Implementation of solar energy at ESS for power supply and waste heat recycling

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Abstract

The advanced research that is being carried out in different science fields today requires advanced technologies; for the study of distant places and hidden elements of our universe tools like The Hubble Telescope, Voyager 2 and the Very Large Array has been to great use. In the same way, a neutron source and its instruments enable scientist to see and understand basic atomic structures and forces. It can be compared with a giant microscope for the study of different materials. The European Spallation Source, ESS, is a multidisciplinary research facility that is being built in Lund, Sweden. The facility, that will host the most intense pulsed neutron beams in the world, is a significant step forward in the science of everyday life.

Even though ESS will contribute greatly to the future research, the facility will be a large power consumer increasing the total power consumption in Lund with almost 30 %. To reduce the environmental impact ESS is committed to an energy concept where the use of new efficient technologies, waste heat recycling and renewable energy will result in a carbon-neutral science facility.

Due to the hazards present at the ESS site, there will be large amounts of land serving the purpose as a barrier to the citizens of Lund. This land cannot, for obvious reasons, be used for agriculture or habitation and will therefore remain unused. However, due to ESS commitment to be carbon neutral, this thesis aims to study the possibility of implementing a solar field on some of this otherwise unused land. This thesis shows that there is enough available solar irradiation and land area to implement a solar field that completely could cover the energy needs of the ESS linear accelerator. The thesis also presents a possible connection from the solar field to ESS where power could be exchanged between the solar field, ESS and the utility grid.

Another aim of the project is to investigate the concept of also extracting thermal energy from the solar field using existing technologies, which involves letting water flow at the back of the panels to extract heat. The heated water could then be used for district heating or in food production systems. The thesis shows that the amount of thermal waste heat energy extracted from ESS could almost double by also collecting the available thermal energy from the solar field.

Keywords: Waste heat recycling, heat extraction, Photovoltaic thermal hybrid collectors, ESS modulators, maximum power point tracking
Acknowledgments

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At last we would like to show our greatest appreciation to Getachew Darge and Johan Björnstedt, who has helped us with various practical implementation problems as well as overall guidance during the thesis project.
## Abbreviations

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<tr>
<td>ESS</td>
<td>The European Spallation Source</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>MBIOT</td>
<td>Multi-Beam Induction Output Tube</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>PV/T</td>
<td>Photovoltaic/Thermal</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>FPC</td>
<td>Flat-Plate Collector</td>
</tr>
<tr>
<td>PVGIS</td>
<td>Photovoltaic Geographical Information System</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracking</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse-Width Modulation</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>AFE</td>
<td>Active Front End</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated-Gate Bipolar Transistor</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Metal Oxide Semiconductor Field Effect Transistor</td>
</tr>
<tr>
<td>EMF</td>
<td>Electromotive Force</td>
</tr>
</tbody>
</table>
Nomenclature

Table 2: List of Nomenclature

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<th>Explanation</th>
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<tbody>
<tr>
<td>$E_p h$</td>
<td>photon energy</td>
</tr>
<tr>
<td>$E_{ph}$</td>
<td>bandgap energy</td>
</tr>
<tr>
<td>I</td>
<td>solar panel current</td>
</tr>
<tr>
<td>$I_0$</td>
<td>dark saturation current</td>
</tr>
<tr>
<td>V</td>
<td>solar panel voltage</td>
</tr>
<tr>
<td>q</td>
<td>charge on an electron</td>
</tr>
<tr>
<td>k</td>
<td>Boltzmann’s constant</td>
</tr>
<tr>
<td>T</td>
<td>absolute temperature</td>
</tr>
<tr>
<td>n</td>
<td>solar panel ideality factor</td>
</tr>
<tr>
<td>$I_L$</td>
<td>light-generated current</td>
</tr>
<tr>
<td>$I_{sc}$</td>
<td>short circuit current</td>
</tr>
<tr>
<td>$V_{oc}$</td>
<td>open circuit voltage</td>
</tr>
<tr>
<td>$W_p$</td>
<td>maximum power output</td>
</tr>
<tr>
<td>$\eta$</td>
<td>solar panel efficiency</td>
</tr>
<tr>
<td>$K_L$</td>
<td>constant dependent of the semiconducting material in a solar cell</td>
</tr>
<tr>
<td>$E_{thermal}$</td>
<td>thermal energy collected from the PV/T prototype</td>
</tr>
<tr>
<td>m</td>
<td>mass of a material</td>
</tr>
<tr>
<td>C</td>
<td>specific heat capacity of a material</td>
</tr>
<tr>
<td>$W_{thermal}$</td>
<td>thermal power collected from the PV/T prototype</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>the heat transfer through a flat solid material</td>
</tr>
<tr>
<td>$k$</td>
<td>thermal conductivity of a material</td>
</tr>
<tr>
<td>A</td>
<td>surface area</td>
</tr>
<tr>
<td>$\Delta \theta$</td>
<td>temperature difference at the top and bottom surfaces of a flat solid material</td>
</tr>
<tr>
<td>x</td>
<td>thickness of a flat solid material</td>
</tr>
<tr>
<td>$S_f(t)$</td>
<td>solar panel shadow factor as a function of time</td>
</tr>
<tr>
<td>$\theta$</td>
<td>panel inclination angle</td>
</tr>
<tr>
<td>$\alpha(t)$</td>
<td>altitude of the sun over the horizon as a function of time</td>
</tr>
<tr>
<td>$U_f$</td>
<td>utilization factor of a solar field</td>
</tr>
<tr>
<td>$A_e(t)$</td>
<td>panel effective collecting area as a function of time</td>
</tr>
<tr>
<td>$A_f$</td>
<td>total solar field area</td>
</tr>
<tr>
<td>$d\phi$</td>
<td>varying magnetic flux</td>
</tr>
<tr>
<td>N</td>
<td>number of turns of transformer</td>
</tr>
<tr>
<td>S</td>
<td>cross-sectional area of the core</td>
</tr>
<tr>
<td>B</td>
<td>magnetic flux density</td>
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1 Introduction

This introductory chapter includes the background required to motivate the thesis project; a short introduction to the ESS facility in Lund and the ESS vision about a carbon-neutral science facility and the possible measures to reach this vision. Further, the reader is introduced to the project goals and restrictions.

1.1 The European Spallation Source

The European Spallation Source, ESS, is a multidisciplinary research facility that is being hosted by Sweden and Denmark, involving 17 European countries. The center, that is being built in Lund, will consist of an accelerator–based neutron source that will provide the most intense pulsed neutron beams in the world providing new opportunities for researchers in the fields of material sciences, energy and fundamental physics, just to mention a few. [1]

1.2 Energy concept

One of the main motivations for Sweden to host the project is the commitment of ESS to be the first carbon-neutral large scale science facility in the world. One of the cornerstones to this energy concept is to invest in waste heat recycling, particularly waste heat from the new accelerator facility, utilized in form of heated cooling water. It is anticipated that the total amount of surplus energy is 254 GWh annually. In order to optimize the utilization of this excess heat energy, the cooling system is calculated to operate at three temperature levels; 30°C, 55°C and 80°C. The three different levels of hot water could then be utilized for appropriate applications; the high-temperature water can be transferred and recycled directly into the district heating network in Lund whereas the lower temperatures are suitable to be utilized in food production systems. [1]

Another cornerstone of the energy concept is the choice of advanced energy efficient technologies; the ESS linear accelerator will provide an average beam power of 5 MW and 97% of the beam power will be supplied by superconducting accelerating structures that operate at -271°C. At these temperatures and with the niobium metal lining in the walls of the accelerating structures, there is virtually no energy dissipated and almost all of the energy supplied to the accelerating structures is transformed into beam power. [1]

To power the accelerator, conventional power from the grid must be transformed into an energy form suitable for filling the superconducting structures. The type of energy used in the accelerator is electromagnetic waves oscillating at a frequency of 704 MHZ. At most other accelerator facilities, the conventional grid power is transformed into RF power using devices called klystrons. The efficiency of these klystrons in operations is typically 35%. However, engineers at the ESS Accelerator Division are developing a new type of RF power source called a multi-beam induction output tube (MBIOT). The goal for this RF power source is to have an operational efficiency over 65%. A source with this efficiency could reduce the amount of waste heat generated by the accelerator RF systems by almost 50%. [1]
The last cornerstone of the energy concept is the use of renewable energy. The amount of electrical energy required for the operation of ESS is approximately 270 GWh/year, this equates to an increased power consumption of 20-30% in Lund. Therefore ESS is committed to renewable power production to compensate for the increased energy consumption caused by the facility\textsuperscript{[1]}. The ESS energy concept is illustrated in Figure\textsuperscript{[1]}

1.3 Project aims and purpose

The ESS site occupies 74.2 hectares of land north-east of Lund and, because of the nature of hazards present at the site, most of this land remains unoccupied and serves the purpose as a barrier to the general public. This area can therefore not be used for agriculture or habitation. The idea to exploit solar energy, on some parts of this land, as a source of renewable energy has come to the scientists at ESS and LTH attention. However, since the solar cells are relatively inefficient at producing electricity the use of land would not be optimal. Therefore, to extract more energy per square meter, this thesis aims to study a conceptual idea where an implementation of a solar field at the ESS site could be used for two purposes; the photovoltaic energy produced by the PV panels could be used to power the accelerator and the radiant heat from the panels could be harvested through heated water. Because of the location of solar plants, either far from urban areas or in warm climates, most solar plants do not try to capture the thermal energy. The greatest obstacle to using solar heat energy is the logistics of a distribution system for supplying heat. However, because of Sweden’s commitment to reducing global warming and its climate, many communities in Sweden have adopted district heating systems to make substantial reductions in \( CO_2 \) emissions. Engineers at LTH and ESS have begun wondering if the district heating system in Lund could be utilized for distributing excess solar heat energy captured from photovoltaic panels that could be installed at ESS. The main objectives of this thesis could be summarized according to the following list:

- Investigate whether it is possible to extract useful heat energy from a PV panel in the form of heated water for industrial scale utilization. The experiments will be carried out using
1 INTRODUCTION

- a prototype panel created by the thesis students.
- Propose an electrical topology for the connection between the solar field and the ESS modulator.
- Propose a control system so that maximum power point tracking is possible.

1.4 Restrictions

Due to the limited amount of time for the thesis project the focus will be to simulate and analyze results from one PV/T panel prototype and the concept of extracting both heat and electric energy. Therefore this project only includes one proposition for a full field configuration. For the electrical connections between the solar field and ESS only one topology will be studied, the model will also be scaled down for laboratory purposes. Proposed improvements to the circuit as well as the PV/T prototype are included in the further work chapter at the end of the report.
2 Theory

The first part of this chapter contains the theory of solar electric energy required for the project; the available irradiation in Lund, a case study of a possible solar field configuration as well as the theory of photovoltaic cells. The last part of this chapter includes the theory of solar thermal energy; a case study of collecting thermal energy from the proposed solar field and the existing technologies that could be used.

2.1 Solar potential in Lund

Exploitation of solar energy in Sweden is commonly dismissed because of the high northern latitude. However, in spite of this, the solar potential in Lund is actually comparable to that of Solarpark Meuro in Germany, which generates some 166 MW peak power. Comparing with southern Europe and North Africa, which have the highest irradiation levels in the world, the solar potential in Lund constitute some 60% of the available irradiation in these places. The available irradiation in Lund and in the area of Solarpark Meuro is illustrated in Figures 2 and 3 which are recovered from the Photovoltaic Geographical Information System (PVGIS).

Figure 2: Colour scale representation of solar irradiation. [19, 20].

![Solar irradiation in southern Sweden.](image1)

![Solar irradiation in Germany.](image2) Solarpark Meuro is marked with a red square.

Figure 3: Comparison between southern Sweden and Solarpark Meuro
### 2.2 Possibility of a solar field at the ESS site

#### 2.2.1 Available land at the site

The ESS site occupies 74.2 hectares of land north-east of Lund and, because of the nature of hazards present at the site, most of this land remains unoccupied and serves the purpose as a barrier to the general public. This area can therefore not be used for agriculture or habitation, instead it could host a large solar field. The available land at the site, assuming utilization of all green space as well as building roofs and the accelerator shielding berm, is 41.2 hectares or 55% of the total site. The site, with possible locations for solar arrays, is shown in Figure 4.

![Figure 4: ESS site master plan with possible locations for solar arrays.](image)

#### 2.2.2 Field configuration and power output

Since the solar field will power the ESS modulators, the size of the solar field is limited by the peak power that the modulators can absorb. The current design of the accelerator calls for 35 modulators with each modulator rated at 650 kW giving a total power capability of 23 MW. Further description of the modulators is included in chapter 3. Though there are many ways to configure the solar field, only one configuration is studied in this thesis. However, some illustrative pictures of how different field configurations affects the power output are also included so that it is possible to conduct further studies on the subject.

The field will consist of rows of inclined PV panels directed towards the south. These rows are oriented along the east-west direction. To keep the adjacent rows of PV panels from shadowing each other, the rows must be separated by a certain distance. The fraction of the solar panel that will be shadowed by the panel to the south is a function of the panel inclination and the
altitude of the sun over the horizon. The function is presented below.

\[
S_f(t) = \frac{1}{U_f} \left( \frac{U_f \sin(\theta) - (1 - U_f) \cos(\theta) \tan(\alpha(t))}{\sin(\theta) + \cos(\theta) \tan(\alpha(t))} \right) > 0
\]  

(2.1)

Where \( \theta \) is the inclination of the PV panel and \( \alpha(t) \) is the altitude of the sun over the horizon as a function of time as illustrated in figure 5. The utilization factor, \( U_f \), is the ratio of the area of land occupied by PV panels compared to the total field area. The shadow factor, \( S_f(t) \), influences the effective collecting area, \( A_e(t) \), according to

\[
A_e(t) = A_f \frac{U_f}{\cos(\theta)} \left( 1 - S_f(t) \right)
\]  

(2.2)

Where \( A_f \) is the total field area. Note that the definition of the shadow effect in the above equations is a pessimistic estimate because the equations do not take diffuse light into account. To minimize the shadow effect, the panel inclination should be as low as possible while still collecting the maximum amount of sun. This is of course a matter of optimization.

Assuming the peak irradiation in Lund at noon is 1000 W/m\(^2\), which is a likely assumption when using data from PVGIS, graphs over different field configurations are extracted. Figure 6 shows the panel area required to produce 25 MW, for a clear sky on the summer solstice in Lund, as a function of the PV panel inclination angle. By assumption, the sun altitude is 58° with a PV panel efficiency of 17% and a transmission efficiency of 85%. Figure 7 shows the total land area required to produce a peak power of 25 MW as a function of utilization factor and inclination angle. The yearly electrical energy output as a function of solar field size for various inclination angles is shown in Figure 8 on page 20.
Figure 6: Panel area required to produce a peak power of 25 MW at noon for a clear sky in mid-June in Lund with a PV panel efficiency of 17 % and a transmission efficiency of 85 % as a function of inclination angle [28].

Figure 7: Field area as a function of field utilization factor for various inclination angles to produce a peak power of 25 MW at noon for a clear sky in mid-June in Lund with a PV panel efficiency of 17 % and a transmission efficiency of 85 % [28].
Figure 8: Total yearly electrical energy output versus field area for various inclination angles to obtain a peak power of 25 MW at noon for a clear sky in mid-June in Lund with a PV panel efficiency of 17% and a transmission efficiency of 85% [28].

Small inclination angles yield the most overall electrical energy for a given amount of land, which is desirable since the land at ESS is limited. This is because that small inclination angles minimizes the shadow effect. However, low inclination angles require a higher utilization factor that could be problematic for installation and maintenance. A reasonable compromise is to choose a panel inclination angle of 10 degrees and a field area of 25.1 hectares. A possible field layout is shown in Figure 9.

Figure 9: Possible layout of a 25.1 hectare solar field at the ESS site [28].
Table 3 shows the major design parameters and power output for the proposed field. It is obvious that the yearly average electrical energy of 5.8 MW, assuming 5000 operation hours per year, is more than enough to compensate for the 5 MW supplied to the accelerator. [28]

Table 3: Proposed design parameters for a 25 MW peak power solar field at ESS. [28]

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<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
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<tr>
<td>Field Area</td>
<td>25.1</td>
<td>Hectares</td>
</tr>
<tr>
<td>Field Utilization Factor</td>
<td>71.5</td>
<td>%</td>
</tr>
<tr>
<td>Panel Inclination Angle</td>
<td>10</td>
<td>degrees</td>
</tr>
<tr>
<td>Panel Electrical Efficiency at 25°C</td>
<td>17</td>
<td>%</td>
</tr>
<tr>
<td>Electrical Transmission Efficiency</td>
<td>85</td>
<td>%</td>
</tr>
<tr>
<td>Panel Area</td>
<td>18.2</td>
<td>Hectares</td>
</tr>
<tr>
<td>Shadow Winter Solstice</td>
<td>23</td>
<td>%</td>
</tr>
<tr>
<td>Peak Electrical Power on Summer Solstice</td>
<td>25</td>
<td>MW</td>
</tr>
<tr>
<td>Daily Electrical Energy on Summer solstice</td>
<td>6.4</td>
<td>MW-Day</td>
</tr>
<tr>
<td>Yearly Electrical Energy</td>
<td>3.3</td>
<td>MW-Year</td>
</tr>
<tr>
<td>Yearly Average Electrical Energy, assuming 5000 operation hours per year</td>
<td>5.8</td>
<td>MW</td>
</tr>
</tbody>
</table>

2.3 Photovoltaic cells

2.3.1 The photovoltaic effect and semiconductors

The basis for photovoltaic cells is the photovoltaic effect, which occur when semiconducting materials are exposed to light; the result is the rise of an electrical current through the material. When a photon hits the surface of a semiconductor there are two possible outcomes; if the energy of the photon is less than the band gap energy of the semiconductor the photon will pass through the material without having any impact. If the photon energy is equal to or larger than the band gap energy the photon will interact with electrons in covalent bonds. The covalent bonds are broken by the photon energy and thus the electron is excited to the conducting band where it is free to move within the semiconducting material [8]. In conventional solar cells the radiation energy above the band gap (the excessive energy after an excitation of an electron) does not contribute to the electrical energy generation because that the over-excited electron will relax down to the edge of the conduction band releasing thermal energy on the way. This thermal energy is wasted as heat that will cause an increase of temperature to the solar panel [9]. The two different scenarios are illustrated in Figure 10.
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Figure 10: The two possible scenarios when a photon hits a semiconducting material. $E_{ph}$ is the photon energy and $E_g$ the bandgap energy of the material.

2.3.2 p-n junctions and basic construction of solar cell

A solar cell is essentially a p-n junction which is constructed by joining a p-type semiconductor, which has an excess of electrons, with a n-type semiconductor, which has an excess of holes. This is causing a diffusion of holes from the p-side to the n-side and a diffusion of electrons from the n-side to the p-side. The diffusion of electrons, in turn, yield an opposing electric field over the depletion region of the junction. If one applies a voltage to the junction the electric field is reduced, when equilibrium is reached a current is produced which will increase exponentially with the applied voltage. This is described by the well known ideal diode equation. When exposed to light the equation becomes

$$I = I_0(e^{qV/nkT} - 1) - I_L \tag{2.3}$$

Where $I$ is the current, $I_0$ the dark saturation current, $V$ the applied voltage, $q$ the charge on an electron, $k$ Boltzmann’s constant, $T$ the absolute temperature, $n$ the ideality factor and $I_L$ the light-generated current.

There are two parameters limiting the power output from a photovoltaic cell for a given irradiance, operating temperature and area; the short circuit current $I_{sc}$ and the open circuit voltage $V_{oc}$. The power output from a photovoltaic cell is given by the product of the current and voltage, hence represented by the rectangle fitted under the I-V curve in Figure 11 on the next page. The maximum power output, $W_p$, is then the largest area for this rectangle and a common parameter for solar panels [8].

2.3.3 Effects of varying operating temperature

As the idea of this thesis is to collect hot water from a solar panel, it is important to understand how a change in operating temperature affects the solar cell. The effect of varying operating temperature on the I-V curve characteristics is shown in Figure 12 on the facing page.
It is obvious that the power output, thereby the electrical efficiency, decreases with increasing operating temperature. The change in electrical efficiency as a function of operating temperature, in the range 0-150 °C is described by function \( \eta(T) = \eta_{25C} \left(1 - K_L(T - 25)\right) \) (2.4)

where \( \eta_{25C} \) is the electrical efficiency of the solar cell at 25 °C. \( K_L \) is depending on the semiconductor material of the solar cell and \( T \) is the operating temperature of the solar cell. Typical values, assuming the use of polycrystalline, are 17% and 0.0048/°C for \( \eta_{25C} \) and \( K_L \), respectively.
2.4 Possibility of collecting thermal energy from the solar field

Solar cells are relatively inefficient at producing electricity. The solar field described in subchapter 2.2 only converts 14.5%, including 15% transmission losses, of the solar energy into usable electrical energy leaving 85.5% to be lost in heat. This wasted energy equates to some 19 MW-years annually. At most locations of solar plants, either far from urban areas or in warm climates, there is no interest or need to try to capture this heat energy. The greatest obstacle to using solar heat energy is the logistics of a distribution system for supplying heat. However, because of Sweden’s commitment to reducing global warming and its climate, many cities in Sweden have adopted district heating systems to make substantial reductions in CO₂ emissions. Engineers at LTH and ESS are interested in if the district heating system in Lund could be utilized for distributing excess solar heat energy captured from photovoltaic panels that could be installed at ESS.[28]

The major issue for obtaining both photovoltaic- and thermal energy from solar cells simultaneously is, as described in subchapter 2.3.3, the temperature at which the solar cells operate. For efficient distribution in district heating systems, the temperature of the water must be relatively high; in the order of 80°C. Temperatures below 50°C are inefficient for distributing heat and thus not as useful[28]. The following calculations are made with the assumption that it is possible to extract 80°C water from the PV panels.

Since the need for district heating is less in the summer months, a possible compromise, to increase efficiency, would be to change the operating temperature of the solar panels during the year; the panel operating temperature could be high in the winter, thus enabling some 80°C water to be delivered to the district heating network. In the summer, the panel operating temperature could be somewhat lower, thereby increasing the electrical efficiency. There are several ways to regulate the operating temperature of the panel, some of which will be presented in the discussion chapter at the end of the report.

As shown in Figure 13a on the facing page most of the demand for heating in Lund is for the months October through April. Figure 13b on the next page shows a possible temperature profile of the panel during the year. Figure 14 on the facing page shows that the yearly thermal energy available at 80°C for such a concept using the solar field described in table 3 on page 21 is 6.4 MW-years.
2 THEORY

(a) Heating degree days (blue) and average temperature (red) in Lund. The data is obtained from PVGIS.

(b) Possible temperature profile of a solar panel that collects both photovoltaic- and thermal energy during the winter and only photovoltaic energy during the summer. The electrical efficiency includes 15% transmission losses.

Figure 13: Demand of heating (a) and temperature profile of a panel (b) during a year in Lund.

Figure 14: Available thermal energy for the solar field specified in table 3 on page 21 operated with the temperature profile shown in Figure 13b.

As shown in Figure 15 on the following page, the yearly photovoltaic energy collected is 3 MW-years which is 90% of the photovoltaic energy of a field operating at a constant temperature of 25°C. Again, assuming the number of operations hours per year of 5000 hours, 3 MW-years of photovoltaic energy could provide an average rate of 5.2 MW for accelerator operations, which is more than enough to compensate for the entire amount of energy supplied to the beam.
As mentioned earlier, a cornerstone of the ESS energy concept is the recycling of waste heat into the Lund district heating system. Assuming that one third of the 35 MW of heat dissipated at ESS is recycled into district heating during the 5000 hours of operations per year, the amount of recycled heat sent back to the district heating system would be 6.7 MW-year. Adding the 6.4 MW-years of heat collected from the solar field could almost double this number.

2.5 Thermal theory

Collecting heat from solar panels is a relatively established technology which involves letting a fluid such as water or glycol flow at the back of the solar panel to collect the heat and then flow the heated fluid through a heat exchanger to distribute the captured thermal energy. There are many companies on the market that provide photovoltaic and heating solutions but on a residential scale\[28\]. This subchapter aims to describe some of these, already existing, technologies as well as some thermal calculations for estimating the power extraction.

2.5.1 Solar thermal collectors

Solar thermal collectors are devices that absorb solar radiation, transform it into heat, and transfer the heat to a heat-carrying medium such as air, water or oil. There are two main kinds of solar collectors; non-concentrating or stationary and concentrating. However, this thesis will only focus on the non-concentrating flat-plate collector (FPC), which has an indicative temperature range of 30-80°C, with water as heat-carrying medium\[10\]. A typical FPC-system, as seen in Figure 16 on the next page, contains the following parts:
• Cover material (glazing)
• Absorber plate that absorbs a large portion of the solar radiation
• Tubes for transportation of the heat-carrying fluid
• Insulation to keep the heat inside the thermal collector and thereby minimize energy losses

Figure 16: A cross-section of a typical FPC [11].

The flat plate collector’s basic working principle is that incoming solar radiation hits the covering material, where it passes through with minimal losses. Unheated water enters the collector module through tubes, which are placed on the back of the absorber plate. When the radiation hits the absorber plate a large portion is absorbed as heat and transferred to the heat-carrying water in the tubes. The heated water is then transported away from the collector module for utilization.

To obtain optimal efficiency of the FPC the orientation and tilt angle of the collector should be considered. The collectors should always face the equator, meaning that they should face south on the Northern Hemisphere. The optimal tilt angle for the collector is equal to the latitude of the location with variations of 10-15 degrees depending on the application [10]. The optimal inclination angle in Lund would therefore be $55^\circ \pm 10^\circ - 15^\circ$. There are some advantages of the FPC-design that make them suitable for this thesis; they are cheap to manufacture and they can collect both diffuse and beam radiation.

2.5.2 Photovoltaic thermal hybrid solar collectors

As seen in previous sections the photovoltaic and the thermal collector are useful when converting solar radiation into electrical energy and thermal energy, respectively. The idea behind the hybrid PV/T system is that by combining the two systems the performance of the PV collector can increase and, at the same time, extract thermal energy. Due to the efficiency drop on a PV panel, when operating at high temperature, the fluid can regulate the temperature on behalf of the electrical efficiency. Hence, with this system, both heat and power can be produced simultaneously.

The combination of the two systems changes the characteristics of both. An effective thermal collector can be distinguished by its good absorption and heat transfer and the higher the desired
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temperature the larger amount of insulation is needed\textsuperscript{22}. Insulation in the meaning of both the box and adding top surfaces to decrease the heat losses. A system without a glass cover will have reduced thermal performance due to the heat losses to the ambient but a better electrical performance. If a glass is added the additional reflection will affect the PV-module\textsuperscript{16}. Zondag et al. reported that both electrical and thermal performance of the PV/T is lower than that of them separated. However, the use of two PV/T collectors instead of two separated systems will give better results. This is especially important when the field area is limited.\textsuperscript{16}

2.6 Thermal calculations

To estimate the collected thermal energy from the PV/T prototype equation 2.5 is used.

\begin{equation}
E_{\text{thermal}} = mC\Delta T \tag{2.5}
\end{equation}

where $E_{\text{thermal}}$ is the collected thermal energy, $m$ the mass, $C$ the specific heat capacity of a material and $\Delta T$ the temperature change.

For estimating the thermal power the collected energy is simply divided by the duration of the experiment according to equation 2.6.

\begin{equation}
W_{\text{thermal}} = \frac{E_{\text{thermal}}}{\text{experiment duration}} \tag{2.6}
\end{equation}
3 Electrical connection to ESS

This chapter includes descriptions of the essential parts for electrical connection between the solar field, the utility grid and ESS. First is a description of the overall connection, this is followed by a description of the DC/DC converter and the control structure required for MPPT control. Last is a description of the Simulink model that was used as a base for the practical implementation.

3.1 Overall connection

The accelerating structures in the ESS facility will be powered by RF transmitters that require special power converters; they convert the AC power, provided by the utility grid, into pulsed waveforms that feed the electron guns that, in turn, energize the transmitters. These special power converters are commonly referred to as modulators. The team of engineers from LTH and ESS is developing a new type of modulator called Stacked Multi-Level Topology Modulator. The main feature of this modulator is a parallel configured input charger and a series output voltage stack. The parallel input chargers keep the voltage at low levels so that the precision control that is required by ESS can be achieved with standard components. The capacitor charger units consist of an AC/DC power converter, an Active Front End (AFE), followed by a DC/DC power regulator that controls the voltage level to the modulator. At the junction between the AC/DC converter and the DC/DC converter, a multi array of solar panels can be plugged in via a simple step-up DC/DC converter providing MPPT control to guarantee that maximum power is always extracted from the field. Due to the size of the field the irradiation could be somewhat irregular, therefore it is important that one DC/DC converter does not control too many panels; one suggestion is that every row of PV panels is controlled by one DC/DC converter. Figure 17 shows the modulator and the connection points for the solar field.

Figure 17: Circuit diagram showing the connection points for the solar field to the modulator.

[28]
The AC/DC AFE units of the modulators are based on the same power electronic structures as those of conventional solar inverters and are fully power reversible. This junction can thus be thought of as a three-way electrical valve in which:

- When the sun is shining, power is pulled from the solar cells to power the RF transmitters and minimal power is pulled from the electrical grid for regulation.
- When the sun is partly shining, power is pulled from the solar cells and the grid to power the RF transmitters. The AC/DC and DC/DC converters automatically regulate how much power comes from each source.
- When the sun is not shining, power is pulled only from the grid to power the RF transmitters.
- When the sun is shining and the accelerator is not running (when in a maintenance period), the power from the solar cells is back-feed to the grid to add additional power to the electric grid.

An illustration of the overall connection is shown in Figure 18.

Figure 18: Block diagram of the overall connections between the utility grid, the solar field and the ESS facility. [28]

3.2 DC/DC Converter - reference topology

The reference design, shown in Figure 19 on the next page, was suggested by the project supervisor. The essential components for this circuit are a MOSFET half-bridge for conversion to AC...
3 ELECTRICAL CONNECTION TO ESS

to voltage, a step-up transformer and a diode rectifier bridge.

![Diagram](image)

**Figure 19:** Reference design provided by the supervisor for the step-up DC/DC converter.

### 3.3 Control Structure

In order to properly control the half bridge a MPPT algorithm should be used; the PV panel output current and voltage are measured to calculate the power extracted from the panel. The reference signal for the PWM duty cycle is then calculated, using the common “Perturb & Observe” algorithm, to assure that maximum power is extracted. The algorithm block diagram is shown in Figure 23 on page 33.

#### 3.3.1 Pulse Width Modulation

To control the half-bridge MOSFETs pulse with modulation (PWM) is used. The conventional PWM is generated by a sawtooth wave with a reference voltage in a comparator. When the value of the reference signal is more than that of the sawtooth wave, the PWM signal is in the high state; one. Otherwise the PWM signal is in the low state; zero. By changing value of the reference signal it is possible to control the duty cycle of the signal. This method is illustrated in Figure 20.

![Diagram](image)

**Figure 20:** Conventional PWM generation where the green line is the sawtooth modulator wave, the red line is the reference signal and the black line is the output signal (control signal).

In this thesis the PWM signal is constructed by using two sawtooth modulator waves, together with the same reference signal, in a comparator. One of the modulator waves is phase-shifted by 180°. The phase-shifted signal controls the lower MOSFET while the other controls the upper MOSFET. The duty cycle is, as usual, controlled by changing the reference signal. Since the
same reference is used for both PWM signals they have the same duty cycle. To avoid a short
circuit through the MOSFETs the value of the duty cycle must be strictly less than 50%, meaning
a combined duty cycle strictly less than 100 %, creating a deadtime. Otherwise the transistors
would be conducting simultaneously. The special PWM is shown in Figure 21.

![Special PWM signal](image)

**Figure 21:** Special PWM used in the thesis for control of the half-bridge MOSFETs. In the
upper graph the black line is the conventional PWM signal, the blue is the copied phase-shifted
PWM signal and the red is the reference signal. In the lower graph the resulting control PWM
signals are shown with their corresponding colors.

The resulting AC voltage fed to the primary side of the transformer is shown in Figure 22.

![AC voltage fed to transformer](image)

**Figure 22:** The AC voltage fed to the primary side of the transformer. $U_{dc}$ is the output DC
voltage from the solar field.

### 3.3.2 Maximum Power Point Tracking (MPPT) Algorithm

In order to properly control the half bridge a MPPT algorithm should be used; the PV panel
output current and voltage are measured to calculate the power extracted from the panel. The
reference signal for the PWM duty cycle is then calculated, using the common “Perturb &
Observe$^7$ algorithm, to assure that maximum power is extracted. The algorithm flow chart is shown in Figure 23.

**Figure 23:** Flow chart of the Pertub & Observe Algorithm.
4 Simulink model and implementation

In order to perform simulations a model is created using Simulink, specifically the Simulink library SimPowerSystems under SimScape. For simplicity a user-defined function block is used for the MPPT algorithm implementation using the ’Perturb & observe’ technique. The model, seen in Figure 9, essentially contains three parts; the PV panel (1), the DC/DC converter (2) and the control structure (3).

![Figure 24: Schematic of the used Simulink model. The red-marked boxes represent the essential parts of the implementation where 1 is The PV panel, 2 is The DC/DC converter and 3 The control structure.](image)

4.1 Model of the PV panel

The PV panel is modeled using a predefined Matlab/Simulink block based on the ideal diode equation, see equation 2.3 on page 22 for approximating a PV panel. The PV array consists of one Canadian Solar CS5P-220M module type where one module has 96 cells. In the model menu the user can change the amount of strings in parallel and how many that should be in series, thus enabling the user to try different field configurations. Other possibilities is to display the I-V and P-V curve for one module or a complete array. The chosen module delivers a maximum power of 220 W at 1000 W/m² sun irradiation. If required, it is also possible to change the irradiation value. [34]

4.2 Model of the DC/DC converter

The PV array is connected to a DC/DC half bridge converter that is modeled using macro models of a real IGBT, meaning that it does not take the geometry of the device, or any physical process, into account. The half-bridge is connected to a transformer model that, in turn, is connected to the rectifier bridge. At the end of the rectifier bridge there is an output filter.
In Simulink a linear ideal transformer is used for simulations, this means that the voltage ratio is directly related to the turns ratio as seen in equation 4.1.

\[
\frac{V_s}{V_p} = \frac{N_s}{N_p}
\]  

(4.1)

Where \(V_s\) is the voltage on the secondary side, \(V_p\) the voltage on the primary side, \(N_s\) the number of turns on the secondary side and \(N_p\) the number of turns on the primary side.

The relation of the turns ratio defines the transformer to either a step-up or a step-down transformer. In this thesis it is desired to have a step-up converter, that is, a transformer whose secondary voltage is greater than the primary side voltage. The step-up ratio of the transformer is, as specified by the project supervisor, set to 1:12.

### 4.3 Control structure in Simulink

In the simulations the Perturb & Observe algorithm, see Figure 23 is used but with some modifications; the control structure includes three subsystems that are combined to obtain a PWM reference signal. The systems are the MPPT controller, an output current controller and a PWM Generator. Instead of a duty cycle reference, the MPPT block generates a current reference. This reference is used, together with the measured converter output current, in a PI controller block. The PI controller block computes an output based on the difference between the reference signal, generated by the MPPT block, and the measured output current. The output, generated by the PI controller, is used to form a duty cycle reference for the PWM Generator. After the PI controller block there is a saturation limit that keeps the value of the duty cycle reference within the interval 0-100 %. In the PWM block there are two PWM generators, where one is phase shifted, just like described in subchapter 3.3.1. The PWM switching frequency for the system is, as specified by the project supervisor, set to 20 kHz.
5 Practical implementations

Previous chapters only discuss the theory and technologies behind the project at ESS. A Simulink model is also constructed to conduct some preliminary simulations before any practical work. To get some real world results a PV/T prototype and an electrical circuit, based on the reference topology in chapter 3.2, was built. This chapter aims to present descriptions of the practical design of the PV/T prototype, the electrical circuit, together with explanations of the different parts, and at last how the data acquisition was performed using an Arduino Uno.

5.1 Design of the PV/T model

In Figure 25 the PV/T model can be seen. The model consists of two PV panels, styrofoam insulation, a copper plate, a copper tube, a cover of glass, mineral wool, plastic tubes and three temperature sensors. A clearer figure of the different parts can be seen in Figure 26. The bill of material can be seen in Appendix B.2.

Figure 25: Picture of the PV/T prototype used in the experiments.

Figure 26: Sketch of the PV/T prototype used in the experiments.
The PV panel is a 36-cell monocrystalline PV module with a maximum power of 10 W at standard test conditions; 25 °C operating temperature and 1000 W/m² artificial sunlight. At maximum power the panel has a voltage of 17.5 V and a current of 0.57 A. The open-circuit voltage and short circuit-current are 21.5 V and 0.65 A, respectively. Each panel has a dimension of 640x135x25 mm. The panel is manufactured by the Swedish company Solarlab Sweden.[7]

The absorber plate is a 900x300x5 mm large copper plate. The dimensions are chosen to match the two PV panels, that are connected in series, and copper is used because of its high thermal conductivity. A thin layer of heat sink paste is applied between the PV panels and the absorber copper plate to increase the thermal conductivity.

The copper tube is bent as seen in Figure 27 and placed under the absorber plate. To assure that the heat transfer, from the absorber plate to the tube, is as high as possible thin copper stripes are placed on top of the tube to fix it against the plate. The copper tube is connected to a plastic tube that leads to a water reservoir. To minimize the heat losses from the part of the tubes that are exposed to the ambient mineral wool is wound around them.

Figure 27: Copper tubes underneath the absorber plate.
Underneath and on the sides of the PV module a 10 cm thick styrofoam insulation is placed to reduce heat losses to the ambient. To further reduce heat losses a 5 mm thin cover glass is placed on top of the module. As mentioned in subchapter 4.5.2, the glass cover can reduce some of the electrical efficiency but instead increase the thermal efficiency.

Three temperature sensors are placed on different locations on the module; one on top of the panel, one between the panel and the absorber plate and one close to a tube underneath the absorber. The placement of the sensors were chosen to measure the difference in temperatures between the layers and to observe how the heat transfer was between them.

### 5.2 Circuit

The reference design, provided by the supervisor, can be seen in Figure 19 on page 31. The implemented circuit consists of the same parts as the reference but with some added components to make it applicable; a MOSFET driver circuit to control the half-bridge, snubbers on the MOSFETs and the rectifier diodes as well as measurement equipment. These will all be presented in-depth in this subchapter. The electronic schematic can be seen in Figure 28. For a bill of material for the electrical circuit see Appendix B.1.
Figure 28: Schematic of the electrical circuit.
5.2.1 MOSFET driver circuit

To drive the power MOSFETs in the half-bridge circuit a MOSFET driver is used. The 14 pin IR2110PBF high and low side driver is chosen because of its high working frequency and its compatibility to operate with low-and high-side switches. The functional block diagram can be seen in Appendix C. It includes features such as a floating channel designed for bootstrap operation, fully operational to +500 V and tolerant to negative transient voltage.[29]

The circuit schematic for the driver and its connecting pins can be seen in Figure 29. Pin configuration and functionality is given below[29][30].

![Figure 29: The MOSFET driver circuit.](image)

**LO, 1, low side gate drive output** The output of the low side with respect to ground. A high signal in to LIN means that the low side of the MOSFET is wanted, meaning a high output on LO.

**COM, 2, low side return**
This is a return path to the low side and the connection to ground on the low side.

**VCC, 3, low side supply**
The low side supply voltage should be between 10-20V, in this case it is set to 15V. If VCC is not set to at least 10V the driver will shut down to protect the MOSFET, a so called undervoltage lockout.

**VS, 5, high side floating supply return**
Provides floating voltages to drive the high side of MOSFET.

**VB, 6, high side floating supply**
Provides floating voltages to drive the high side of MOSFET.

**HO, 7, high side gate drive output**
The high side channel logic input switch HO between the positive of the supply and its ground.
in accordance with the input command. A high signal to HIN drives the high side MOSFET, meaning a high output is provided on HO and a low signal means the high side is off.

**VDD, 9, logic supply**
The logic supply voltage to the driver can vary between 3-20V dependent on the VSS input. VDD is set to +5V and has a Logic "1" input threshold slightly higher than 3V.

**HIN, 10, logic input for high side gate driver output (HO), in phase**
Logic input for the driver, a high signal means that the high side MOSFET is on. See chapter about PWM, [3.3.1] to learn how the signals are sent in.

**SD, 11, logic input for shutdown**
The shutdown control, when a low signal is sent the driver is enable, when a high signal is sent the driver shuts down. It can be used as protection, for example if over-voltage or over-current occurs.

**LIN, 12, logic input for low side gate driver output (LO), in phase**
Logic input for the driver, a high signal means that the low side MOSFET is on. See chapter about PWM, [3.3.1] to learn how the signals are sent in.

**VSS, 13, logic ground**
The logic supply is ground.

**Bootstrapping**
In the driver circuit there is one bootstrapping connection, that pulls up the voltage by using positive feedback to feed part of the output back to the input without causing oscillation [31]. At the same time it sustains the voltage level above the threshold level and maintains the voltage in the bootstrap capacitors. D1, C3 and C4, together with the driver, form the bootstrapping circuit.

C1 and C2 form a filter to get a clean input from the +5 V supply voltage.

R1 and R2 limits the current to the MOSFET gate while D2 and D3 discharges the gate capacitance of the two MOSFET.

R3 and R4 acts as pull down resistors to ensure a low voltage level to the MOSFET. The pull down resistors attenuates noise and prevents accidental turn-on of the MOSFETs.

L1 and L2 form a choke filter on the output of the rectifier bridge to block the AC components from reaching the output load.

### 5.2.2 Transformer design

The transformer used in the circuit was made by the thesis students since no transformer, that met the specifications, was found. The structure of the transformer, T1, seen in Figure [30] is a two-winded step-up transformer with a turn ratio of 1:12.
A Ferrit core of type ETD59 was bought from Elfa. Figure 31 shows the dimensions of the obtained core, where the cross-section, $S$, is needed to calculate the number of turns on the primary and secondary windings, equation 5.2.

The voltage induced to the primary side is proportional to the rate of change of flux, equation 5.1.

$$V_p = N_p \frac{d\phi_p}{dt} \quad \text{(5.1)}$$

Where $V_p$ is a time varying voltage, $N_p$ number of turns and $d\phi_p$ a varying magnetic flux, and vice versa for the secondary.
From equation [5.1], the universal average EMF equation for a half cycle voltage of any wave shape, equation [5.2] can be obtained and used to calculate the number of turns for either winding.

\[ V = 4NSfB_{\text{peak}} \]  

(5.2)

Where \( V \) is the voltage, \( N \) the number of turns, \( B_{\text{peak}} \) the magnetic flux density and \( S \) the cross-sectional area of the core.

The finished product can be seen in Figure 32.

![Figure 32: The transformer built by the thesis students.](image)

To control that the transformer had been winded properly, the leakage inductance was measured indirectly. Sometimes when a transformer is not winded good enough, some part of the flux on the primary side may not be transferred to the secondary. This leakage can then be seen as an additional impedance that is in series with the primary side. A high leakage inductance is undesirable for the circuit used in the project, since it limits the flow current and results in a lower output voltage.[38]

The leakage inductance was measured by first applying a short circuit on the primary and measure the secondary inductance and likewise for the other side, short circuit on the secondary and measure the primary inductance. Thereafter the ratio of the leakage inductance can be calculated with equation [5.3]. Where the leakage inductance is proportional to the number of turns squared [38].

\[ \left( \frac{N_p}{N_s} \right)^2 = \frac{L_p}{L_s} \]  

(5.3)
5.2.3 Snubbers

When the MOSFETs, Q1 and Q2, are turning off, leak inductance may cause voltage spikes to appear. To protect the circuit from the over-voltage diode snubbers was added to take care of the leak inductance. In Figure 33 the snubbers placed over Q1 and Q2 are seen. The diode is placed to protect the MOSFET from inductive reversed current.

![Figure 33: Schematic of the diode snubber.](image)

For the rectifier bridge in Figure 34 high voltage spikes were noticed, therefore, to minimize this over-voltage a capacitance was placed in series with two parallel resistors over the diodes, D6-D9. When the diodes are switched off, the leakage inductance and parasitic capacitance can appear as a resonant circuit that oscillates at high frequency. Snubbers were used to alleviate the problem; the RC snubber circuit across the diodes eliminated the oscillation almost completely. The results of how the circuit behaved before and after the snubbers were placed can be seen in Figures 46 and 47 in chapter 7.2.
5.3 Data acquisition with the Arduino

To control the electrical circuit and collect data an Arduino was used, see appendix A for more information about the device. The Arduino Uno microcontroller board offers 14 digital input/output pins, of which 6 can be used as PWM outputs and 6 as analog inputs. To manage the microcontroller a software dedicated for Arduino was used. The programming language is very easy and basic and there is a lot of example code on the webpage [4].

The specification from the supervisor for the frequency of the PWM was 20 kHz, due to restriction from the Arduino the frequency had to be set to 31 372.55 Hz, see [35] for more information of how to adjust the PWM frequency of an Arduino. By manipulating the PWM timers of the microcontroller a custom PWM could be created instead of using the built in function analogWrite(pin, dutyCycle). Where "dutyCycle" is a value between 0 and 255 and "pin" is one of the chosen PWM pins [36]. The timers have a prescaler that generates the timer clock. By dividing the clock speed by a prescaler, the resolution, the timer clock frequency can be obtained. The Arduino Uno has two timers at an 8-bit resolution and a clock speed of 16 MHz, the theoretical max frequency on the output of the PWM is then 64 kHz. The closest generated frequency by the Arduino, regarding the specification, was 31 372.55 Hz. Hence, this frequency was used in the experiments.

Figure 35 shows the connection from the Arduino breadboard to the electrical circuit (PWM to IR2110) and the different sensors. From the 3 temperature sensors the connection to the Arduino are 3 voltage divider circuits. Where the sensor, a 10 kΩ thermistor, is set in series with a 10 kΩ resistor to produce an output that is a fraction of the input. This is due to the limitation of the analog input pin that is limited between 0 V and 5 V [37].
Figure 35: Schematic of the connections to the Arduino for data acquisition and control.

For the code used for data acquisition from the Arduino the reader is referred to Appendix D. The Arduino software program sends the readout from the sensors continuously through the serial interface. The information from the serial port is read by external software programs such as Processing or GoBetwino, depending on the operating system, that saves the data into a .txt file. The data from the water temperature sensor had to be gathered separately with Arduino due to output problems with the external software.
6 Experimental setup

The experimental setup, shown in Figure 36 for this project is fairly large and involves a couple of instruments; one 12 VDC voltage generator (1) supplying the water pump, one voltage generator with one 5 VDC output and one 15 VDC output (2) supplying different parts of the electrical circuit, one Arduino Uno (6) for data acquisition and control of the electrical circuit, one computer (3) for data acquisition, one water reservoir with 2 liter water and a water pump circulating the water with a flow rate of 2.2 liter/minute (4), the PV/T panel prototype (5) and the electrical circuit (6). A scheme over the experimental setup connections is illustrated in figure 37 on the following page.
Figure 37: Setup connections for the whole PV/T system.
7 RESULTS

7 Results

7.1 Simulation results

The PV and IV curve for different irradiation levels for the PV used in the simulation can be seen in Figure 38.

Figure 38: IV curve (upper) and PV curve (lower) of the PV model used in the simulations. The blue line represents an irradiation of 1000W/m² whereas the magenta line represents other irradiation levels.

Figure 39 shows the MPPT output power from the simulated circuit.

Figure 39: Output power from the PV model (magenta) and measured output power from the converter (blue).
Figures 40 and 41 represent the AC voltage of the transformer used during simulations. Figure 40 shows the AC voltage on the primary side, an estimated voltage of $\pm 24$V while Figure 41 shows the AC voltage on the secondary side that is about $\pm 290$V.

**Figure 40:** AC voltage on the transformer primary side.

**Figure 41:** AC voltage on the transformer secondary side.
7.2 Measured results

Figure 42 shows the measured IV and PV curve for one of the PV modules from Solarlab. The measurement was made Mars 12 at noon with a clear sky and a temperature of 5 °C, the irradiation level at this time of year, according to PVGIS, is approximately 500 W/m². The panel was inclined roughly 40° facing south. The maximum power is calculated to 7.25 W with measured values of the current and voltage, which were 0.49 A and 14.75 V, respectively. The short-circuit current was measured to 0.51 A and the open-circuit voltage to 22.36 V.

![Module IV-Curve](image1)

![Module PV-Curve](image2)

(a) IV-curve for one PV panel used for the experiments.

(b) PV-curve for one PV panel used for the experiments.

**Figure 42:** IV and PV curves for one 10 W solar module from Solarlab.

In Figure 43 the result of the power output from the PV after a 3 hour measurement in the sun can be seen. The measurement was made August 9 with start at 09:28, it was a clear sky with some cumulus clouds and a temperature of 18 °C. The panel was facing south with an inclination of roughly 40°.

![PV Output](image3)

**Figure 43:** Output power for the PV panel during 3 hours.
For simplicity the electrical properties of the circuit were tested using a voltage generator, providing a constant clean DC voltage, instead of the PV/T prototype.

The number of turns for the transformer is calculated with [5.2] rewritten to [7.1] together with the information in Figure 31 that the radius of the core is 0.011 m.

\[ N_p = \frac{V_p}{4\pi r^2 f B_p} \]  

Where:
\[ V_p = 25 \text{ V} \]
\[ r = 0.011 \text{ m} \]
\[ f = 20 \text{ kHz} \]
\[ B_p = 0.2 \text{ T} \]

With equation [7.1] and the presented values, \( N_p \) is estimated to 4 turns, meaning that \( N_s \) should be 48 turns since a step-up ratio of 1:12 was desired.

Figure 44 shows the voltage step-up of the transformer when a voltage of 10 VDC, from a voltage generator, is supplied to the PV input. On the primary side, Figure 44a, the voltage was measured to ±5 V, and on the secondary side, Figure 44b, the voltage was measured to ±62.5 V. Which gives a ratio of 12.5.

The leakage inductance of the transformer secondary side, \( L_s \), was measured to 19 µH and 128.5 nH on the primary side, \( L_p \). By rewriting equation [5.3] to equation [7.2] this ratio was estimated to 12.16.

\[ \left( \frac{L_s}{L_p} \right) = \frac{N_p}{N_s} \]  

Figure 44: AC voltage on both sides of the transformer. The step-up ratio is approximately 12.5.
7 RESULTS

The output DC voltage, before and after the output filter, L1 and L2 in the electrical circuit Figure 28, can be seen in Figure 45.

(a) DC voltage before the output filter.  
(b) DC voltage at the circuit output.

Figure 45: DC voltage before and after the output filter.

As seen in Figure 46a, the voltage spike across a diode on the rectifier, D6-D9 in Figure 28, could reach values around 350 V when the input voltage on the PV was 20 V. After adding the snubbers, Figure 46b, the voltage spike was almost entirely attenuated.

(a) Voltage spike over a diode at the rectifier bridge before using a snubber.  
(b) Voltage spike over diode at the rectifier bridge with a snubber.

Figure 46: Oscilloscope pictures of the voltage spike before and after using a snubber over diode on rectifier bridge.
Figure 47 shows the oscillation over a diode, D6-D9 in Figure 28 before (a) and after (b) the adding of the snubbers.

Figure 47: Oscilloscope pictures of the oscillation before and after using a snubber over diode on rectifier bridge.
7.3 Heat extraction

The change of temperature for the various sensors during a 3 hour measurement can be seen in Figure 48. The measurement is the same as that of figure 43 on page 51 and hence the conditions are the same as described previously. The different colors represent the different sensors, blue is the temperature on top of the PV, red between the PV and absorber, green underneath the absorber and purple for the water temperature.

![Temperature changes of the system](image)

**Figure 48:** Temperatures change during a 3 hour experiment on PV system.

The parameter values of equation 2.5 on page 28 and 2.6 on page 28 are thus; $m = 2\, \text{kg}$, $C = 4.2\, \text{kJ/kgK}$, $\Delta T = 42\, \text{K}$, $\text{experimentduration} = 10800\, \text{s}$.

By using these equations it is calculated that the amount of thermal energy, in the form of heated water, extracted from the PV/T prototype is 352.8 kJ meaning a thermal power extraction of roughly 33 W.
7 RESULTS

7.4 Simulations of another scenario

The scenario that the solar field, specified in Table 3 on page 21, operates with a summer temperature of 25 °C and a winter temperature of 55 °C is shown in the Figures below. Figure 49 shows the daily and integrated electrical power and Figure 50 shows the available thermal energy during one year for such operation.

Figure 49: Daily and integrated electrical power during one year for the solar field specified in Table 3 on page 21 with operation temperatures of 25 °C and 55 °C in summer and winter, respectively.

Figure 50: Available thermal energy during one year for the solar field specified in Table 3 on page 21 with operation temperatures of 25 °C and 55 °C in summer and winter, respectively.
8 Discussion

8.1 Simulations

The aim for implementing the Simulink model is to get familiar with the reference topology. The model could also form a foundation for further work on field configurations and different irradiation scenarios, among other things. Since the Simulink library SimPowerSystems was used it was rather easy to implement the reference design under ideal conditions, which was intended.

The model IV and PV curve can be seen in Figure 38 on page 49. It is easily seen that the current and voltage levels are, at the maximum power point, 4.7 A and 47 V, respectively. At this point the maximum power is roughly 220 W. By comparing this to Figure 39 on page 49 we can conclude that the maximum power is extracted from the PV panel model and that the MPPT algorithm seems to work properly. In Figures 40 and 41 on page 50 the transformer primary and secondary side voltages can be seen. The primary side voltage is roughly ± 24 V while the secondary side voltage is about ± 290 V, meaning a step-up ratio of 1:12, just as desired. By looking at the curves it is also clear that the PWM works as expected since there is a dead time between the plus and minus voltages.

8.2 Electrical experiments

The maximum power output from the PV panel, used in the experiments, is 10 W, as specified by the manufacturer. However, as can be seen in Figure 42 on page 51, the measured power output from one PV panel was approximately 7.3 W at its maximum. A reasonable explanation for the lower power output is that the 10 W power were extracted under standard test conditions with 1000 W/m² irradiation while the experiments were carried out at considerably lower irradiation levels.

Assuming that the maximum power output from one panel is 7.3 W, the maximum power output from both panels should be approximately 14.6 W. In Figure 43 on page 51 showing the power output from the panels, it can be seen that the peak power was 9.5 W, with variations from 5 W neglecting the complete power drops. The output from the MPPT algorithm was not as expected; the generated PWM reference was too high and could thus harm the circuit. After realizing that the MPPT implementation did not work as expected a constant combined PWM duty cycle of about 70% was used. This can partly explain the poor result of the electrical power extraction.

The performance of the transformer can be seen in Figure 44 on page 52. Since the curves are similar to the simulation results and the step-up ratio was about 1:12.5, the transformer worked as expected.

Figure 45 shows the improved result of smoothing the output DC voltage with 2 inductors in parallel, the choke filter removed the alternating current components of the rectifier output while still allowing the DC components to reach the load. This part was improved during the work and the best results are obtained when high-current inductors were used.
The design of the electrical circuit is to be thought of as a reference design. Since the design lack restrictions the choice of component values, to the circuit in Figure 28 were empirically found.

When choosing the components for the RC snubbers on the rectifier diodes, the voltage across one diode was measured and the frequency of the oscillation of the overshoot was visible with the oscilloscope, see Figure 47a. The oscillation frequency was measured to 2 MHz. To have the signal properly filtered a time constant of 2 periods is required. The time constant was thus determined to 1 μs. The component values are then calculated as $1 \, \mu s = time\text{constant} = RC$.

The first attempt was a capacitor of 10 nF, which meant that the resistor could be 1 kΩ. When using these values the oscillation was damped a little bit, but not enough. The result improved much more when a 1 nF capacitor was set in series with 2 resistors in parallel of 1.5 kΩ instead. This is the result that can be seen in Figure 47b, since no oscillation was seen when changing the time resolution of the oscilloscope no close-up figure of the oscillation for this is needed.

Although the circuit seems simple in the schematic, the interpretation is difficult due to all the parasitic elements, from the capacitors, the switches and the parasitic elements between the transformer windings, when using a high switching frequency.

### 8.3 Heat extraction experiments

In order to get some real world results for the thesis a PV/T prototype was constructed, with essential theory for the construction taken into consideration. The FPC design is, as described in subchapter 2.5.1, cheap to manufacture and is for that reason suitable for large scale implementation, which is a desirable property since the field area at the ESS facility will be large. However, there were some different issues during the project; the first idea was to build a PV/T panel where it was possible to extract air from the module, thus creating a vacuum, to reduce heat convection. By creating vacuum during the months when heat extraction is the priority and remove the vacuum during the months when extraction of photovoltaic energy is the priority, the panel operating temperature could be regulated. This idea turned out to be rather bad because that the vacuum had to be close to perfect, requiring expensive equipment, to make any difference. Another idea is to change the panel operating temperature by regulating the water flow through the pipes at the back of the copper absorber plate. Though this idea seemed good, it was never attempted due to the bad weather conditions this summer and the limited time scope for this project.

In the case study of the thesis project it is assumed that 80 °C water can be extracted from a PV/T panel. However, as shown in figure 48 on page 55, the real world water temperature only reached 62 °C. One crucial factor for not reaching the 80 °C water is the losses between the different layers; it can clearly be seen that there is quite a large difference in temperature between the different layers of the module. An explanation to the losses between the PV panel and the absorber is due to that the backside of the panel is not entirely flat and therefor a full connection between them is not possible. The panel top temperature is roughly 85 °C and if one were to design a more optimal PV/T panel, maybe it could be possible to extract close to 80 °C water. The estimated thermal power extracted from the panel is roughly 33 W, which is presented in the result section. Thus, by optimizing the different parts of the prototype, more thermal energy could be extracted. Another reason for not reaching the desired temperature was the flow rate of the circulating water; in the thesis a constant flow rate of 2.2 liter/minute
was used. By regulating the flow rate it might be possible to obtain other temperatures, where a higher flow rate would mean a lower operating temperature vice versa. This would make it possible to choose panel operating temperature with respect to energy demands.

Since the time scope for this thesis was limited the 62 °C water was accepted and another scenario was studied; to operate at 25 °C in the summer months and 55 °C in the winter months. As mentioned in the introduction a water temperature of 55 °C could be utilized in food production systems for things such as fish tanks and green houses, this idea is however just in a speculation phase. The 55 °C water could then, instead of the district heating system, be connected to the 55°C temperature level of the cooling system at ESS. Simulations of this scenario are presented in Figures 49 and 50 on page 56 and show that the amount of electrical power could be 3.15 MW-years and the amount of thermal energy 6.2 MW-years.
9 Conclusions and further work

The work in this thesis presents one possible way to implement a solar field, which would compensate the required beam power at the ESS facility as well as proposes a possible connection enabling power exchange between ESS, the utility grid and the solar field. The thesis also includes some preparatory work for further studies with more detailed and optimized field configurations. It has been established that, if 80 °C water could be extracted from the PV/T panels, the water could be connected to the district heating system in Lund. If the water only reaches lower temperatures, as in this thesis, the water could still be utilized in food production systems. Regardless the application the utilization of thermal energy from the solar field would almost double the amount of energy extracted from waste heat recycling.

What differs this work from other existing approaches is that it reviews the possibility to extract the thermal energy for an industrial scale. It should also be clarified that the thesis is a feasibility study for the future solar project at ESS.

The work carried out during the thesis has reveals many promising areas for further development. A few of these areas worth of further analysis can be summarized according to:

- During the thesis project only one possible field configuration is studied. To get a more adequate basis for future field implementation, more in-depth studies of different configurations should be performed, that is, optimization of inclination angle, field area, utilization factor, number of series and parallel connected panels among other things.
- The electrical circuit built during this project is mostly produced using an empirical approach to investigate a concept; none of the components are hence optimized. To achieve a circuit that could be used as a connection between the real solar field and the ESS modulator it is advisable to optimize the components using simulation software such as SPICE or LTspice. This would save both money and time investigating the various faults.
- In the thesis case study an electrical transmission efficiency of 85% was used. This would be the case for normal distribution of photovoltaic energy extracted from a solar field. However, since the electric energy from the solar field will be consumed on-site and because of the already existing connection to the power electronic topology of ESS, the efficiency could be much higher; the only losses would be the almost negligible transmission losses and the losses of the DC/DC converters connecting the solar field to the modulators. Further work should include detailed calculations on these small losses to strengthen the advantage of consuming power on-sight.
- The MPPT is investigated together with the Simulink model, which gives good results as presented in the thesis. However, when the implementations were done in Arduino, the results were not as expected. This could be a simple programming mistake but the error was not found and, because of that, a constant duty cycle was used during the measurements instead. Therefore, a working implementation of the MPPT on Arduino is desirable for future projects.
- Arduino Uno is chosen as microcontroller because of its simplicity and the fact that there are countless of example projects online. The Arduino Uno is also a rather cheap microcontroller. For extending projects, one thing worthy looking over is the choice of microcontroller; even though the Arduino is easy to use it had some limitations in the choice of PWM frequencies.
- The PV/T prototype has a few flaws; the absorber plate is too thick which resulted in...
large losses of thermal energy, the PV panels are in bad contact with the absorber and not completely covered with cells (there are only cells in the middle part of the panels) and the cover glass is not made specifically for PV modules meaning a lower transmission factor than that of other glass available on the market. For an improved version of the prototype the choice of absorber plate, PV panels and cover glass should be done with respect to detailed preliminary thermal simulations of how the heat propagates throughout the entire module.

- Due to bad weather conditions during the summer only one continuous measurement, with simultaneous extraction of heat and electric power, could be conducted. The data presented in the heat extraction results are from this single measurement. Any further work to this thesis should thus include more measurements.

- In this thesis the water could not reach the desired temperature of 80 °C. If higher water temperatures can be achieved with an improved PV/T prototype it would be worth studying the utilization of the water in more detail.
References


REFERENCES


REFERENCES


A  Software

Simulink

For simulation purposes Simulink was chosen as simulation software. It is developed by MathWorks for modeling and solving dynamic systems. The program requires a license and is available for GNU/Linux, Mac OS X, and Windows. With the toolbox SimPowerSystems, in addition to Matlab and Simulink, one can simulate power electronic devices without too much effort. [2]

ExpressPCB

ExpressPCB is a software used for schematics and PCB design. It is free and available for Windows systems. The program is easy to use and it is possible to order the board from the company as well, after finishing the layout. [3]

Arduino Software

The Arduino Software (IDE) is a free, java-based and open-source software, it allows the user to write java-based code and download it to an Arduino microcontroller board. The software is available for GNU/Linux, Mac OS X, and Windows. [4]

GoBetwino

The GoBetwino is a software that helps the Arduino with some features it cannot do, for example as a port forwarder. It is a free software that only works with Windows. The program was used to save the data that the Arduino collected while running the tests. [5]

Processing

Processing is a free open-source programming language and development environment for GNU/Linux, Mac OS X, and Windows. It is a well documented and has hundreds of libraries that extends the software. For the thesis it was used to help save the data that the Arduino collected. [6]
### B Bill of Material

#### B.1 Bill of material for the electrical circuit

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ACS712CTR20A-T

66
B.2 Bill of material for the PV/T

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67
C Functional block diagram of IR2110PbF
D Code

D.1 Control and PV data collector, Arduino

// Definitions

#define CURRENT_SCALING 0.048828125 // the scaling value for raw adc reading to get solar amps // 5/(1024*0.100)
#define VOLTAGE_SCALING 0.0455729167 // the scaling value for raw adc reading to get solar volts // (5/1024)*(R1+R2)/R2
#define PWM1_PIN 9 // the output pin for the pwm (only pin 9 available for timer 1 at 50kHz)
#define PWM2_PIN 11 // the output pin for the pwm
#define PWM_MAX 40 // the value for pwm duty cycle 0-49.9%
#define PWM_MIN 1 // the value for pwm duty cycle 0-49.9% (below this value the current running in the system is = 0)
#define PWM_START 35 // the value for pwm duty cycle 0-49.9%
#define PWM_INC 1 // the value the increment to the pwm value for the ppt algorithm

// Global variables

double pwm = 0; //pwm 
duty cycle 0-49.9%
double delta = PWM_INC; // variable used to modify pwm duty cycle for the ppt algorithm
double tmp = 0;
double temp0=0;
double temp1 = 0;
double sum0 =0;
double sum1 = 0;
double amps=0;
double PVcurrent = 0;
double PVvoltage = 0;
double PVpower = 0;
double oldPVpower = 0;
double PVTopTemp = 0;
double inBetweenTemp;
double heatSinkTemp;
double CurrentTime = 0;
double StartTime = millis();
double ElapsedTime;
double count = 0;

//

void setup() {
  TCCR2B = TCCR2B & B11111000 — B00000001; // Set prescaler of timer 2 (pin 3&11), gives a frequency of 31.340 kHz
  TCCR1B = TCCR1B & B11111000 — B00000001; // set prescaler of timer 1 (pin 9&10), gives a frequency of 31.340 kHz
}
TCNT1=0x7FFF;  //Set Timer1 Counter Register to half of its maximum value (32767)
Serial.begin(9600);  // open the serial port at 38400 bps
pinMode(PWM1_PIN, OUTPUT);  // define D9 as output
pinMode(PWM2_PIN, OUTPUT);  // define D11 as output
pwm = PWMSTART;  //Starting value for PWM
}

//—————————————————————————————————————————
void set_pwm(void)
{
  if (pwm >= PWMMAX)
  {   // if pwm is greater than PWM MAX then set it to PWM MAX
    analogWrite(PWM1_PIN, map(PWMMAX, 0, 100, 0, 255));
    analogWrite(PWM2_PIN, map(PWMMAX, 0, 100, 0, 255));
  }
  else if (pwm <= PWMMIN)
  {   // if pwm is less than PWM MIN then set it to PWM MIN
    analogWrite(PWM1_PIN, map(PWMMIN, 0, 100, 0, 255));
    analogWrite(PWM2_PIN, map(PWMMIN, 0, 100, 0, 255));
  }
  else
  {
    analogWrite(PWM1_PIN, map(pwm, 0, 100, 0, 255));
    analogWrite(PWM2_PIN, map(pwm, 0, 100, 0, 255));
  }
}

//—————————————————————————————————————————
void read_data(void)
{
  for(int i = 0; i <= 100; i++) // loop through reading raw adc values 100 number of times
  {
    temp0=analogRead(A0); // read the input pin for current measurement
    temp1=analogRead(A1); // read the input pin for the voltage measurement
    sum0 += temp0; // store sum for averaging
    sum1 += temp1;
  } // average sum
  sum0 = sum0/100; // divide sum by 100 to get average
  sum1 = sum1/100;
  PVTopTemp = analogRead(A3);
  inBetweenTemp = analogRead(A4);
  heatSinkTemp = analogRead(A2);
  // Calibration for current
  amps = CURRENTSCALING*sum0 - 25; // 2.5/0.100 = 25
  PVcurrent = abs(amps-0.13);
  // Calibration for voltage
  PVvoltage = sum1*(5.0/1024.0)*(16.8/1.8); //read input voltage from PV-panel
  // Calculation of power
  PVpower = PVcurrent*PVvoltage;
  // Calculation of temperature
  PVTopTemp = calcTemp(PVTopTemp);
  inBetweenTemp = calcTemp(inBetweenTemp);
  heatSinkTemp = calcTemp(heatSinkTemp);
}
double calcTemp(double rawValue) {
    tmp = log(((10240000/rawValue) - 10000));
    tmp = 1 / (0.001129148 + (0.000234125 + (0.0000000876741 * tmp * tmp))* tmp);
    tmp = tmp - 273.15; // Convert Kelvin to Celsius
    return tmp;
}

void mppt(void) {
    if (oldPVpower == PVpower) { // if previous watts are greater change the value of
        delta = -delta; // delta to make pwm increase or decrease to maximize watts
    } 
    pwm += delta; // add delta to change PWM duty cycle for PPT algorithm (compound addition)
    oldPVpower = PVpower; // load old watts with current watts value for next time
    set_pwm(); // set pwm duty cycle to pwm value
}

String double2string(double nbr, int nbrOfDecimals) {
    String returnString = "";
    int i = nbr;
    returnString += nbr; // whole number part
    int j;
    for (j=0; j<nbrOfDecimals; j++) {
        // iterate through each decimal digit for 0..nbrOfDecimals
        nbr -= i;
        nbr *= 10;
        i = nbr;
        returnString += i;
    }
    return returnString;
}

void data_log(double PVcurrent, double PVvoltage, double PVpower, double PVTopTemp, double inBetweenTemp, double heatSinkTemp, double pwm, double ElapsedTime) {
    Serial.print("#S—LOGTEST—[");
    Serial.print(double2string(PVcurrent,0));
    Serial.print("t");
    Serial.print(double2string(PVvoltage,0));
    Serial.print("t");
    Serial.print(double2string(PVpower,0));
    Serial.print("t");
    Serial.print(double2string(PVTopTemp,0));
    Serial.print("t");
    Serial.print(double2string(inBetweenTemp,0));
    Serial.print("t");
    Serial.print(double2string(heatSinkTemp,0));
}
D.2 Water data collector, Arduino

#include <OneWire.h>
#include <DallasTemperature.h>
// Data wire is plugged into pin 2 on the Arduino
#define ONE_WIRE_BUS 2
// Setup a oneWire instance to communicate with any OneWire devices (not just Maxim/Dallas temperature ICs)
OneWire oneWire(ONE_WIRE_BUS);
DallasTemperature sensors(&oneWire); // Pass our oneWire reference to Dallas Temperature.
void setup(void)
{
    // start serial port
    Serial.begin(9600);
    Serial.println("Dallas Temperature IC Control Library Demo");
    // Start up the library
    sensors.begin();
}
void loop(void)
{
    // call sensors.requestTemperatures() to issue a global temperature
    // request to all devices on the bus
    sensors.requestTemperatures(); // Send the command to get temperatures
D CODE

Serial.println(sensors.getTempCbyIndex(0)); // Why "byIndex"? You can have more than one IC on the same bus.
// 0 refers to the first IC on the wire
}

D.3 Processing

import processing.serial.*;
Serial myPort;
PrintWriter output;
String value;
void setup() {
    String portName = Serial.list()[5];
    myPort = new Serial(this, portName, 9600);
    output = createWriter("data.txt");
}
void draw() {
    if (myPort.available() > 0) {
        value = myPort.readStringUntil("\n");
        if (value != null) {
            output.println(value);
        }
    }
}
void keyPressed() {
    output.flush();
    output.close();
    exit();
}