground. But the care should be taken not affect the landfill cap during the installation.

[2] Due to waste deposition at the landfill gas generation occurs and changes of gas and liquid pressures can cause deformations of the landfill. These deformations are referred to as Settlements

4

Methods

The method followed for the different aspects of the study is presented in this chapter,

4.1 Life Cycle Assessment

In this section, the methodology followed for the LCA is described and also what is included in the main phases of the LCA study of the solar photovoltaic plant is explained. The LCA is performed using the open source software called openLCA. The LCA is performed only for the poly-crystalline silicon based solar modules.

4.1.1 System Description

The following sections describe the system under study in detail and how it is modelled on OpenLCA software along with the assumptions made and the limitations of the study.

4.1.2 Goal and Scope Definition

The goal and purpose of the study as mentioned before is to estimate the environmental impact of the establishing the photovoltaic plant. Along with that the purpose is to perform the inventory of all the required materials and to identify the which activity in the life cycle of the PV system contribute the most to the environmental impact.
The scope of the LCA study is to defining the system boundary, functional unit and choosing the impact categories.

1. **Functional unit:** With in the scope of the study, the functional unit is the KWh of energy generated by the solar plant. The study focuses on the cradle to grave LCA modelling of photovoltaic plant. It is notable that the mono crystalline and thin film technologies are outside the scope of this study.

2. **System Boundary:** Here the processes that needs to included in the analysis is defined and it is as shown in the 4.1. The figure 4.1 shows the system boundaries for the solar panels and a similar approach is adopted for the balance of system components. The study cradle to grave study covering the end-of-life recycling of the PV systems components. That is, the analysis covers all the production process steps from raw material (cradle) to finished

products ready to be transported and installed at the landfill site and operation phase of the PV plant (gate) and finally the analysis includes the end-of-life recycling (partial) of the PV system components.

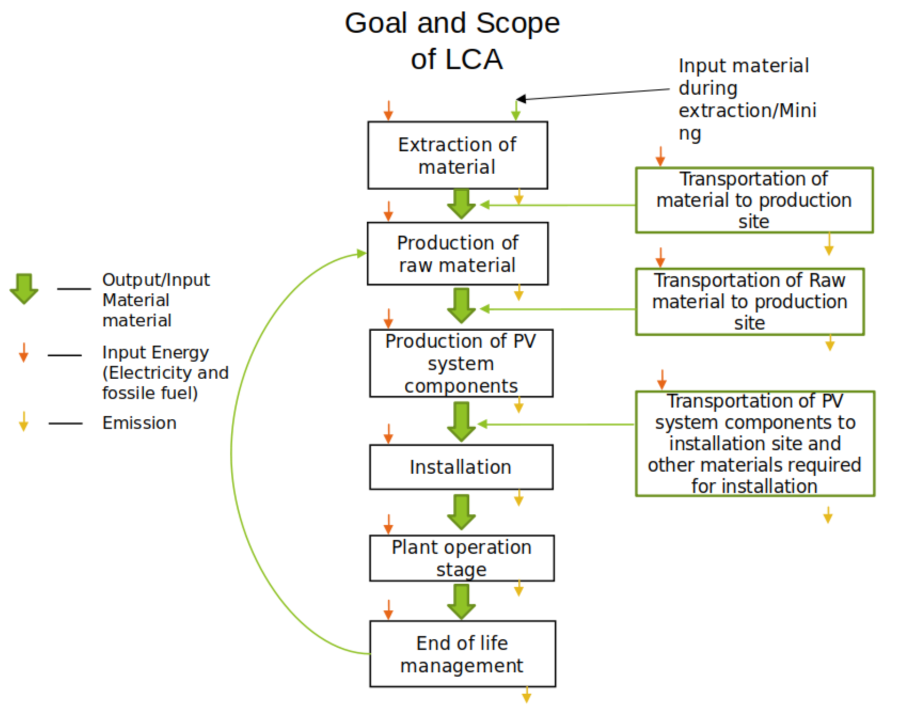

Figure 4.1: Technical System Boundary

3. **Geographic coverage:** Since the manufacturing of the components Solar PV systems occurs in different parts of the world. So the geographic coverage includes the countries in Europe and China.

Table 4.1: Geographic Coverage

Solar PV system component	**Country**
Photovoltaic Module	China
Inverter	Europe
Mounting	Italy / Europe
Electric Installation	Europe

4. **Time Coverage:** The time coverage of the study includes the technical operation life time of the solar PV plant i.e, 30 years.
5. **Impact categories (LCIA):** The LCIA categories chosen for this study are global warming, acidification, Human toxicity, Ozone depletion and Energy consumption

4.1.3 Inventory Analysis

In life cycle inventory analysis (LCI), all the data in regard to the production of the required components, transportation, installation, operation and EOL treatment of the PV systems are collected. The data is collected from the previous studies made by de Wild-Scholten [33] and Fthenakis [9] in 2010 and 2015 and also, ecoinvent data base is used for the LCI modelling using openLCA software tool. Refer to appendix for the LCI data in Appendix A, B, C and D.

4.1.4 Impact Assessment

The environmental loads obtained from the inventory analysis are tuned into relevant information that express the impact during the production, transportation, installation, use phase and EOL handling of PV system components on the environment. The following impact categories are chosen for this study,

1. **Global warming:** The gases which increases the radiative forcing[1] in the atmosphere are characterised under this category. The gases such as CO_2, methane, CFCs[2] and nitrous oxide has the potential to contribute to climate change and is expressed as Global Warming Potential (GWP). The GWP is measured in terms of CO_2 equivalent.

2. **Acidification Potential:** It is mainly caused by SO_2 and NOx but other pollutants such as HCL and NH_3 are included in this category. The acidification potential of these gases are measured by its capacity to form H^+ ions.

3. **Human toxicity:** It is an impact category that reflects the potential harm of a unit of chemical released into the environment to humans. It can be dangerous to humans through ingestion, inhalation or even contact. It is evaluated based on both the inherent toxicity of a compound and its potential dose. The impact category is measured in 1.4-dichlorobenzene equivalents.

4. **Ozone depletion:** CFCs, halons and HCFCs are the major causes of ozone depletion. Ozone layer shields the earth from harmful ultraviolet rays from the sun. Damage to the ozone layer reduces its ability to prevent UV light entering the earth's atmosphere which leads to increase in the amount of ultraviolet light reaching the earth's surface. Ozone depletion potential of different gases is measured relative to the reference substance CFC-11 and expressed in kg CFC-11 equivalent.

4.1.5 Modelling on OpenLCA

In this section the modelling approach, limitations of the study and the assumptions made has been described,

[1]Radiative forcing refers to the capacity of the gases to absorb infrared radiation and thus increase the temperature of the atmosphere

[2]CFC stands for Chlorofluorocarbons

4.1.5.1 Limitations and Assumptions

1. **Limitations:** In the LCA study, the impact from the transportation of electrical installation i.e fuse box, electric cables and electric meters from suppliers to installation site is not included due to the lack of data availability. Moreover, the study doesn't include the positive impacts or credits of utilising the landfill site since it has very limited applications due to threats posed by the damaging the landfill cap for any recreational activity at the landfill site.

   Due to lack of data availability the End of Life modelling of the PV system components is incomplete meaning that the transportation and management of materials such as silicon at its end of life hasn't been included in the study.

2. **Assumptions:** Due to the requirement of the company the analysis was performed for the inverter of capacity 125KW but the data was only available for 570KW of capacity. So the data for 125KW inverter was calculated from the data from the data for 570KW inverter by assuming a linear proportionality among them. The life time of the inverter is assumed to be 15 years which is included in the calculation.

   A similar assumption was made with respect to the material and energy requirement for the electric installation equipment. The material and energy flows were basically calculated from the data from electric installation for a 570 KW_P PV plant by assuming a linear proportionality between the two.

   In case of End of Life handling of the PV system components a recycling rate of 90% was assumed based on the conversation with photovoltaic panels recyclers based in the United States of America.

4.1.5.2 Designing the model on OpenLCA

The figure 4.2 depicts the model that has been built using OpenLCA software. It is evident from the figure that the study addresses the cradle to grave LCA, which starts from the silicon feed-stock production via wafer- and cell- to module manufacturing to its use phase. The LCA of other PV system components starts from the extraction of raw material - to manufacturing of final products to its use phase and finally its disposal.

The challenge was to model the use phase which spanned over 30 years. Since the functioning unit is kWh of electricity produced from the PV plant. The model was simulated for producing 90000 MWh of electricity (3000 MWh over 30 years of operation). While modeling the use phase, the material and/or component input to erect the PV plant was divided by their respective lifetime (ex. The amount of solar module required to install a 1 kWh capacity PV plant was divided by 30 years since the analysis covered the entire lifetime of the plant. Similarly, the amount of inverter required was divided by 15 years which enabled to account for their replacement in the LCA). This is done in order to avoid the overestimation of material and energy consumption for manufacturing PV system components. Finally, the model was simulated and the results were compiled.

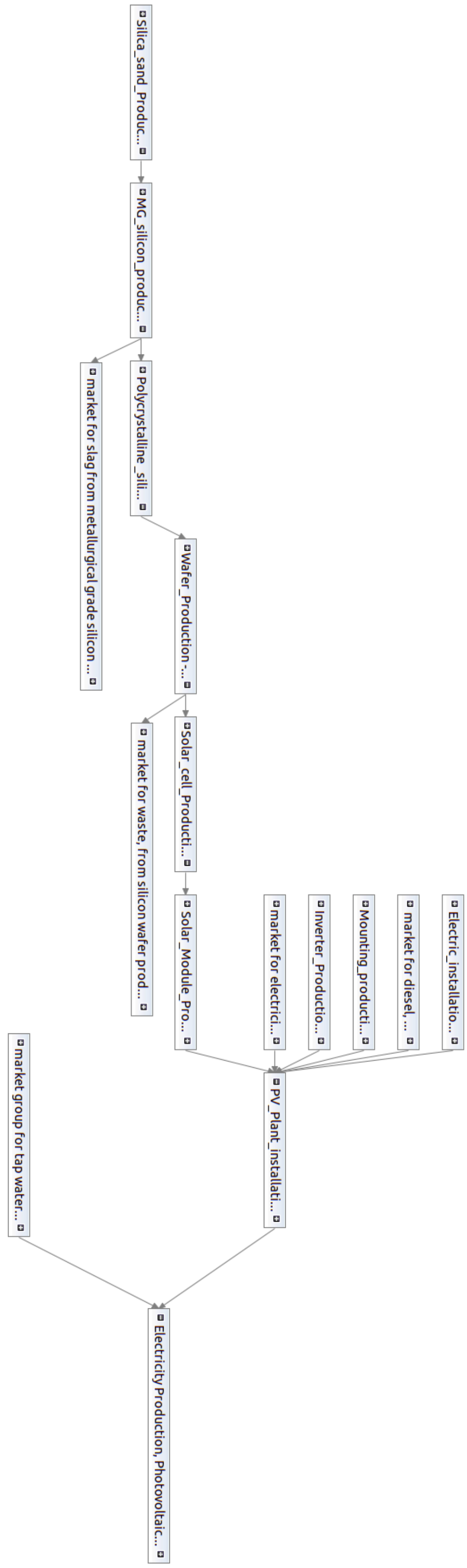

Figure 4.2: LCA model on OpenLCA

4.1.5.3 Sensitivity Analysis

The sensitivity analysis is conducted for different percentage of recycled material used during the production phase of PV system components. As mentioned in the limitations, recycling of silicon used in PV panel is not included in the study hence it is not one of the recycled material used in manufacturing of PV system components. In the analysis three scenarios are assessed with different percentage (80%, 50%, 0%) of recycled aluminium and steel used in the manufacturing of the PV system components (ex. 80% of recycled aluminium and steel used in manufacturing mounting system and remaining 20% of the raw material is virgin material). Later the results from each scenario is assessed to check the impact of using recycled material.

4.2 Economic Analysis

The following sections describe the cost calculation and the method followed to assess the economic feasibility of investing in the PV plant.

4.2.1 Cost Calculation

The cost calculation has been made for the entire life time of the plant, i.e, 30 years. The investment cost calculation is based on the data drawn from the prestudy made by Mölndal Energi.

1. The largest part of this cost is made up of photovoltaic modules.
2. The cost of the ground screw type of anchoring system for the mounting structure is 400 SEK/kW.
3. Similarly cost of the concrete foundation based mounting system is considered to be 550 SEK/kW
4. The estimated cost for procurement support and geological survey is SEK 150 kSEK and 80 kSEK respectively. The budget also includes an item for the unforeseen expenses of SEK 0.5 million.

The table 4.2 represents the economic data that is used for the calculation of the investment and operation and management cost.

Table 4.2: Economic data

Data	Value
Discount rate	5.00%
Inflation (i)	1.46%
Economic lifespan	30
Capital recovery factor	0.0650

The operation and management cost is calculated based on the following data in table 4.3.

Table 4.3: Operation and Maintenance Cost

Data	Value
Infrared camera and security personnel	10,000 kr
Production supervision, license (included in contract 5 years)	10,000 kr
Handling of operating alarms, rounding, mowing, fault remediation	55,000 kr
Insurance	25,000 kr
Land cost, fee from Mölndal municipality	12,000 kr

An analysis on the investments with the future cash flows can be made considering the discount rate and economic life time of the plant.

$$C_{inv} = C_{INV} * \frac{r * (1+r)^n}{(1+r)^n - 1} \tag{4.1}$$

Where, C_{inv} is the annualised invest cost, C_{INV} is the total investment cost, r is the discount rate, n is the economic life time of the solar plant and $\frac{r*(1+r)^n}{(1+r)^n-1}$ is the capital recover factor[3].

Further, calculation of levelized cost of electricity (LCOE) from solar photovoltaic plant express the production cost per unit of electricity produced from the solar plant which is distributed per unit of electricity produced by the plant [29].

$$LCOE = \frac{C_{inv} + C_{FixO\&M}}{AEP} \tag{4.2}$$

Where, AEP stands for Annual Electricity Production.

4.2.2 Revenue Calculation

The method followed for the calculation of the revenue is based on the actual electricity prices for the years 2015 and 2018 from Nordpol. The electricity prices retrieved from the Nordpol are in hourly resolution. So in order to calculate the revenue from the solar plant for every hour the equations 4.4, 4.5 and **??** are used and hourly production from the solar plant is estimated based on 2019 weather profile.

The model for estimating revenue built is based on the electricity prices of the year 2015 and 2018 for the region SE3 for the first 10 years i.e until 2030 and for the next 20 years the calculation is based on the estimated electricity prices or the year 2030. The model uses the electricity prices and solar generation with hourly resolution.

The solar generation for the entire life time is calculated based on the 2019 weather profile. But a reduction in the solar generation during the life time of the solar plant due to degradation of solar panel. The reduction the generation is introduced in the

[3]A capital recovery factor is the ratio of a constant annuity to the present value of receiving that annuity for a given length of time.

calculation using a constant equalling 0.2% which represents the degradation in the solar panel.

$$Generation_{(n+1)_t} = Solargeneration_{(n+1)_t} * d \tag{4.3}$$

Where, t =1, 2, 3...8760, and n= 0, 1, 2, 3...29 stands for number of hours in a year and and d = 0.2% is the Degradation rate of solar panel represents the degradation of solar panels. The degradation in solar panel is accounted for every year in the calculation. An inflation rate is used to accommodate the changes in price level of electricity price over some period of time.

The following equation is used for calculating hourly revenue in year 1. Where n = 0 and y = 1.

$$Revenue_{(n+1)_t} = Generation_{(n+1)_t} * Electricity\ Prices_{yt} \tag{4.4}$$

The following equation is used for calculating hourly revenue from year 2 to 30, , Where n =1, 2...29 and y = 0, 1, 2...29.

$$Revenue_{(n+1)_t} = Generation_{(n+1)_t} * (Electricity\ Prices_{(y+1)_t} * (1 + i)) \tag{4.5}$$

Where, i is the inflation rate. Further, the revenue generated from year 1, 2...30 is calculated by adding the hourly revenue generated in the respective year thus calculating the yearly revenue for every year that the plant remains in operation.

$$Revenue_{year} = \sum(Revenue_t) \tag{4.6}$$

4.2.3 Scenario Analysis

A total of 4 scenarios are built to access the revenue generation from the PV plant. The scenarios utilises the electricity prices from year 2015 for a worst case scenario since it is the lowest in the past 5 years and 2018 for modelling the best case scenario. As mentioned earlier the revenue for the first 10 years during the life time of the plant is based on 2015 and 2018 and for the remaining 20 years is based on the mode 2030 prices. There are two electricity profiles modelled for the year 2030 one considering the deployment of renewables collaboration among different actors such as heating sector, transportation and household (i.e variation management strategies) and the other is where there is no collaboration among the different sectors even after the deployment of renewable technologies. Both of the profiles has been used for modelling electricity prices from year 2030 i.e from year 11 to year 30 of the photovoltaic plant.

Scenario 1: Year 1 to 10 based on 2015 electricity price profile and from year 11 to 30 based on projected 2030 electricity price profile with no collaboration.

Scenario 2: Year 1 to 10 based on 2015 electricity price profile and from year 11 to 30 based on projected 2030 electricity price profile with collaboration.

Scenario 3: Year 1 to 10 based on 2018 electricity price profile and from year 11 to 30 based on projected 2030 electricity price profile with no collaboration.

Scenario 4: Year 1 to 10 based on 2018 electricity price profile and from year 11 to 30 based on projected 2030 electricity price profile with collaboration.

5
Results

5.1 Technical challenges

Photovoltaic and landfill are two different business hence it requires different resources and expertise. It is of importance to see the PV system and the landfill as an integrated system, meaning that they are not to be treated separately. It is recommended that the landfill site should be old so that it can be assured that most of the settling has already taken place. Here the settling refers to the deformation that has occurred due to gas generation and changes in gas and liquid pressure which influences the porosity and cause deformation of landfill [6]. Additionally, landfills with wastes such as construction debris are preferred over the landfills containing biodegradable wastes[24]. Since the Kikås landfill is both old and stopped receiving any MSW (Municipal Solid Waste) since 1972, makes it a suitable site to establish a PV plant. Installation of photovoltaics at landfill requires important aspects are driving forces such political initiative and the growing need for renewable energy. The following sections addresses the challenges faced during the installation of the Photovoltaic plant on the landfill area,

5.1.1 Condition of the landfill site

Present condition of the landfill plays a major role while establishing the solar plant. Hence technical aspects regarding the settlements and landfill cap.

1. **Landfill settlements:** As mentioned earlier, due to waste deposition at the landfill gas generation occurs and changes of gas and liquid pressures can cause deformations of the landfill. These deformations are referred to as Settlements [6]. These settlements should be considered while planning solar PV plant on the landfill because they have the capability to disrupt the solar array positions and cause the crack in landfill cover [25]. The settlements can be described in three stages,

    (a) The first stage refers to the immediate compression occurring as a result of self-weight and eventual external loads on the waste. They are usually triggered in case of heavy mounting structures are used during the construction stage[6].

    (b) The second stage of settlement, the primary compression will occur due to the dissipation of gas and water landfill in the first few months.

(c) Finally the third stage, referred to as the secondary compression, "is caused by slippages, delayed compressions and reorientation of particles in the landfill which can occur over many years after the waste was placed in the landfill".[25]

The settlements at the landfill can be reduced by applying dynamic compaction to decrease the settlements and it can also be achieved by selective removal of waste. In case of Kikås, the landfill has been closed for more than 10 years and also from 1972 MSW has not been deposited there which makes measures to reduce the settlements unnecessary. The absolute degree of active settlement depends on the depth of the waste heap, the type of waste present, the method of placement, and age of the landfill[31].

2. **Landfill cap:** The landfill cap system at Kikås is shown in Figure 3.2. The strength or the thickness of the protective layer is around 0.8m which is mainly made up of clay. According to Avfall Sverige, the bentonite mixtures or any synthetic layers such as geomembranes can be used as a sealing layer as long as they are approved by the authorities. This is true in case of Kikås landfill cap system. The important factor which decides the suitability of the landfill are the site conditions. The factors such as thickness of each sealing layer plays a major role in choosing the mounting techniques that available for solar PV installation. In order to avoid damaging of the sealing layers, the foundation or the anchoring system used for mounting system is quite limited. In case of any damages to the sealing layer will result in huge environmental impact due to release of harmful gases such as methane and carbon dioxide.

   Usually the landfill area are not flat meaning that there will be slopes which needs to be addressed to make the site less hilly. The conditions and soil stability at the location where there are slopes needs to tested or analysed. The vegetation in area can create challenges like shadowing the solar panels which influences the production from the plant.

5.1.2 Side Slope Stability

Landfill site should be accessed for the stability of the cap. More importantly such assessment should be performed on the side slopes [24]. Building a solar PV plant on the side slopes of the landfill whose angle is much larger than 5 degrees is complicated due to shadow effects. Besides, the need for erosion and storm water control systems will be high. In addition, an increase in operations and maintenance costs may occur over time for repairs to the side slope [24]. A strong foundation is needed to install the solar PV plant on the side slope to withstand the dynamic loads.

5.1.3 Weather conditions

The southern part of Sweden is the region whose weather is characterised by its windy and rainy conditions. Since the solar PV plant is going to situated in south western part of Sweden, it will be exposed to similar weather patterns. In addition the trees or any other vegetation that exists near the plant needs to cleared in order to avoid the shadow effects on the solar panels. Such clearing of trees will expose the landfill site to more wind which increases the wind load that might damage the solar panels. To overcome such issues the mounting system and foundation should be robust enough to withstand the wind loads. Another factor to consider is the snow and ice loading. The accumulation of snow and ice on PV system components will increase the weight of the system and thus can affect the landfill cap [24].

Apart from the wind, rain is another weather condition that needs to given attention. Even though it does not create a considerable impact on the solar panels or the mounting platforms, it is problematic to the landfill itself. The possibility of percolation of rain water through the sealing layers and reach the waste will be higher if there are any cracks in the cap system. The cracks might occur naturally, but the possibility of occurrence of crack in the cap is higher during the installation of photovoltaics. This depends on the type of mounting system used during the installation.

5.1.4 Design consideration to install the Solar PV plant

1. **Mounting System and Foundation:** The planned installed capacity of the solar PV plant is 3MW. The type solar panels used in the PV plant only affects the production. It does not have any influence on the land fill cap apart from its weight. Where as mounting structure, foundations or the platform used to mount the solar panels has the major impact on the stability of the cap especially in the sloping regions of the landfill cap. The foundations that is going to be placed on the sloping areas needs to given extra support for the stability and reduce the movement. The movement of the foundations or the mounting structure might case damages to the cap.

   The weight capacity of the landfill that is the capability of the landfill to handle the load per m^2 area (kg/m^2) needs to be estimated. Knowledge of such number will be helpful in choosing the mounting technology that is whether to use screw based mounting or the concrete based mounting technology to mount the solar panels. The pros and cons of different mounting technology will be explained in section 5.3.

2. **Grid connection:** When Solar PV power integrated into the grid, which is a renewable energy resource, hosting capacity is the amount of Solar PV power that can be added to a transmission and/or distribution grid enough not to cause power system operational violations of set limits [16]. The connection is likely to bring impact challenges of integration and operations of the grid. According to the thesis report [16], the integration of solar PV power for the distribution grids in general causes an increase in voltage level, decrease in voltage drop and losses. According to [16], integration of large ground utility PV systems causes an increase in line loading of the feeder cable/line to the coupling substation to the grid.

3. **System components:** There are several components which are required to build the solar plant. Most important of all are the solar panels. There are several technologies available such as mono-crystalline, poly-crystalline and thin film cells. The choice can be made based their performance but in this case their weight should be considered since the load bearing capacity of the landfill is of concern [24]. According to the prestudy made by Mölndal Energi poly-crystalline solar panels are being preferred since they are cheaper than the mono-crystalline panels. The table 5.1 describes the interaction among system components and landfill characteristics which is necessary for choosing the type of PV module and anchoring system. Hence, an investigation on the load bearing capacity of the site is needed and recommended before the final decision in this regard.

Table 5.1: Interaction among the system components and characteristics of landfill [25]

PV system components	**Capping**	**Settling**	**Preparation of site**
Crystalline silicon Modules	No possibility of integration among geomembrane and PV system	• Risk of breakage • Expensive substructure to withstand settling	Preferably mounted on the flat land
Concrete Foundation	Enables Mountings to be mounted without much damages to cap	Excess weight on the settlement and risk of damage	Adding a layer of soil to reduce the slope.
Screw type anchoring system	Penetrates the landfill cap	–	Necessary to provide sufficient thickness pf top soil.
Fixed tilt mounting structure	–	Less weight hence probability of stimulating the settlement is less	Possible to mount on both flat and sloping area of the land fill.

5.2 Non technical challenges

The challenges which are non technical are usually permit application and policies. Since the solar PV installation is an upcoming solution. It is fact that the laws that puts regulation and policies on the installation of Solar Panels on the landfill. This influences on getting the permit needed to conduct such operation on the landfill. This will not be discussed further since the focus has been given to technical challenge.

Furthermore, landfills can be protected by fences to avoid theft. But it is an advantage when the solar panels are theft-proof. Even though the landfill is not fenced, there are often activities on site such as recycling and other waste handling activities that reduce the risk of theft and damage and save on security costs.

5.3 Possible solution to Technical challenges

The technical challenges which were mentioned above should be addressed carefully and extensively. Because if they are not taken care of properly then it would lead to damages for the solar Panels and failure of the landfill cap, which will produce a considerable impact on the environment.

The mounting technology used will be a major factor and solution to the technical challenges mentioned in section below. The following describes the mounting technologies that can be used on the landfill cap,

5.3.1 Geo technical survey

A Geo-technical survey needs to be conducted to determine the suitability of the site to establish solar PV plant. The survey can reveal the condition of the landfill cap and necessary steps that needs to be taken to address the possible damages in the cap over time. This helps in choosing the mounting system that is best suited to be used depending the load bearing capacity of the landfill.

5.3.2 Concrete Foundation

The solar panels mounting structure can be anchored using concrete foundations. The utilisation of concrete foundation (See figure 5.1) to anchor the mounting structure considered to be well or a good option to minimise the risks associated with construction. The advantage of using the concrete foundation instead of using screw type of anchoring is that, the greater weight allows the solar panels to be angled to a higher angle as it increases the production electricity from the solar panels. In addition to that the solar plant can withstand greater wind loads. But there are few downside to using concrete foundations, the concrete production is an energy intensive process and has a large carbon footprint. Along with those disadvantages, if concrete foundations are used then the space between each row of solar panels will be more to avoid the shading effect. This, in turn reduces the installed power per surface area of the landfill cap.

Considering the landfill Fort Carson in Colorado, USA, as an example the PV modules are placed on ballasted concrete footers [24] meaning that the concrete foundations have been used to anchor the mounting structure of the solar panel. The concrete footers were chosen because the capping layer consisted of 0.6 m of soil, which was considered thick enough since the landfill only contains construction debris [25]. In such cases choosing the concrete foundations seems like an inevitable choice given that the screw type anchoring system posses the threat of damaging the landfill cap by puncturing it.

Figure 5.1: Solar panels anchored using concrete foundation (Image source: HP Solartech)

The challenge with concrete foundations and other weighted platforms is to calculate a dimension meaning a right amount of them so that they can handle wind and snow loads without being so heavy that the landfill is adversely affected.

5.3.3 Screw type mounting structures

Screw type mounting method (See figure 5.2) where a ground screw is inserted into the ground, which is available in varying lengths and sizes. The arguments against the screw type mounting are the risks involved in damaging the sealing layer and that there is a risk that the rain water would affect the leachate from the landfill.The limited depth entails however, more screws are required than with a regular installation. This means that ground screw is a more expensive solution than concrete or ballasted mounting system. Refer figures below for description.

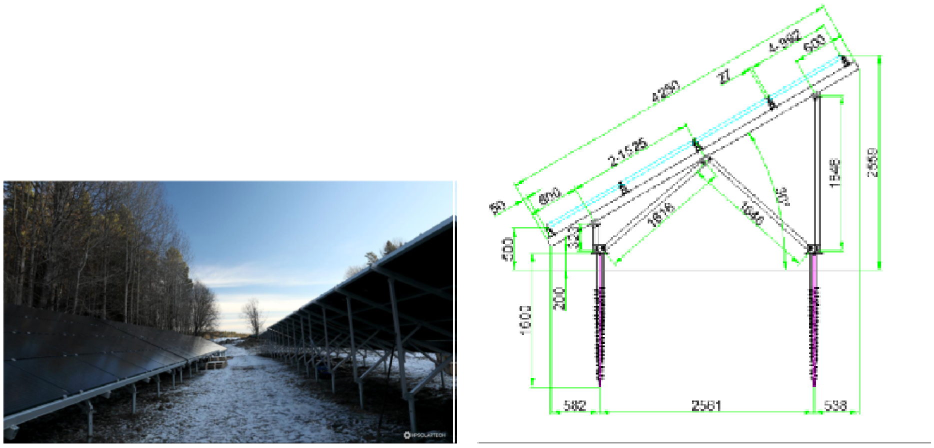

Figure 5.2: Screw type Mounting Structure (Image source: HP Solartech)

However, in cases where the vegetation and top soil layer above the sealing layer have a sufficient depth over the entire surface ground screws are the solution. In addition, they are better than other solutions on sloping surfaces.

5.3.4 Ground-penetrating oblique inserts anchoring system

The ground-penetrating oblique inserts anchoring system (Tree type mounting system) is a good alternative to the concrete foundation and screw type anchoring system. The device can be sized depending on the operating load and condition [2]. It allows avoiding the concrete footing, with a considerable saving of time and labour by avoiding excavation, casting and waiting for the materials to set [2]. Besides, it doesn't need to be inserted too deep into the ground as shown in figure 5.3.

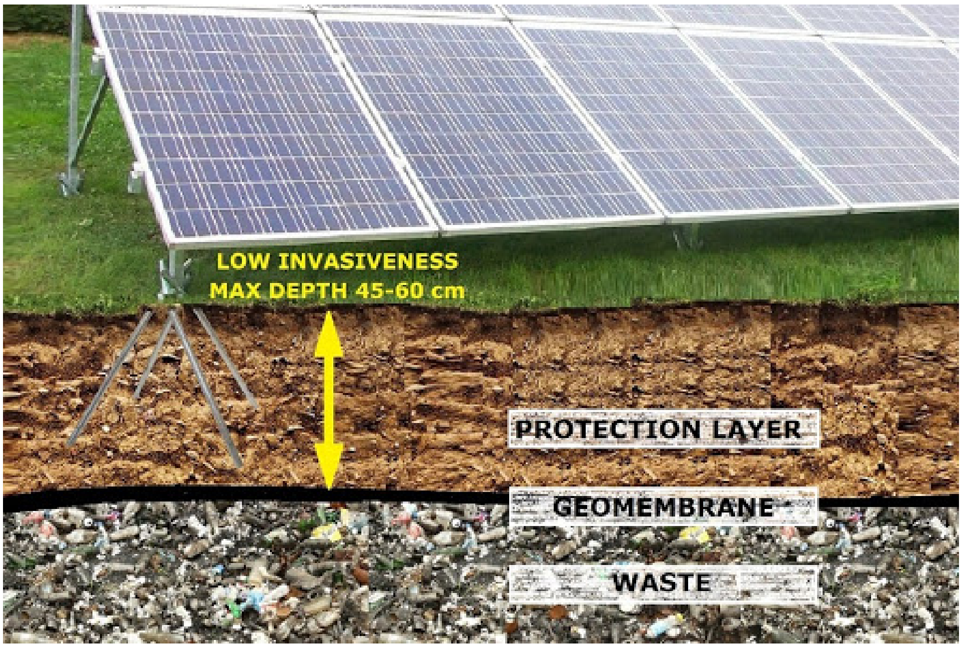

Figure 5.3: Ground-penetrating oblique inserts anchoring system [7]

5.3.5 Renusol Console +

The platforms have the shape of an angled trough and are open at the top to be filled with ballast. In wind-exposed locations, at the edges of the plant, more ballast is used for the platforms to handle larger wind loads. These type of mounting structure does not pose risks such as damaging the sealing layer and allow fugitive gases to escape from the landfill.

Figure 5.4: Renusol Console+

The angled trough has a hollow space which can be filled with ballast to increase the weight to withstand the wind and snow loads. One disadvantage of these type foundations is that they can be subjected to shadow effects from the surrounding vegetation on the landfill.

5.3.6 Remedying or preparation of the landfill

In order to avoid the failure or rupture of the sealing layer of the landfill, an extra layer of soil can be added. Addition of an additional top soil layer may be necessary to achieve a slope that is favourable to supporting a solar system. Moreover, it can provide extra thickness to install a robust mounting structure. Adding an extra layer of soil will help in flatten out the sloping area which will reduce the instabilities in the sloping region of the landfill.

5.3.7 Remediation of the landfill with respect to Methane emission

It is important to focus on taking care of methane emission from the landfill if there is any emissions because of its global warming potential. According to [14], there are different mitigation measures that can be utilised based on further investigation. And to mention a few, oxidation filters and development of the existing gas venting system to a gas extraction system. Oxidation filters will be a better option considering that they are economically viable option but considering the uncertainties in the remaining gas potential, a gas extraction system could be a system that is worth investigating [14]. Gas extraction is a good solution if the existing gas venting system can be used and developed but it involves additional costs and uncertainties [14]

5.3.8 Thin film solar PV

A thin-film solar cell is manufactured by depositing one or more thin layers of photovoltaic material on a substrate, such as glass, plastic or metal. Such solar panels can be directly attached to the geomembrane where it is the top layer of the landfill [11]. Geomembrane can be attached on a foundation consisting of a thin concrete layer, separated by wooden beam splices. This foundation technique is used in Malagrotta landfill in Italy [3].This foundation was built to avoid breakage of the concrete in case of settling and also avoid theft of solar panels [3] [25].

5.4 Operation and Maintenance of the plant

The maintenance consists of two part, one maintenance of the landfill and other is maintaining the solar PV plant. Maintenance of the landfill include clearing the vegetation that grows on landfill. Based on the status of the landfill when it was finally covered maintenance it may also include leachate management. Photovoltaic panels usually have a 25-year performance [17] warranty which can be extended to 30 years based on working and weather condition. Where as inverters needs to be changed at least once. Typically, inverters come with a standard of 5-year or 10-year warranty and they life time can be expected to last 10–15 years. Annual check on the Wire and rack connections should be performed [17]. It is important to have safe routines for maintenance, good spare part maintenance and good repair readiness.

The operation of both solar panels and inverters will lead to their reduced performance over time, regardless of maintenance even if it is used under optimal conditions. In case of solar panels, a number of aspects can affect how fast the efficiency drops. Some of these are manufacturer, model, type, climate and assembly. "In a meta-analysis, efficiency was seen to decrease by 0.8-0.9% per year for crystalline panels" [12]

5.5 Summary of Technical Challenges and Solutions

The table 5.2 summarises the challenges and possible solution while installing the photovoltaic plant at Kikås landfill if any of the mentioned challenges reveal themselves during a Geo technical survey,

Table 5.2: Challenges and potential solutions [24]

Complication	Challenges	Potential remedy
Side slope	• Anchoring solar panels • Storm water • Soil Erosion • Snow and wind loading	• Light weight solar panel mounting system • Re-grading and soil amendments
Settlement	• System foundations • Gas and leachate piping • Infiltration • Deformation in the landfill cap	• Fixed tilt mounting structures • Light weight shallow footings and ballast • Using Renusol console + mounting technology
Weather conditions	• System foundation • Electric Installation	• Robust mounting structure • Avoidance of side slope placement
Maintainance	• Survey to analyse landfill settlements • Vegetation management • Checking soil erosion	• Panel height allowing for routine landscaping practices • Spacing among the solar array

5.6 Life Cycle Assessment

The LCI data used and the results obtained from the LCA is described under this section,

5.6.1 Life cycle Inventory

The Life cycle inventory phase involves the data collection and compilation that is for the LCA study. Here the LCA model has been built for Modules, inverter and mounting system is made separately and combined at the end to complete the analysis.

5.6.1.1 Solar Panel

The material and energy flows for the production of multi crystalline solar panel are investigated and complied here. The data for this analysis is obtained from the study made by M.J. de Wild-Scholten and E.A. Alsema [33] and also from the IEA report on "Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems" [9] and from the ecoinvent database.

The LCI for the multi crystalline silicon modules includes the poly-crystalline silicon feed stock purification, crystallisation, wafering, cell processing, and module assembly. However,the data do not represent the state-of-the art Si modules with a wafer thickness of 200 micro meter [9]. The Life cycle inventory data for photovoltaic module production is shown in Appendix A.

5.6.1.2 Inverter, Mounting and Electric Installation

The LCI data for the manufacturing of inverter and mounting i.e Balance of system components is obtained from ecoinvent data base. The data set representing the inverter production has been modified to represent the data equivalent for the manufacturing the 125KW capacity inverter by assuming linear proportionality. See appendix B

The data used for the mounting production represents the installation of the mounting system needed for the open ground mounting of 1m^2 PV panel. This data-set starts from the needed components for the photovoltaic mounting system. The data-set also includes data on packaging materials and the protection fence materials. However, this data-set doesn't include the electricity use for erection of the mounting system. See appendix C.

The LCI data-set for the electric installation represents the material required for the production of different components of the electric installation for a 0.210kWp photovoltaic power plant namely the fuse box, electric cables, and the electric meter. Please refer Appendix 3 for the LCI data. See appendix D.

5.6.2 Life cycle Impact Analysis

The life cycle impacts were assessed in 4 categories. In this chapter, the environmental impact of each process involved in the manufacturing and installation of PV system components is presented. The Table 5.3 shows the life cycle impact per kWh of electricity generated.

Table 5.3: Life cycle Impact assessment results per functional unit

Impact category	Unit	Base case
Global Warming Potential - GWP100	kg CO_2 eq./kWh	0.0751
Acidification potential	kg SO_2 eq./kWh	0.0004
Ozone layer depletion	kg CFC-11 eq./kWh	4.68E-09
Human toxicity	kg 1,4-dichlorobenzene eq./kWh	0,143

The table 5.4 shows the quantified results for each impact category for different PV system components. And from the results it is clear that major portion impact arises from production and transportation of the solar panel due to the electricity mix and burning of fossil fuels during transportation.

Table 5.4: Impact arising from manufacturing and transportation of PV system components

Impact Category/ Process Flow	Global Warming Potential	Acidification Potential	Ozone Layer Depletion	Human Toxicity
Reference Unit	kg CO_2 eq.	kg SO_2 eq.	kg CFC-11 eq.	kg 1,4-dichlorobenzene eq.
Solar Panel	5.11E+06	2.66E+04	3.32E-01	9.47E+06
Mounting	1.62E+06	8.92E+03	8.50E-02	2.62E+06
Inverter	3.09E+04	5.00E+02	4.13E-03	7.53E+05
Diesel	3876.53189	28.95122	0.00066	3.58E+03
Electric installation	56.24901	2.09577	9.05E-06	7.69E+02
Electricity	11.73891	0.06793	9.81E-06	5.19E+01
Total	6.77E+06	3.61E+04	4.21E-01	1.29E+07

5.6.2.1 Sensitivity Analysis

The sensitivity analysis is conducted for different percentage of recycled material used during the production phase of PV system components. As mentioned in the limitations, recycling of silicon used in PV panel is not included in the study hence it is not one of the recycled material used in manufacturing of PV system components. Aluminium and steel are two recycled material that are used in the production phase to analyse how the impact results will vary depending on the amount recycled material used instead of virgin aluminium and steel. But recycling of other materials such as glass, copper, brass is included in the analysis. But none of them were considered to be used during the production of PV system components instead of virgin materials due to the lack of data .

An observation can be made from the following results. Reduction in environmental impact is observed in each of the chosen impact categories due to the usage of recycled aluminium and steel during the production of solar panel and mounting system. But a significant reduction in impact is observed in production of mounting since the amount of aluminium used is much higher compared to other PV system components. Hence higher the recycled aluminium lesser is the impact generated from mounting system. The environmental impact from the PV system components other than solar panel and mounting system remains same since they are manufactured by virgin material. The following tables represent the results for the chosen impact categories in this study,

1. **Global Warming Potential**

Table 5.5: Global Warming potential in kg CO_2 eq.

Process	Solar Panel	Mounting	Inverter	Diesel	Electric installation	Electricity
80% recycled	4.57E+06	3.72E+05	3.09E+04	3876.531	56.249	11.738
50% recycled	4.75E+06	7.88E+05	3.09E+04	3876.531	56.242	11.738
Base case	5.11E+06	1.62E+06	3.09E+04	3876.531	56.249	11.738

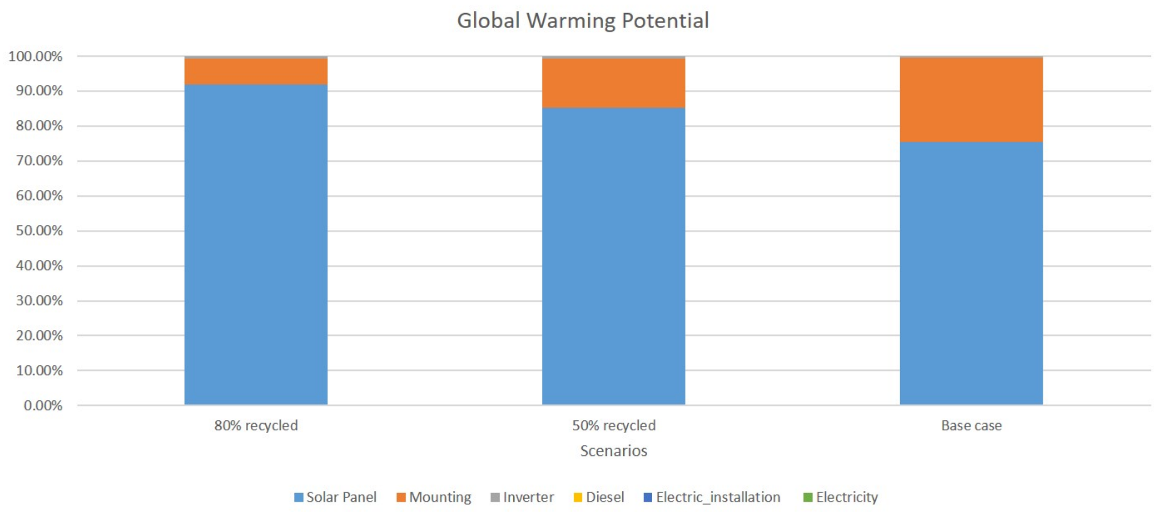

Figure 5.5: Global Warming Potential

2. **Acidification Potential**

Table 5.6: Acidification Potential in kg SO_2 eq.

Process	Solar Panel	Mounting	Inverter	Diesel	Electric installation	Electricity
80% recycled	2.24E+04	2.22E+03	5.00E+02	28.95122	2.09577	0.06793
50% recycled	2.38E+04	4.67E+03	5.00E+02	28.95122	2.09571	0.06793
Base case	2.66E+04	8.92E+03	5.00E+02	28.95122	2.09577	0.06793

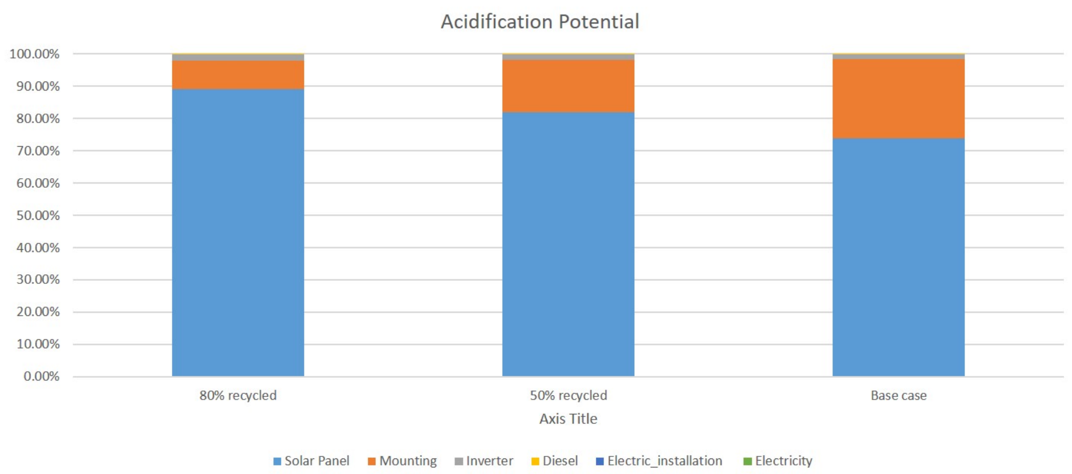

Figure 5.6: Acidification Potential

3. **Ozone Layer Depletion**

Table 5.7: Ozone Layer Depletion in kg CFC-11 eq.

Process	Solar Panel	Mounting	Inverter	Diesel	Electric installation	Electricity
80% recycled	2.72E-01	2.33E-02	4.13E-03	0.00066	9.05E-06	9.81E-06
50% recycled	2.93E-01	4.37E-02	4.13E-03	0.00066	9.05E-06	9.81E-06
Base case	3.32E-01	8.50E-02	4.13E-03	0.00066	9.05E-06	9.81E-06

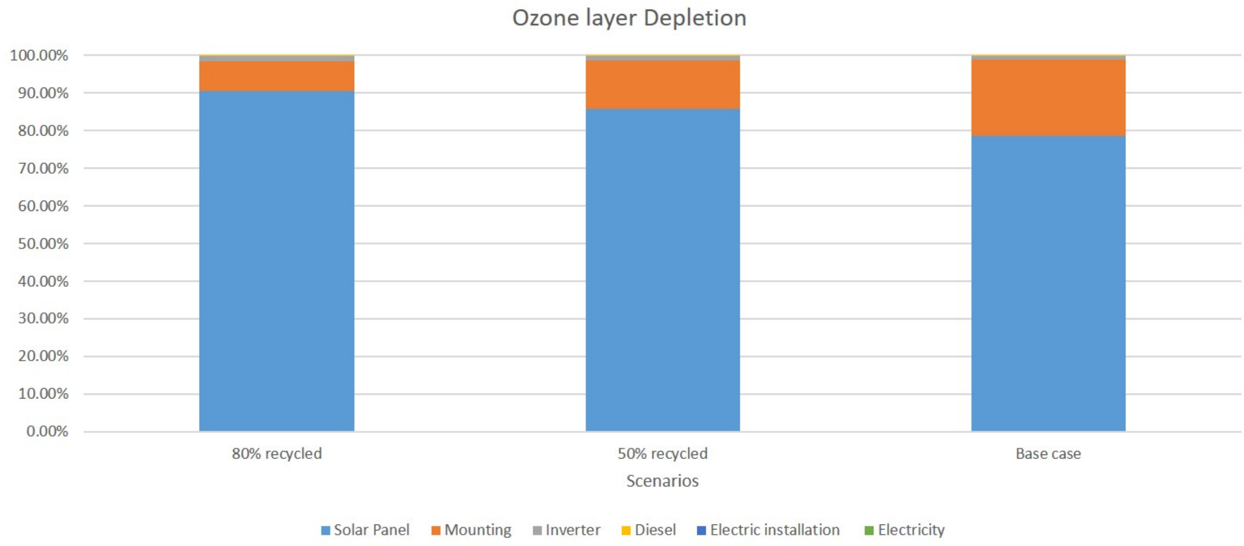

Figure 5.7: Ozone Layer Depletion

4. **Human Toxicity**

Table 5.8: Human Toxicity in kg 1,4-dichlorobenzene eq.

Process	Solar Panel	Mounting	Inverter	Diesel	Electric installation	Electricity
80% recycled	6.15E+06	2.04E+05	7.53E+05	3.58E+03	7.69E+02	51.91198
50% recycled	7.69E+06	1.20E+06	7.53E+05	3.58E+03	7.69E+02	51.9119
Base case	9.47E+06	2.62E+06	7.53E+05	3.58E+03	7.69E+02	51.91186

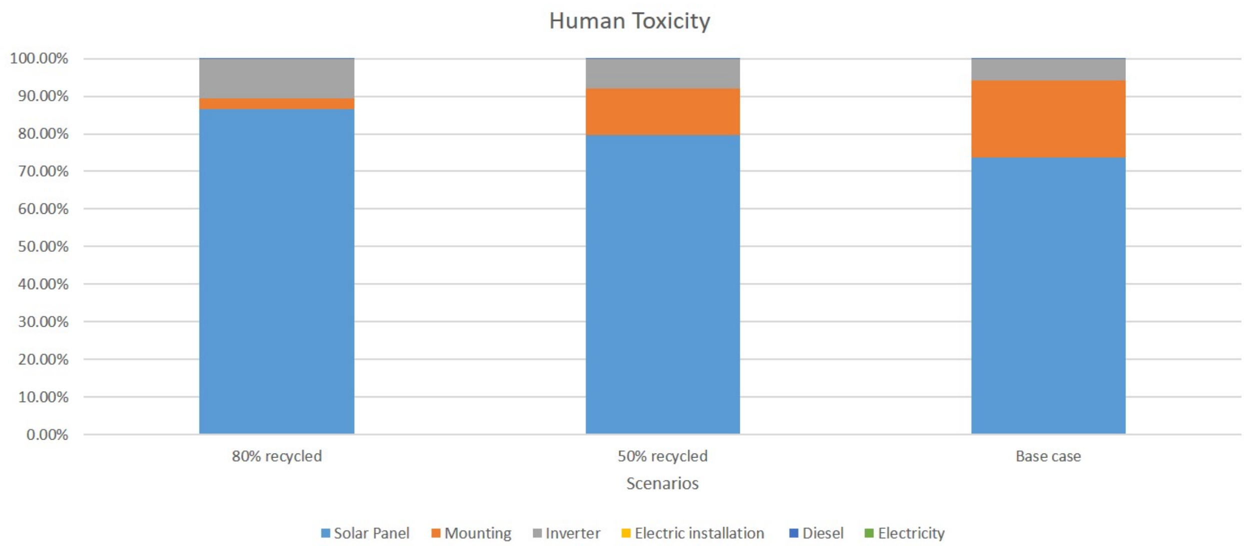

Figure 5.8: Human Toxicity

5.7 Economic calculation

The following section describe the analysis performed to determine the economic feasibility of investing in the solar photovoltaic plant of 3MW capacity. The Levelised cost of electricity produced from the PV plant will be 1.66 SEK/kWh (0.19$/kWh)The following sections describe the revenue generated from the PV plant over its life time for every year. One observation can be made in the following graphs and that is there is drastic change in revenue after year 10 and that is because of using projected electricity price profile as a base from the year 11 to year 30.

5.7.1 Scenario 1

Year 1 to 10 based on 2015 electricity price profile and from year 11 to 30 based on projected 2030 electricity price profile with no collaboration.

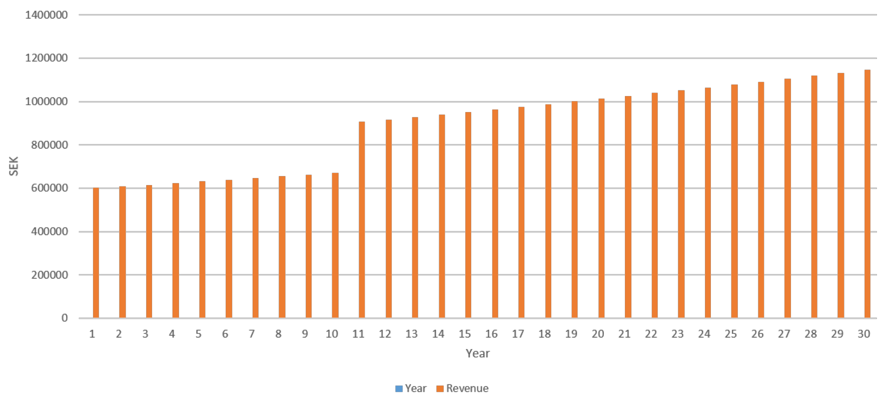

Figure 5.9: Yearly Revenue for Scenario 1

5.7.2 Scenario 2

Year 1 to 10 based on 2015 electricity price profile and from year 11 to 30 based on projected 2030 electricity price profile with collaboration.

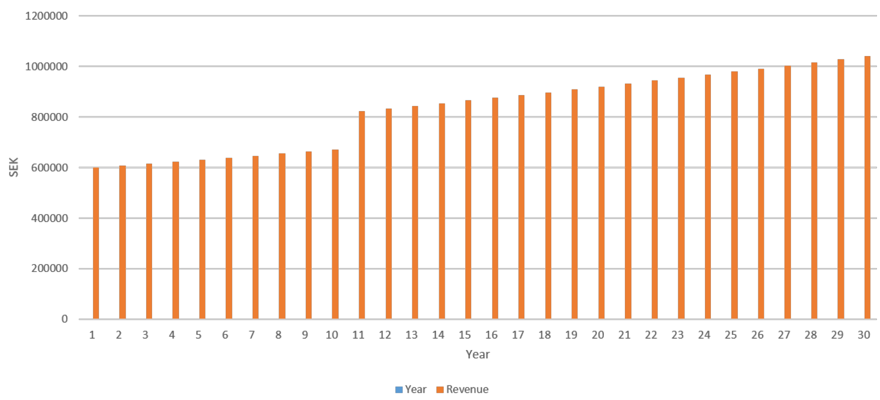

Figure 5.10: Yearly Revenue for Scenario 2

5.7.3 Scenario 3

Year 1 to 10 based on 2018 electricity price profile and from year 11 to 30 based on projected 2030 electricity price profile with no collaboration.

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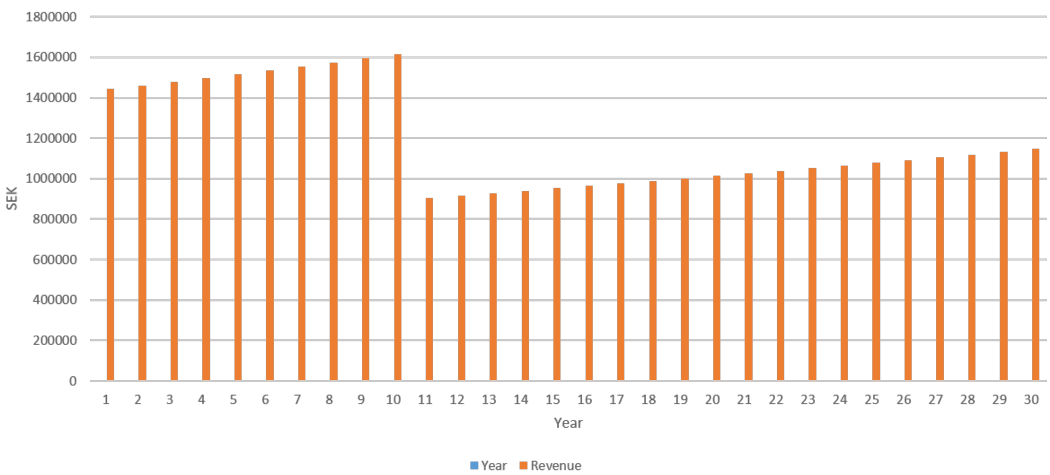

Figure 5.11: Yearly Revenue for Scenario 3

5.7.4 Scenario 4

Year 1 to 10 based on 2018 electricity price profile and from year 11 to 30 based on projected 2030 electricity price profile with collaboration.

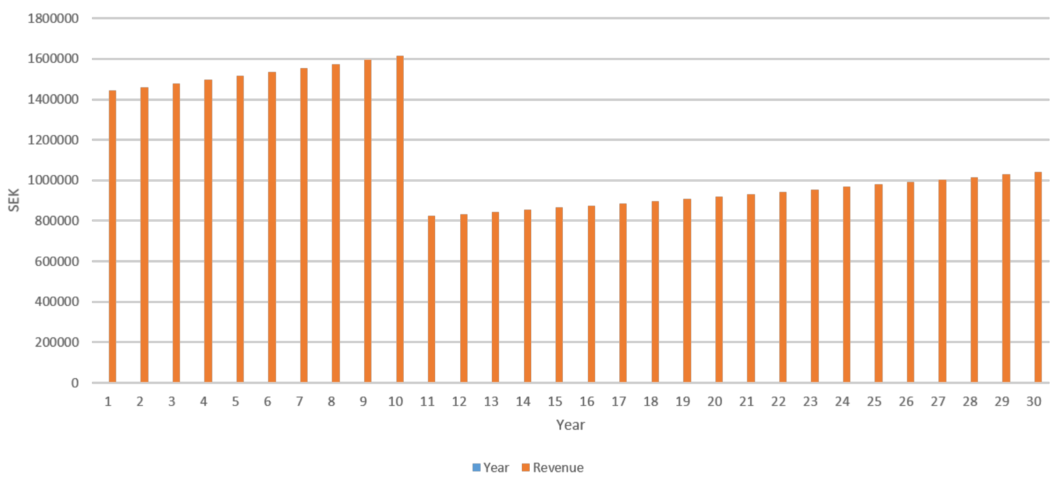

Figure 5.12: Yearly Revenue for Scenario 4

5.7.5 Comparison of scenarios

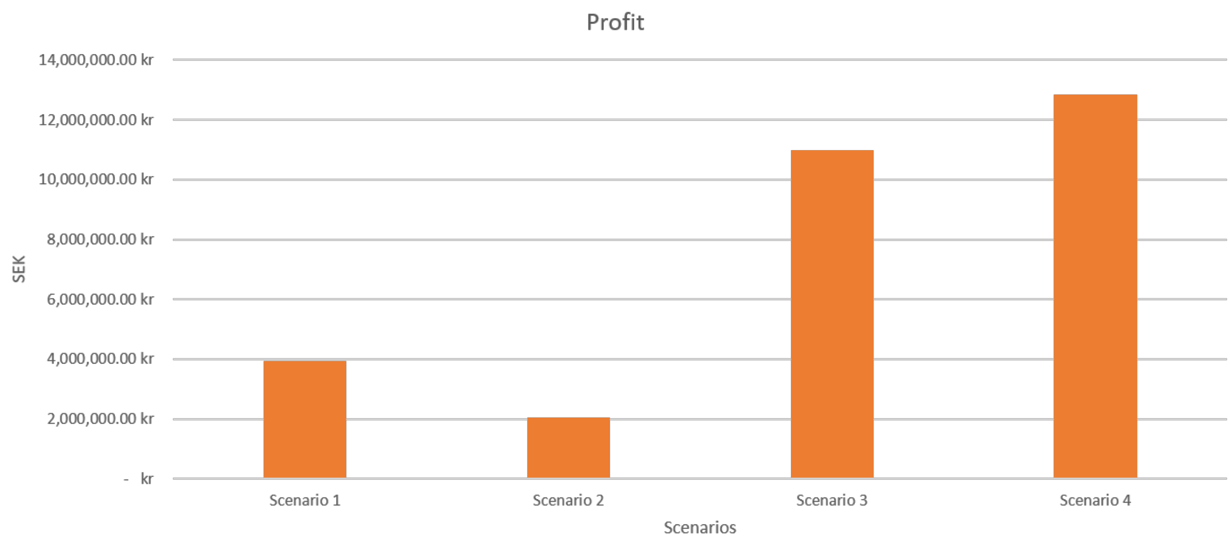

Figure 5.13: Profit

The figure 5.13 shows that the profit for the scenarios built by using 2015 electricity prices generates less revenue when compared to scenarios that are based on 2018 meaning that the electricity price profile was better in the year 2018 from a generator perspective. Since the scenario 1 and 2 are based on 2015 electricity price profile, the profit is much less compared scenarios 3 and 4 (based on 2018 electricity price profile). The figure 5.13 clearly shows that scenario 4 being the Optimistic case.

6
Discussion

As explained under results there are several technical challenges that needs to addressed. Thus a Geo-technical survey needs to be conducted to determine the condition and suitability of the landfill site to install a PV plant. Conducting the survey will provide use full information on side slope stability, load bearing capacity of the landfill cap, identify which location on the landfill needs reinforcement to handle the wind loads and other necessary information. Gathering such information will define constraints while choosing the mounting technology that can be used to install the PV plant.

In order to verify the results from LCA, here a comparison is made with the previous studies. A study made by [13] indicates that area under an irradiation of 900–1000kWh/yr (Similar irradiation to Sweden), the GHG emission rate from PV system was about 0.08 kgCO_2- eq./kWh with a lifetime of 30 years. Also, the results depends on the background system i.e electricity mix of the region where the PV system components are manufactured and material input. For example, the Belgian electricity has a relatively low GWP (0.33 kgCO_2-eq/kWh) due to fact that 55% of the electricity in Belgium is produced by nuclear power plants [13] if the PV system are manufactured in such system then the environmental impact will be lower.The difference in GWP of 1 kWh of electricity between multi c-Si type PV system and fossil fuel is significant. A natural gas power plant has a GWP of 0.53 kgCO_2-eq/kWh where the GWP of a PV-system with a life time of 30 years is 0.08 kgCO_2-eq/kWh. The results from this study shows that the GWP of the PV system is 0.075 kgCO_2- eq./kWh and the PV plant is situated in the area with irradiation around 1000 KWh/yr.

At the end the decision on whether to install the PV plant or not depends on the profit that can be estimated from the PV plant during its life time. Based on the results from each scenario, it is profitable to invest in the PV plant. However, this is an estimation based on the historic electricity prices and modelled electricity prices. In reality the revenue generated could deviate from these results. Also, one of the assumption is that electricity prices is modelled in a way that it will only increase due inflation but in reality it could be lower than the estimated electricity prices for few years which leads lower revenue.

In the future work, the scope life cycle assessment can be expanded by including recycling of all the material in the PV system components assuming that the data is available. A sensitivity analysis by using different impact assessment methods is recommended for the future studies. In the economic analysis, electricity prices are modelled based on inflation but the accuracy of forecasting can be improved by using price elasticity during the calculation which will result in accurate prediction of revenue generated from the PV plant.

7
Conclusion

The major technical challenge is associated with the anchoring system. The anchoring system used to support the mounting structures plays a key role on the stability of the landfill cap. It can be concluded that the ground-penetrating oblique inserts anchoring system is a better alternative to both concrete based and Screw Type anchoring system since it weighs less and oblique inserts doesn't need to be penetrated deeper into the ground. Along, with those advantages it can withstand wind loads close what concrete foundation system can withstand.

The results from the LCA shows that the major portion of the impact is from the manufacturing and transportation of the solar panel but that could be reduced if a different photovoltaic technology can be used rather than the multi-crystalline solar panel. And the study uses the data for the concrete foundation based mounting structure so there is a potential here to reduce the environmental impact by choosing the "Ground-penetrating oblique inserts anchoring system" to mount the mounting structure instead of concrete foundation. Thus there could be lesser impact arising from the manufacturing and transportation mounting structures in reality.

A strategic decision about investing in PV plant should be made considering economic, environmental and social aspects. From the environmental perspective it is feasible since the plant will produce renewable energy and produces lesser environmental impact in comparison to fossil fuels. From an economic point of view it can be concluded that the investing in the PV plant is feasible given that all the scenarios leads to profit and the land resource that is available is free of cost. Mölndal Energi, as a renewable energy company can offer value to its customers by supplying them green energy and possibility to sell shares of their investment to the interested customers and create a revenue stream.

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A

Appendix: Describes the data Lifecycle inventory data for photovoltaic module production

Table A.1: Material and Energy flow for silica sand production

Input		
Flow	**Amount**	**Unit**
Heat, district or industrial, other than natural gas	0.2	MJ
sand	1.04	kg
output		
Flow	**Amount**	**Unit**
Silica Sand	1	Kg

Table A.2: Material and Energy flow Metallurgical grade silicon

Input		
Flow	**Amount**	**Unit**
charcoal	1.70E-01	kg
Coke	2.31E+01	MJ
electricity, medium voltage	1.10E+01	kWh
graphite	1.00E-01	kg
oxygen, liquid	2.00E-02	kg
petroleum coke	5.00E-01	kg
Silica Sand	2.70E+00	kg
silicone factory	1.00E-11	Item(s)
transport, freight train	6.90E-02	t*km
transport, freight, lorry 16-32 metric ton, EURO6	1.76E-01	t*km
transport, freight, sea, container ship	2.88E+00	t*km
wood chips, wet, measured as dry mass	5.50E-01	kg
Output		
Flow	**Amount**	**Unit**
Metallurgical grade silicon	1.00E+00	kg

Waste		
slag from metallurgical grade silicon production	2.83E-02	kg
Emissions to air		
Aluminium	1.75E-06	kg
Antimony	8.87E-09	kg
Arsenic	1.06E-08	kg
Boron	3.15E-07	kg
Cadmium	3.55E-10	kg
Calcium	8.76E-07	kg
Carbon dioxide, biogenic	1.82E+00	kg
Carbon dioxide, fossil	4.05E+00	kg
Carbon monoxide, fossil	1.56E-03	kg
Carbon monoxide, land transformation	7.01E-04	kg
Chlorine	8.87E-08	kg
Chromium	8.87E-09	kg
Cyanide	7.76E-06	kg
Fluorine	4.38E-08	kg
Hydrogen fluoride	5.65E-04	kg
Hydrogen sulfide	5.65E-04	kg
Iron	4.38E-06	kg
Lead	3.88E-07	kg
Mercury	8.87E-09	kg
Nitrogen oxides	1.10E-02	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	1.08E-04	kg
Particulates, 10 um	8.76E-03	kg
Potassium	7.01E-05	kg
Silicon	8.49E-03	kg
Sodium	8.76E-07	kg
Sulfur dioxide	1.38E-02	kg
Tin	8.87E-09	kg

Table A.3: Material and energy flow Ploy-crystalline (solar grade) silicon production

Input		
Flow	**Amount**	**Unit**
electricity, medium voltage	11	kWh
heat, district or industrial, natural gas	186	MJ
hydrochloric acid, without water, in 30% solution state	1.6017	kg
hydrogen, liquid	0.050139	kg
Metalurgical grade silicon	1.13	kg
silicone factory	1.00E-11	Item(s)
sodium hydroxide, without water, in 50% solution state	0.34819	kg
transport, freight train	0.0931	t*km
transport, freight, lorry 16-32 metric ton, EURO6	2.15	t*km
Output		
Flow	**Amount**	**Unit**
Polycrystalline Silicon	1	kg
Waste and Emissions		
AOX, Adsorbable Organic Halogen as Cl	1.26E-05	kg
BOD5, Biological Oxygen Demand	2.05E-04	kg
Chloride	0.035991	kg
COD, Chemical Oxygen Demand	0.00202	kg
Copper, ion	1.02E-07	kg
DOC, Dissolved Organic Carbon	9.10E-04	kg
Energy, waste heat, air	351	MJ
Iron, ion	5.61E-06	kg
Nitrogen	2.08E-04	kg
Phosphate	2.80E-06	kg
Sodium, ion	0.03379	kg
TOC, Total Organic Carbon	9.10E-04	kg
Zinc, ion	1.96E-06	kg

Table A.4: Material and Energy flows Wafer Production

Input		
Flow	**Amount**	**Unit**
acetic acid, without water, in 98% solution state	0.039	kg
acrylic binder, without water, in 34% solution state	0.00385	kg
adhesive, for metal	0.002	kg
alkylbenzene sulfonate, linear, petrochemical	0.24	kg
argon, liquid	1	kg
brass	0.00744	kg
dipropylene glycol monomethyl ether	0.3	kg
electricity, medium voltage	30	kWh
flat glass, uncoated	0.01	kg
heat, district or industrial, natural gas	3.96	MJ
helium	1.36E-04	kg
hydrochloric acid, without water, in 30% solution state	0.00272	kg
nitrogen	0.0533	kg
Polycrystalline Silicon	1.67	kg
Sand, quartz	21.1392	kg
silicon carbide	2.61	kg
sodium hydroxide, without water, in 50% solution state	0.0149	kg
Sodium lauryl sulfate	14.0928	kg
steel, low-alloyed	0.797	kg
tap water	0.00641	kg
transport, freight train	3.86	t*km
transport, freight, lorry 16-32 metric ton, EURO6	0.846	t*km
triethylene glycol	2.168	kg
water, deionised	64.9	kg
wire drawing, steel	0	kg
wire drawing, steel	0.805	kg
Output		
Flow	**Amount**	**Unit**
Wafer	1	m2
Waste and Emissions		
AOX, Adsorbable Organic Halogen as Cl	0	kg
BOD5, Biological Oxygen Demand	0.0295	kg
Cadmium, ion	1	kg
COD, Chemical Oxygen Demand	0.0295	kg
DOC, Dissolved Organic Carbon	0.0111	kg
Heat, waste	74.9	MJ
Nitrogen oxides	0	kg
TOC, Total Organic Carbon	0.0111	kg
waste, from silicon wafer production	3.96	kg

Table A.5: Material and Energy flows for Multi crystalline Solar cell production

input		
Flow	**Amount**	**Unit**
acetic acid, without water, in 98% solution state	4.42E-05	kg
ammonia, liquid	0.00892	kg
argon, liquid	4.01E-04	kg
calcium chloride	0.0315	kg
electricity, medium voltage	14.4	kWh
ethanol, without water, in 99.7% solution state, from fermentation	9.98E-06	kg
heat, district or industrial, natural gas	0.247	MJ
heavy fuel oil	5.06E-04	kg
hydrochloric acid, without water, in 30% solution state	0.00859	kg
hydrogen fluoride	0.403	kg
hydrogen peroxide, without water, in 50% solution state	4.52E-04	kg
isopropanol	8.10E-04	kg
lime, hydrated, packed	0.218	kg
metallization paste, back side	0.00534	kg
metallization paste, front side	0.00912	kg
nitric acid, without water, in 50% solution state	0.293	kg
nitrogen	1.35	kg
oxygen	0.00822	kg
phosphoric acid, fertiliser grade, without water, in 70% solution state	0.00863	kg
phosphoryl chloride	0.0274	kg
polystyrene, expandable	6.36E-06	kg
silicon tetrahydride	0.00261	kg
sodium hydroxide, without water, in 50% solution state	0.0707	kg
sodium silicate, without water, in 37% solution state	0.00117	kg
solvent, organic	0.0113	kg
transport, freight train	0.394	t*km
transport, freight, lorry 16-32 metric ton, EURO6	0.522	t*km
Wafer	1.04	m2
Water, cooling, unspecified natural origin,RER	0.916	m3
water, deionised	251	kg
Output		
Flow	**Amount**	**Unit**
Solar cell	1	m2
Waste and Emissions		
Hydrogen chloride	4.16E-06	kg
hydrogen fluoride	6.90E-04	kg
Lead	7.73E-06	kg
Particulates, unspecified	4.16E-05	kg
Photovoltaic cell waste	0.00431	kg

Silicon	3.17E-08	kg
Silicon dioxide	1.13E-06	kg
Silver	7.73E-06	kg
sodium hydroxide	7.56E-07	kg
tin	7.73E-06	kg
VOC, volatile organic compounds	0.00302	kg

Table A.6: Material and Energy flows for Module (Production of capacity 210 W_P)

Input		
Flow	**Amount**	**Unit**
1-propanol	0.008137783	kg
acetone, liquid	0.012957699	kg
aluminium alloy, AlMg3	2.629135995	kg
copper	0.112678685	kg
corrugated board box	1.195	kg
electricity, medium voltage	4.71	kWh
ethylvinylacetate, foil	1.001599424	kg
flux, for wave soldering	0.00876382	kg
glass fibre reinforced plastic, polyamide, injection moulded	0.187791143	kg
heat, district or industrial, natural gas	4.8659	MJ
hydrogen fluoride	0.0624	kg
isopropanol	1.47E-04	kg
lead	0.004	kg
lubricating oil	0.001606739	kg
methanol	0.0162	kg
nickel, 99.5%	1.63E-04	kg
photovoltaic panel factory	4.00E-06	Item(s)
polyethylene terephthalate, granulate, bottle grade	0.346	kg
polyphenylene sulfide	0.2	kg
polyvinylfluoride	0.112	kg
potassium hydroxide	0.0514	kg
silicone product	0.122	kg
soap	0.0116	kg
solar glass, low-iron	10.07798802	kg
Solar_cell	0.935	m2
tap water	27	kg
tempering, flat glass	10.07798802	kg
tin	0.0129	kg
transport in t*km	209	t*km
transport, freight train	42.5	t*km
transport, freight, lorry 16-32 metric ton, EURO6	5.85	t*km
Output		
Flow	**Amount**	**Unit**
Solar Module	1	m2
Waste and Emissions		
aluminium scrap, post-consumer	2.13*Alluminium_recyc	kg
Carbon dioxide, fossil	0.0218	kg

copper scrap, sorted, pressed	0.103*Copper_recyc	kg
Heat, waste	13.4	MJ
municipal solid waste	0.03	kg
Photovoltaic cell waste	0.015	kg
Silicon	0.003	kg
silicon scrap	0.979	kg
Slags and ashes	0.0547	kg
waste glass	20*Glass_recyc	kg
waste incineration of glass/inert material	20*0.1	kg
waste paperboard, sorted	0.763	kg
waste plastic, mixture	1.68593	kg
waste polyvinylfluoride	0.110395687	kg

B

Appendix : Describes the data Life cycle inventory data for Inverter

Table B.1: Life cycle inventory data for Inverter

Input		
Flow	**Amount**	**Unit**
alkyd paint, white, without solvent, in 60% solution state	5.344517873	kg
aluminium, cast alloy	31.8241746	kg
capacitor, electrolyte type, 2cm height	0.062190754	kg
capacitor, film type, for through-hole mounting	0.082840028	kg
capacitor, tantalum-, for through-hole mounting	0.00558745	kg
copper	81.38243124	kg
corrugated board box	3.303883776	kg
diode, glass-, for through-hole mounting	0.011417834	kg
electric connector, wire clamp	11.51500669	kg
electricity, medium voltage	1112.096996	kWh
fleece, polyethylene	0.072879789	kg
glass fibre reinforced plastic, polyamide, injection moulded	17.24821678	kg
glass fibre reinforced plastic, polyester resin, hand lay-up	10.68903575	kg
inductor, ring core choke type	0.085269354	kg
injection moulding	17.24821678	kg
integrated circuit. logic type	0.006802114	kg
lubricating oil	214.0236475	kg
metal working factory	3.29E-07	Item(s)
polyethylene. high density. granulate	5.344517873	kg
polystyrene foam slab	0.388692209	kg
printed wiring board, for through-hole mounting, Pb containing surface	0.027281335	m2
printed wiring board, for through-hole mounting, Pb free surface	0.027281335	m2
resistor, metal film type, through-hole mounting	0.001214664	kg
section bar extrusion, aluminium	31.8241746	kg
sheet rolling, steel	349.3371228	kg
steel, low-alloyed, hot rolled	349.3371228	kg
transistor, wired, small size, through-hole mounting	0.00923144	kg
wire drawing, copper	81.38243124	kg
Output		
Flow	**Amount**	**Unit**
Inverter_125KW	1	Item(s)
used printed wiring boards	11.87114593	kg
Waste		
waste mineral oil	214.0236476	kg
waste paperboard, unsorted	3.303883776	kg
waste plastic, industrial electronics	55.87450503	kg
waste polyethylene	0.388692209	kg
waste polystyrene	0.388692209	kg

C

Appendix : Describes the data Life cycle inventory data for Mountings

Table C.1: Life cycle inventory data for Mounting system

Input		
Flow	**Amount**	**Unit**
aluminium, wrought alloy	3.46760	kg
concrete, normal	0.000472	m3
corrugated board box	6.95E-04	kg
corrugated board box	0.059	kg
corrugated board box	0.0155	kg
polyethylene, high density, granulate	7.92E-04	kg
polystyrene, high impact	0.00396	kg
reinforcing steel	6.32	kg
section bar extrusion, aluminium	3.47	kg
section bar rolling, steel	5.35823	kg
steel, chromium steel 18/8, hot rolled	0.21781	kg
transport, freight train	5.14	t*km
transport, freight, lorry 16-32 metric ton, EURO6	0.217	t*km
wire drawing, steel	0.95838	kg
zinc coat, coils	0.09583	m2
zinc coat, pieces	0.13591	m2
Output		
Flow	**Amount**	**Unit**
Mountings	1	m2
aluminium scrap, post-consumer	3.4676	kg
scrap steel	6.53443	kg
Waste and Emissions		
waste incineration of ferro metals	6.53443	kg
waste paperboard, sorted	0.07519	kg
waste polyethylene, for recycling, sorted	0.07524	kg
waste polyethylene/polypropylene product	7.92E-04	kg
waste polystyrene isolation, flame-retardant	0.00396	kg
waste reinforced concrete	7.44925	kg

D

Appendix : Describes the data Life cycle inventory data for Electric Installation

Table D.1: Life cycle inventory data for Electric Installation

Input		
Flow	**Amount**	**Unit**
brass	0.00033	kg
brass	1.67781E-06	kg
copper	0.18218	kg
epoxy resin, liquid	5.838E-06	kg
epoxy resin, liquid	2.771E-05	kg
nylon 6	0.00258	kg
nylon 6	0.00127	kg
polycarbonate	3.353E-05	kg
polyethylene, high density, granulate	0.17431	kg
polyvinylchloride, bulk polymerised	0.01105	kg
steel, low-alloyed, hot rolled	0.01300	kg
wire drawing, copper	0.18218	kg
zinc	0.00067	kg
Output		
Flow	Amount	Unit
photovoltaic plant, electric installation	1	Item(s)
scrap copper	0.00033	kg
scrap steel	0.01367	kg
waste electric wiring	0.36035	kg
waste polyethylene/polypropylene product	6.711E-05	kg
waste polyvinylchloride	0.01105	kg

E
Tripled layer Business Model

Key partners

- Municipality of Mölndal.
- Solar panel manufacturers.
- External consultants.
- Waste management department

Key Activities

- Installing the solar plant
- Regular inspection of the land stability.

Value Proposition

- Supply renewable energy to its customers
- Secondary life to landfill
- Solidifies the statement of "Mölndal Energi being the first renewable energy company"

Customer relations

- Provide membership.
- Special memberships to those who buy the shares if they are made available.

Communication channel

- Website
- Regular mail update
- Customer service hot line.
- Social media

Customer segments

- Households in Mölndal and surrounding municipalities.
- Offices.
- May be industries.

Cost structure

- Main cost is in buying the solar panels and other equipment (Material for mounting, inverters)
- Cost involved in as salaries to employees
- Payment to consultants and contractors
- Advertisement case in case of potential possibility.
- Grid connection cost.

Revenue

- Main revenue is generated from selling the generated electricity
- Revenue from selling the shares (not yet decided)
- Revenue from selling the solar panels at their EOL for their secondary use if they are intact or from recycling them.

Figure E.1: Economic layer of the tripled layered business model

Supplies and outsourcing

- Supply of necessary solar panels
- Other PV system components such as inverters, mounting system, electric installation.
- Transmission lines and their instalment.

Production

- Carbon footprint during the production of solar panels
- Carbon footprint of manufacturing the inverters and transmission lines.

Materials

Material required to build the solar park and their impact on environment (LCA).

Functional Value

Environmental impact of the main service or product

End of Life

Environmental impact of EOL solar panels (landfill or recycle or recovery of materials)

Distribution

Transmission lines to transfer electricity and its environmental impact.

Use Phase

Environmental impact during its usage or avoided environmental impact.

Environmental Impact

- Risk of damaging the cap of the land scape.
- Carbon footprint of manufacturing the solar panels
- Carbon footprint due to landfill and recycling of EOL solar panels.
- Environmental Impact during the use phase.

Environmental Benefits

- Replace electricity from fossil base generation.
- Clean energy generation.
- Less carbon footprint in its lifetime.

Figure E.2: Environmental layer of the tripled layered business model

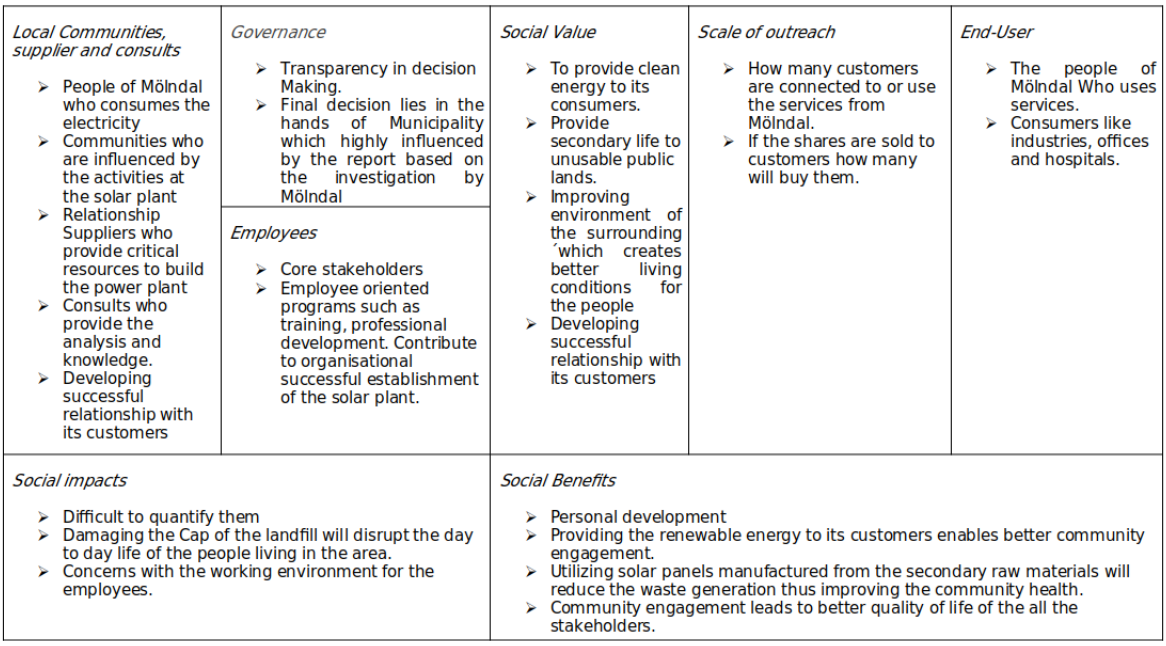

Figure E.3: Social layer of the tripled layered business model

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