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Energiproduksjon med kombinert bruk av solceller og varme/kjøle krets

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Institutt for produktutvikling og materialer

Energy production with solar panels in combination with cooling/heating systems

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Energiproduksjon med kombinert bruk av solceller og varme/kjøle-krets

Energy production with solar panels in combination with cooling/heating system

Oppgaven har til hensikt å undersøke effektiviteten av å kjøle ned solceller for økt strømproduksjon i kombinasjon med produksjon av lavverdig varmeenergi. Målet er å lage en testrigg hvor variabler som kjølesystem, plassering av solcellepanel, vinkling mot sol og varmeproduksjon kan måles og evalueres. På denne måten kan fornybar energiproduksjon og kostnader optimeres for å styrke konkurransedyktigheten mot eksisterende energiproduksjonssystemer.

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Preface

This master's thesis is written spring 2016, at the Department of Engineering Design and Materials at NTNU Trondheim, Norway. The thesis aims to highlight the benefits of using a cooling/heating system in combination with photovoltaic solar panels. Finding new methods to harvest renewable energy and combining existing technologies in new and efficient ways are important contributes of reaching the goal set by The 2015 United Nations Climate Change Conference (COP 21). Amongst the goals were: *Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change* UNFCCC (2015) Article 2, 1(a). The treaty were signed by 177 countries. Along with the shared international goals were the Intended National Determined Contributions (INDCs). Each country were to submit their own INDCs, formulating their own reduction in greenhouse gases from 1990 to 2030. In accordance with Europe Union: *Norway is committed to a target of an at least 40% reduction of greenhouse gas emissions by 2030 compared to 1990 levels* Norway (2015).

Buildings are the largest energy consuming sector in the world, and account for over one-third of total final energy consumption and an equally important source of carbon dioxide (CO2) emissions IEA (2013). Although producing renewable hydropower electricity, Norway top the list of electric power consumption per citizen CIA (2016), only beaten by Iceland. In Norwegian households, 64 % of the electric power is used for space heating, and additionally 15 % for hot water SINTEF (2008). This makes Norway a country well suited for research and development on combined electrical and thermal production.

An overview of global energy potential, total reserves, and annual renewables can be seen in Figure 1. This shows how solar power is annually over ten times more then all other forms of energy combined. If 3% of The Sahara Desert was covered in solar panels with 20 % efficiency it would be enough to supply the whole world with energy. Learning how to harvest the power of the sun in an efficient way that reflects the human needs for energy will in the long run be crucial to the survival of the human race.

As you can see on Figure 2 fossil fuels dominates as today's energy source. In addition, the

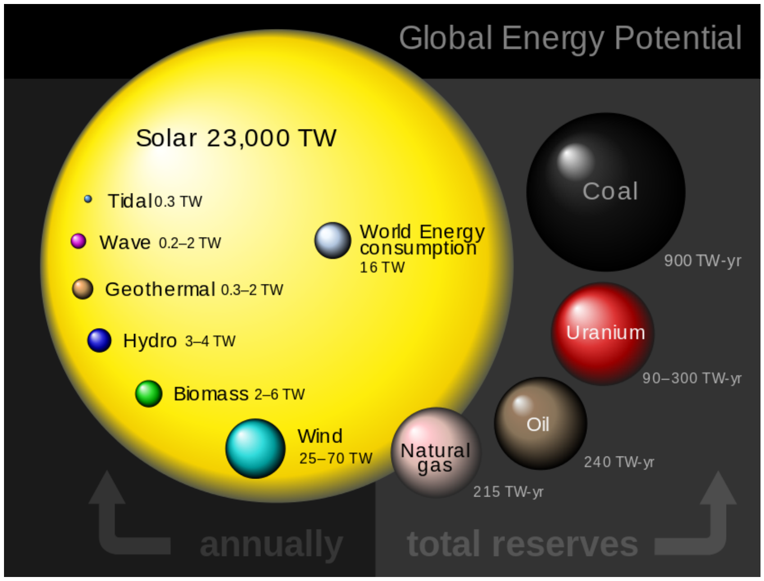

Figure 1: Overview of Global Energy Potential Perez and Perez (2009)

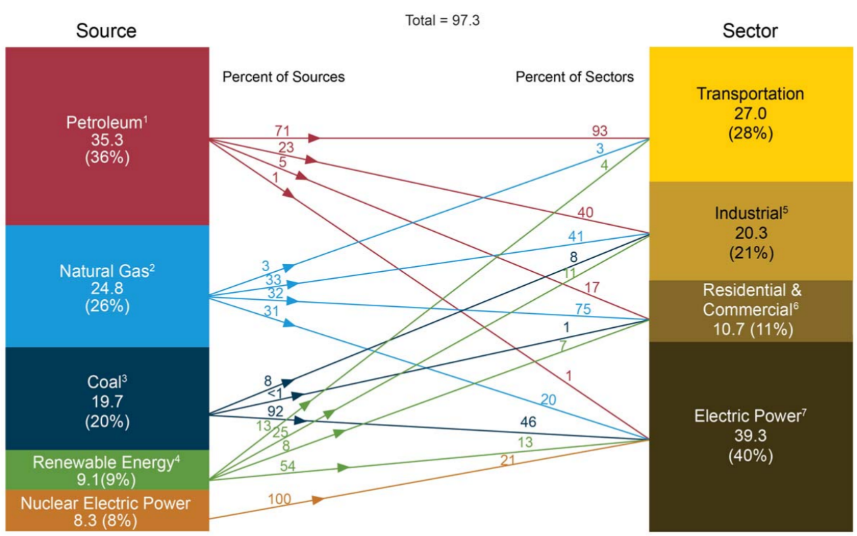

Figure 2: Primary energy consumption by source and sector in the U.S. EIA (2011)

thermal energy from the fuels are often converted to mechanical energy before use. This results in approximately 70-75% energy loss in petrol/gasoline cars, 60% loss in diesel engines and 67% loss in coal-fired power stations. Electric motors on the other hand have about 10% energy loss. Mechanical energy can also be used in a heat pump, where thermal energy is extracted from the surroundings. This way, using one watt of high-grade energy will result in multiple watts of thermal energy, based on the difference in temperatures/coefficient of performance. It can also be seen on Figure 2 that petroleum, coal and nuclear electric power each have specific consumer sectors. Renewable energy and natural gas however are more applicable, and provides energy in all sectors.

The idea of constructing a combined photovoltaic solar panel and a cooling/heating system came from the fact that photovoltaic solar panels are more efficient in colder operating temperatures. A temperature difference of 1 degree will result in about 0,5% more efficient solar panel. This is however not a new concept. The idea of a solar assisted heat pump (SAHP) was first introduced by Sporn and Ambrose (1955). Combining this with a photovoltaic panel has been proposed by a number of researchers as presented in the literature survey. This concept are however especially applicable in Norway, where the need for thermal energy is especially high due to the cold climate. The writer of this thesis agrees with Kjellsen (2016) that; *A proper test-rig where new solar-collector evaporator designs, different compressors, expansion valves and other components easily could be changed would greatly facilitate the speed of experiments and results ... Key components should be easy to change so that a range of experiments can be conducted in a short time comparing different components and refrigerants.* Although building a complete, working test rig in six months might be ambiguous for one person, this is the starting point for this master's thesis.

Trondheim, 2016-06-10

Magnus Størdal Lund

Acknowledgment

First of all i would like to thank my two supervisors Trygve Magne Eikevik and Bjørn Haugen. Bjørn Haugen gave necessary approvals and fundings that made it possible for me to build the test rig. Trygve Magne Eikevik showed great interest in the subject and made it easy for me to start my master's thesis. He and Reidar Tellebon have helped me with the test rig with parts from the Department of Energy and Process Engineering. I want to thank SINTEF Living Lab for letting me use one of their REC260PE solar panels. I would also like to thank Trondheim Stål for providing me with the water- and lazer cut aluminum plates on the test rig. The aluminium backplate was further milled at the Department of Engineering Design and Materials, and I would like to thank Per-Erik Heksem and Børge Holen for their help. I would like to thank Technium AS aswell, for letting me use their 3D printer.

Finally, I would like to thank my friends and family, and my girlfriend for their continuous support throughout my education.

M.S.L.

Summary and Conclusions

This masters thesis has reviewed the potential of combining electrical and thermal energy extraction from solar power. Both cold, Norwegian climates and areas with higher level of solar power have been discussed. A test rig has been constructed, and a simplified experiment have been conducted. The experiment shows that there are potential for thermal energy extraction from solar power, even in Norway. The solar panel was cooled down up to 8 degrees, resulting in an estimated 4% increase in electrical energy production, and at the same time a significant thermal energy production. The results from simulations and testing indicates however some potential issues with combining photovoltaic panels and solar collectors. Some new ideas, and recommendations for further work have also been presented.

Sammendrag

Denne masteroppgaven har vurdert potensialet i å kombinere elektrisk og termisk energiutvinning fra solenergi. Både kalde, norske klimaer og områder med høyere grad av solenergi har vært diskutert. En testrigg er konstruert, og et forenklet eksperiment er gjennomført. Forsøket viser at det er potensialet for termisk energiutvinning fra solenergi, selv i Norge. Solcellepanelet ble nedkjølt 8 grader, noe som resulterte i en anslått 4% økning i elektrisk energiproduksjon, og samtidig en betydelig termisk energiproduksjon . Resultatene fra simuleringer og tester viser imidlertid noen potensielle problemer med å kombinere solcellepaneler og solfangere. Noen nye ideer og anbefalinger for videre arbeid har også blitt presentert.

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Chapter 1

Introduction

The goal in this master's thesis is to build a test rig that facilitates research and development on the principles of energy production with solar panels in combination with cooling/heating systems. The rig should reflect real user/consumer applications and consist of commercially available products. Design-for-testing will be emphasized and components and configurations should be easily changeable and adaptable.

1.1 Background

As of today, about 80% of all high-grade electrical energy used in buildings in Norway is used for low-grade heating needs. Air source heat pump (ASHP), geothermal energy, district heating, heat bank and fuelwood are other existing ways of utilising thermal energy alternatively. Norway are already exporting renewable energy from hydroelectric power stations to other countries. Non-renewable electric power needs to be imported to Norway when demand is high and water reservoir levels are low.

Problem Formulation

The problem is to design a system that combines electrical and thermal energy production and storage with consumer needs in an efficient way. In order for it to be sustainable the system must be able to compete with other existing systems on price and level of environmental impact. This is a complex system with many variables. The main focus in this thesis will be to evaluate the suggested concept compared to Norwegian weather and the need for thermal energy. Test results from the experimental setup and calculations will help determine the systems overall performance and identify areas of improvement.

Literature Survey

A photovoltaic thermal hybrid solar collector assisted heat pump water heater (PVTA-HPWH) is presented in Tsai (2015). The system is both simulated and experimentally tested, showing good agreements. *Photovoltaic/thermal (PVT) solar collector can simultaneously produce electricity and heat. It is currently considered the most efficient device to harness the available solar energy ... The recovered heat lessens the effort of vapor compression and reduces the power consumption of compressor. To lower the working temperature of rooftop PVT evaporator not only increases PV efficiency due to lower cell temperature of PV device also enhances thermal efficiency with the heat of recovery of ambient air.* It can be seen from Figure 1.1(e) that the fluctuations in the weather from 12:06-12:22 has little effect on the overall performance of the water heating system.

In R. Zakharchenkoa (2004) a combined system of a photovoltaic panel (PVP) and a thermal collector was studied. The area of the PVP was scaled down compared to the area of the thermal collector. The PVP was placed over the entrance of cold water on the solar heat collector (SHC). This way, the efficiency of the PVP went up about 10%, without reducing the heat extraction in the SHC too much.

The dynamic performance of a photovoltaic solar assisted heat pump (PV-SAHP) is analysed in Jie Ji (2007). The results show that the system have superior coefficient of performance (COP) compared to conventional heat pump systems due to the higher evaporating temperature (see Figure 1.2). By using a refrigerant to cool down the PV-panel the photovoltaic efficiency is also higher.

Bergene and Løvvik (1995) presents a detailed physical model of a hybrid photovoltaic/thermal system. *The model is based on an analysis of energy transfers due to conduction, convection and radiation and predicts the amount of heat that can be drawn from the system as well as the (temperature-dependent) power output.* The model estimates the efficiency of the system to be about 60-80% (thermal + electrical).

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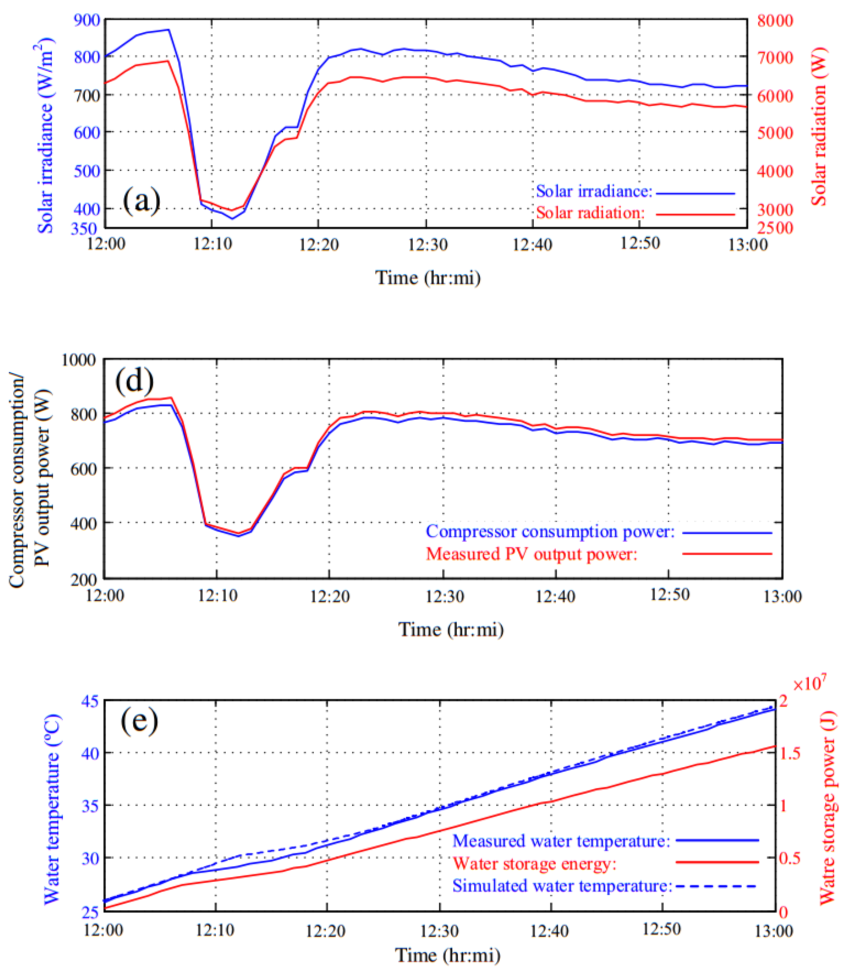

Figure 1.1: From Tsai (2015). Measured and simulated data of PVTA–HPWH system on a mostly sunny day (2013/06/12): (a) Solar irradiance and radiation, (d) compressor consumption power compared with measured PV output power, (e) measured and simulated water temperature and its storage energy of water tank.

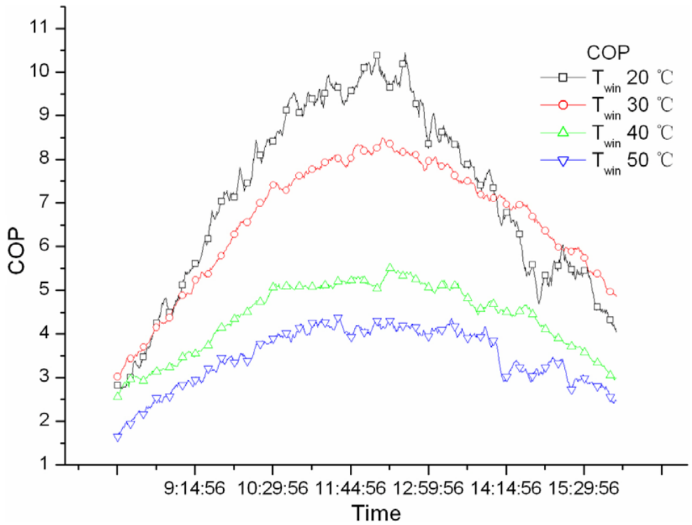

Figure 1.2: From Jie Ji (2007). Daily variation of heat pump COP for different condenser supply water temperature.

What Remains to be Done?

There is no photovoltaic/thermal heat pump (PV/T-HP) operating in Norway today (to the writer of this thesis' knowledge). What remains to be done is therefore to start exploring the possibilities with this concept and evaluate its potential. It will also greatly benefit other countries if Norway manages to implement successful energy producing and saving systems.

1.2 Objectives

The main objectives of this master's thesis are

1. Build a photovoltaic/thermal heat pump (PV/T-HP) test rig
2. Evaluate the performance of the system and compare it with simulations
3. Discuss performance and potential considering Norwegian weather conditions
4. Suggest other ideas, designs and concepts for further work on renewable energy

1.3 Limitations

PV/T-HP is a complex system with wide possibilities and there will be significant limitations in this thesis. The idea of writing about photovoltaic solar panels in combination with cooling/heating systems came from the writer of this thesis, and was not financially supported by an external company. The process will consist of various disciplines, and may prove to be difficult to overcome for one person during one semester. Nevertheless, the worlds need for research and development on renewable energy makes the effort worthwhile. The focus will therefore be to start the construction of a rig that is easy to implement in other similar projects and can be used by other students.

Chapter 2

Equations

The efficiency of solar cells is generally temperature dependent, usually with decreasing efficiency as the temperature increases because of the temperature dependence on mobility, diffusion length and lifetime of minority charge carriers and on the saturation current Fahrenbruch and Bube (1983).

From Fahrenbruch and Bube (1983) an empirical relation of the power P from a solar cell is given by

$$P(T_s) \approx (\eta_0 - c(T_s - T_a))E \tag{2.1}$$

where T_s and T_a is the temperature of the solar panel and ambiance respectfully, η_0 is the efficiency of the solar cell at its reference temperature, c is the temperature dependence factor from the specific panel and E is the total available irradiance. From Bergene and Løvvik (1995) we have that the total efficiency of the solar cells is

$$\eta_S = \eta_0 - c(T_S - T_a) \tag{2.2}$$

In a DX-SAHP the temperature of the solar panel will decrease as heat energy is drawn from it, acting as the evaporator in a heat pump. From Bergene and Løvvik (1995) we have that the thermal efficiency, or the ratio of the generated heat to the incoming solar irradiation is

$$\eta_A = \frac{Q_T}{E \cdot L \cdot W} \tag{2.3}$$

where L and W is the length and width of the solar panel. From the first law of thermodynamics and the Carnot efficiency we have that the maximum theoretical efficiency of a heat pump (COP) is

$$COP_{Heating} = \frac{T_{Hot}}{T_{Hot} - T_{Cold}} \tag{2.4}$$

where T_{Hot} and T_{Cold} is the temperature at the condenser and the evaporator, respectively. The exergy efficiency of the complete system can be evaluated for comparison other solar and thermal energy collectors:

$$\eta_B = \frac{B_{out}}{B_{in}} = \frac{P(T_S)) + Q_{HW}(1 - \frac{T_a}{T_{HW}})}{E + W_c} \tag{2.5}$$

where Q_{HW} and T_{HW} are thermal energy and temperature of the water in the storage tank and W_c is the work done by the compressor.

2.1 The Test Rig

Originally the test rig was intended to be a small scale table mounted version, for easier building, setup and at reduced cost. Due to the low budget, the plan was to get support from the industry on expensive components, machining and assembly. It turned out to be more difficult then expected, especially as the Norwegian industry is currently under economical pressure due to the low oil prices. When a solar panel finally was at hand it was much bigger and heavier then originally planned, and the design of the rig had to be modified accordingly.

The Assembly

A picture of the rig can be seen on Figure 2.2. It features an aluminium frame from AluFlex item systems, which enables detachable aluminum profiles from their assembly solution. All the profiles are "second hand". The solar panel can be rotated around the upper mounting in order to adjust the angle facing the sun. The bottom aluminium plate is a platform for the water tank, the heat pump assembly, measurement devices, laptops etc. The wheels enables easy movement and mobility.

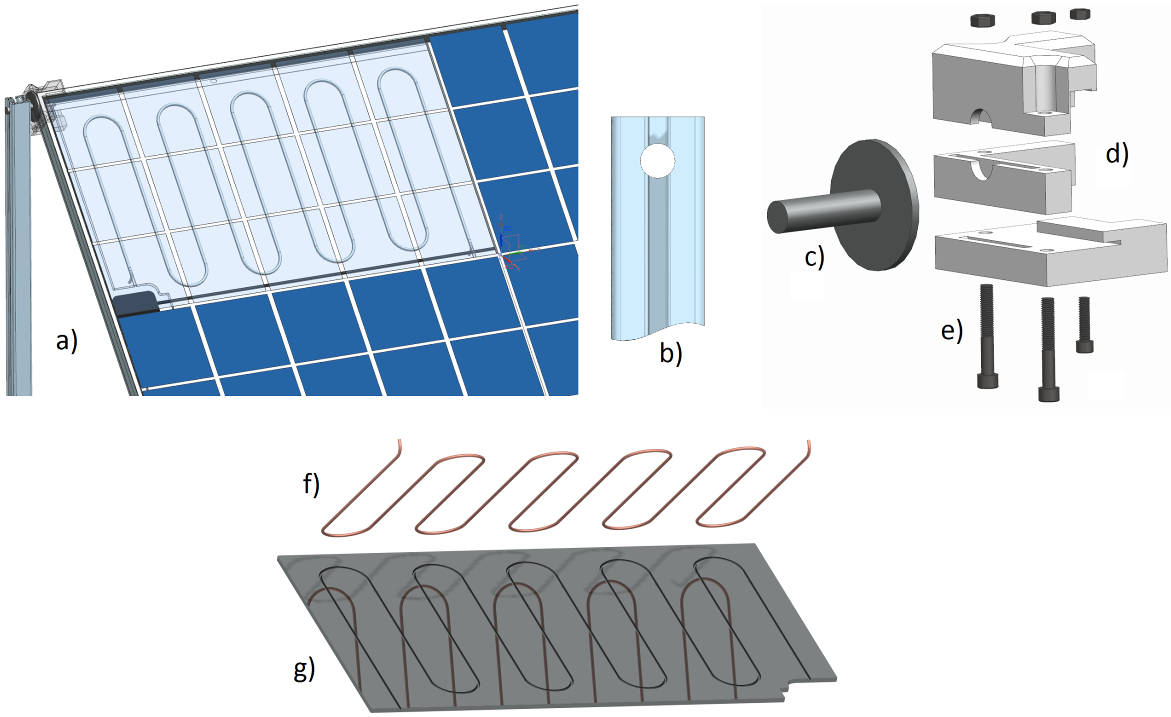

Figure 2.1: Some features on the test rig, a) The assembly, b) AluFlex aluminium profile, c) Custom aluminium hub, d) 3D-printed (PLA-plastic) bracket, e) Standard bolts, M6 x 40 and M5 x 20, f) easily formable copper tubes (Ø5, 5 m), g) 8 mm thick aluminium backplate, watercut by Trondheim Stål, grooves for copper tubes milled at Department of Engineering Design and Materials.

Figure 2.2: The test rig (picture taken 01.06.2016)

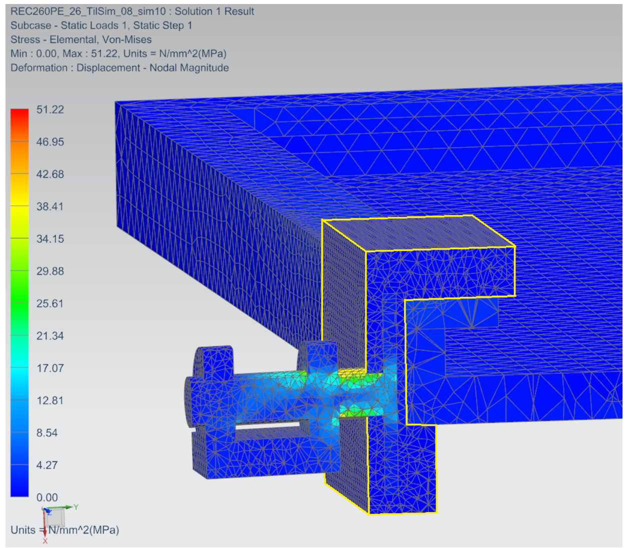

Figure 2.3: FEM-analysis of an earlier version of the 3D printed bracket (highlighted in yellow). Plot shows max stress of 51,22 MPa in the aluminum hub.

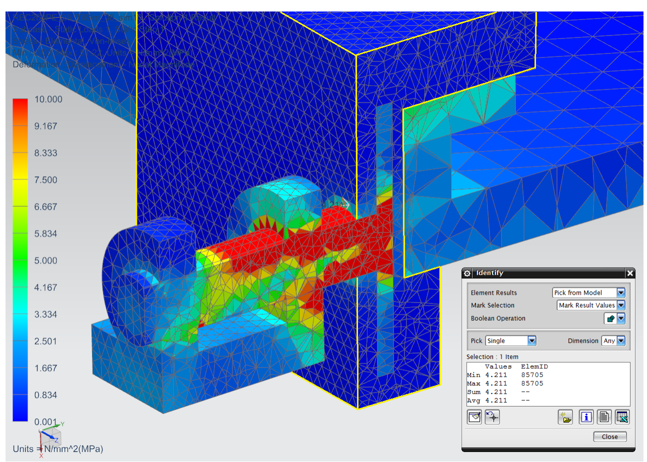

Figure 2.4: Another picture of the same simulation. The value control is set to max 10 MPa. Max stress in 3D printed bracket was 4,211 MPa.

A comment on the 3D printed brackets

The goal was to deliver the REC260PE Solar Panel back to SINTEF in one piece, without any modifications. The challenge was then to design the mounting without drilling any holes in the aluminium frame around the solar panel. The resulting bracket-assembly turned out to be quite challenging to make from aluminium. A cheap and bold alternative was to prototype the bracket on a 3D printer (Fused Deposition Modeling) in PLA plastic. Since the total weight of the solar panel and the backplates were over 50 kilograms, it seemed a good idea to evaluate whether the brackets would be sufficient to hold the static load. Figure 2.3 and Figure 2.4 shows a FEM-analysis of an earlier version of the 3D printed bracket. The plots show that the bracket is subjected to max stress of about 4,2 MPa. Since the yield strength of 3D printed PLA-plastic is around 60 MPa, this analysis reaches the conclusion that the brackets will hold under the static load from the solar panel and the aluminium backplates with a sufficient safety factor.

2.2 Simulations in COMSOL Multiphysics

Simulations in COMSOL Multiphysics were conducted to analyse the performance of the system and especially the thermal conductivity of the materials. A CAD-model representing the geometry of the rig was made in Siemens NX 8.5. The model was then simplified and split up to a symmetric, repeatable representation of the geometry and exported to COMSOL. The materials were then added from the built-in library in COMSOL: Backplate - Aluminium, Tubes - Copper, Fluid in tubes - Water, liquid, Top plate - Polysilicon (Figure 2.5) and Polyethylene (Figure 2.6). The 3D-simulation had Heat Transfer->Conjugate Heat Transfer->Laminar Flow as chosen physics, as this simulates the coupling between heat transfer and fluid flow. Stationary study was chosen because the field variables did not change over time. The inlet temperature of the fluid were set to 283 K. The average inlet velocity of the fluid was set to 1 m/s. The heat received from the sun was simplified to a boundary heat source with an overall heat transfer rate of 18,407 W (equivalent of 500 W/m^2), placed on the top side (see Figure 2.5). Symmetric conditions were set on appropriate walls regarding heat transfer with surrounding geometry. The inlet of the fluid was set to one of the tube openings (see the highlighted picture in Figure 2.6 d). The outlet was set to the opposite side.

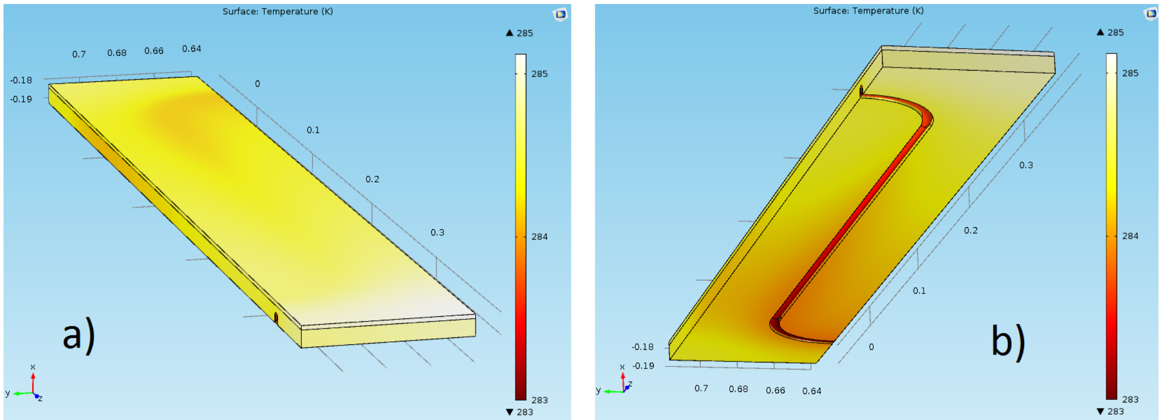

Figure 2.5: Simulation in COMSOL Multiphysics. a) Top side facing the solar panels (material used: Polysilicon). b) Backside, where the aluminium plate and copper tubes are mounted.

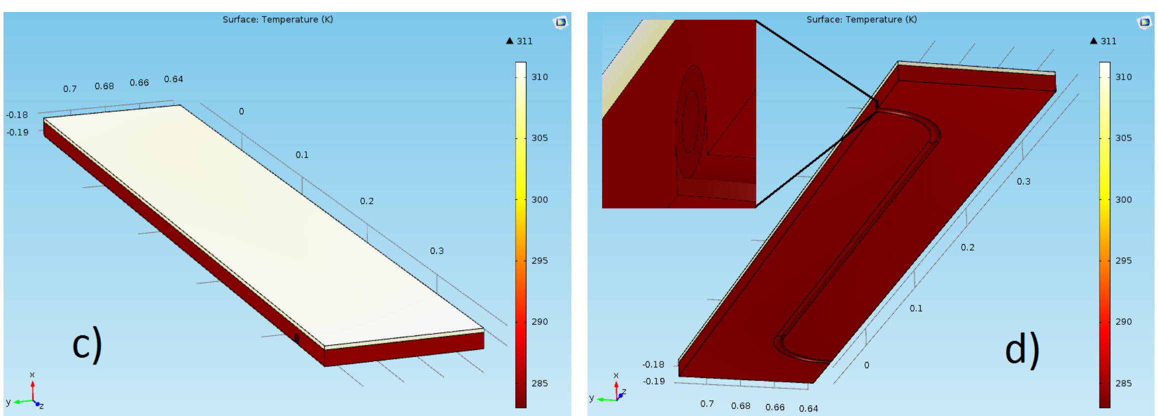

Figure 2.6: Simulation in COMSOL Multiphysics. c) Top side facing the solar panels (material used: Polyethylene). d) Backside, where the aluminium plate and copper tubes are mounted.

2.2.1 Commenting simulation results

The plots show that it is possible to create a more or less uniform cooling of the solar cell panel, with about 2 degrees (Figure 2.5) of maximum difference at relative high rate of heat transfer to the panel (500 W/m^2). The design of copper tubes path, length and fluid velocity can be further developed and evaluated using more or less the same simulation setup. However, the difference between Figure 2.5 and Figure 2.6 reveals a potential unfavorable feature with the solar panel. The only difference between the simulations is the material used on the top plate, with polysilicon (similar to solar cells) in Figure 2.5 and polyethylene on Figure 2.6, (more representable with the REC260PE assembly). As seen in the REC Peak Energy BLK Series data sheet, the solar panel has a back sheet with a double layer highly resistant polyester. This ensures electrical isolation of the solar cells, but also results in thermal insulation between the cooling plate and the solar cells due to the significant difference in thermal conductivity (polyethylene: 0.38 W/mK, polysilicon about 130 W/mK). As a result, the cooling of the solar cell is more or less uniform, but the temperature of the panel stays 27 degrees above the cooling plate (in this simulation).

2.3 Experiment

A small, simplified experiment was set up to test the rig. The experiment was reduced to a PV/T system, without electric energy production as the rest of the rig wasn't finished. This was obviously not optimal, but the main goal of the experiment was to evaluate the potential problem from the COMSOL simulations. The panel was placed as shown in Figure 2.7 and its position was kept constant during the day. Measurements were taken every half hour. The solar power was measured with Velleman DVM1307 Solar Power Meter. The measuring probe was placed normal to the solar panel, as shown in Figure 2.8 a. The temperatures of the inlet water, outlet water, the aluminium backplate and the solar panel was measured with an infrared thermometer, IRT 260. The solar panel was measured on the opposite side of the backplate to evaluate the thermal conductivity, and also on a location distant from the cooling to evaluate the difference between cooling and not cooling.

It should be noted that the temperature of the solar panel was highly fluctuating, varying with the weather conditions and position on the panel. The measurement data can be seen on

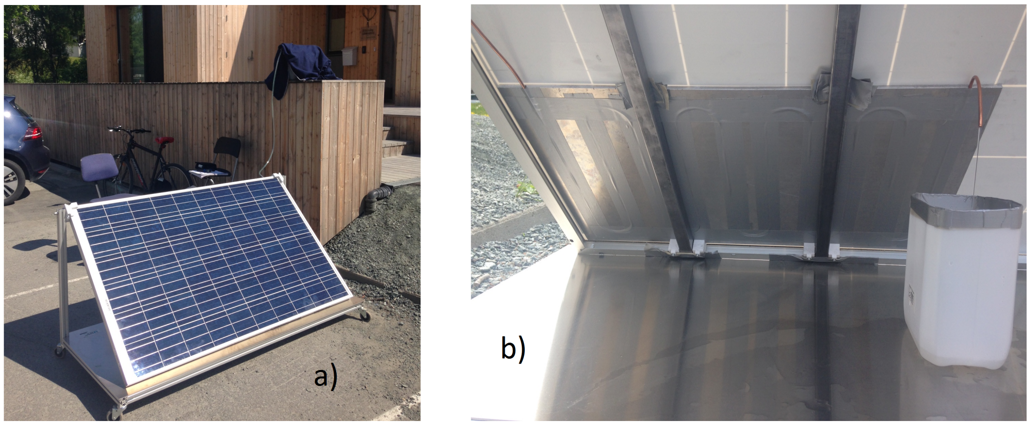

Figure 2.7: Experiment setup, a) shows the positioning of the REC260PE solar panel. b) Inlet of the cooling water to the left. Outlet to the right.

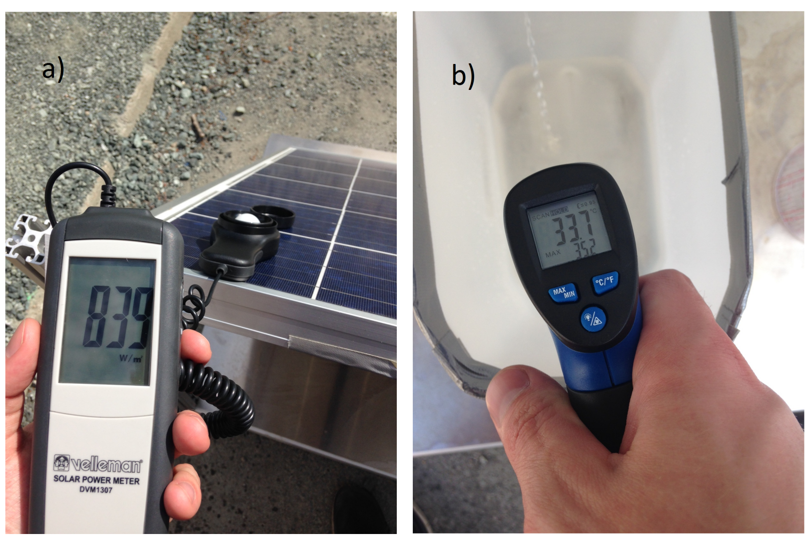

Figure 2.8: a) Measuring the solar power with Velleman DVM1307 Solar Power Meter. b) Measuring the temperature of the outlet water with IR TERMOMETER IRT 260.

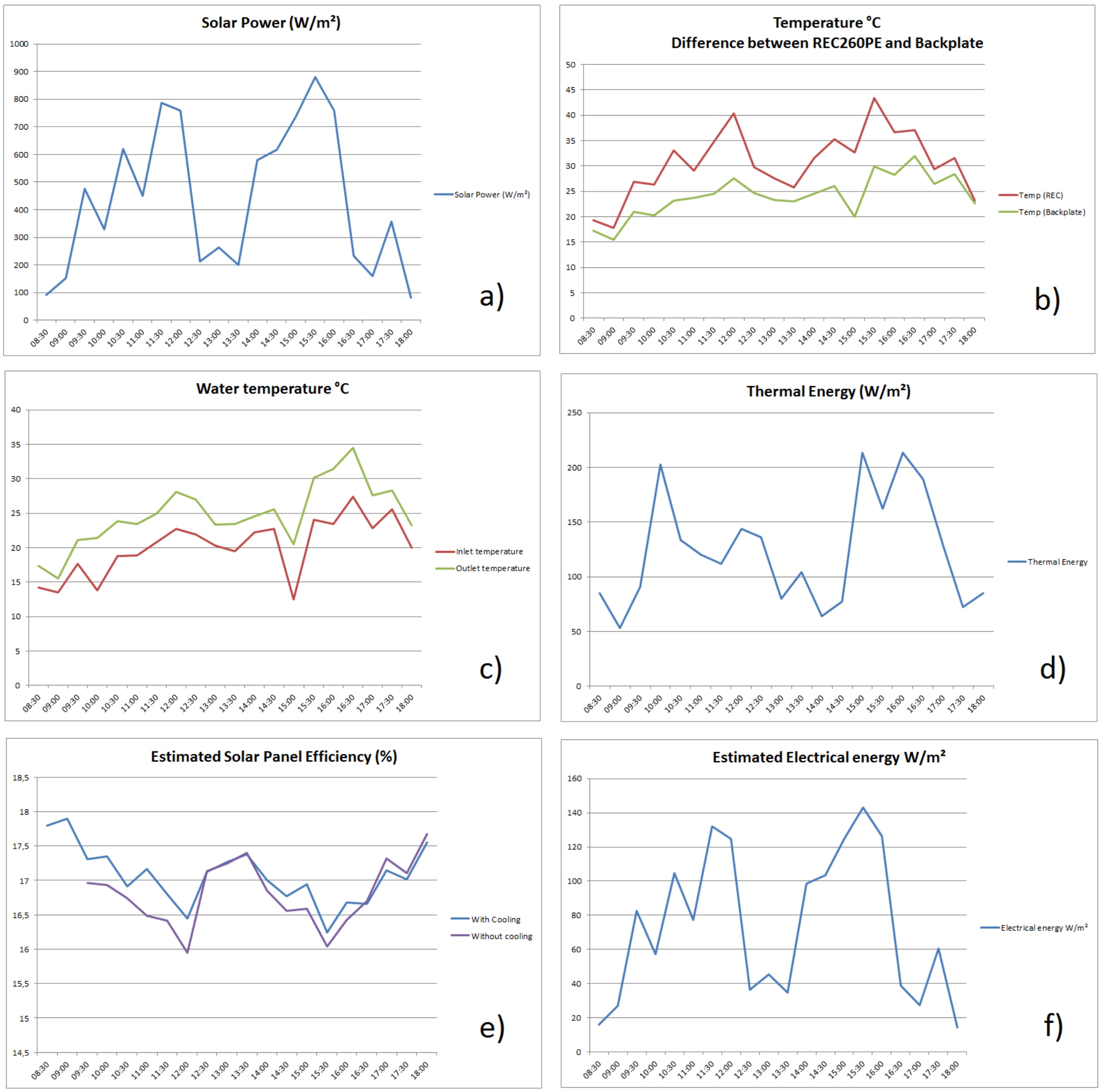

Figure 2.9: Data from the experiment. a) Solar power normal to solar panel, b) Temperatures in solar panel and backplate, c) Inlet and outlet water temperature, d) Thermal energy collected calculated from the difference in water temperature, e) Estimated solar panel efficiency from solar panel temperature, f) Estimated electrical energy produced from solar power and solar panel temperature.

Figure 2.9 a), b) and c).

2.3.1 Commenting on the results from the experiment

The most significant result from the experiment is the measured difference in temperature between the solar panel surface and the backplate, as seen on Figure 2.9 b. The graph shows a difference in temperatures of about 13,5 degrees at maximum, which is not optimal for a system that needs good thermal contact in order to extract thermal energy efficiently. This is however lower then simulated in COMSOL which indicated 27 degrees. This is probably because the COMSOL simulation did not have convection from the ambient air in the analysis. The assumed heat transfer rate of 500 W/m^2 was probably also too high. Figure 2.9 e) shows estimated solar panel efficiency, and the difference between cooling and not cooling the panel. At maximum difference the solar panel efficiency percentage increases about 0,68 points, which is an increase of about 4,14 % by cooling the panel with this experiment setup. Calculating the total energy from Figure 2.9 d) and f) gives an estimated electrical energy production of 2,63 MJ and a thermal energy of 4,28 MJ per square meter throughout the day of testing (June 16, 2016 at NTNU Trondheim, Norway).

2.4 Thermal energy

2.4.1 Thermal Energy Storage

One of the disadvantages with photovoltaic/thermal solar panels (PV/T) and direct expansion solar assisted heat pumps (DX-SAHP) is that when the system is operating at its maximum, i. e. when the sun is shining, the need for thermal energy will be the lowest. One alternative is to store the thermal energy for later use. Seasonal Thermal Energy Storage (STES) can provide a building with heating needs throughout the year. Holes are drilled into the ground deep below the building, containing large amounts of water. This way, solar energy harvested during summer can be used for heating during the winter season. However, since the warm, sunny days in Norway is are less frequent then the cold autoumn/winter/spring nights, a PV/T system alone would not be able to provide buildings with enough thermal energy without using additional heating.

2.4.2 Heat pump and seasonal thermal energy storage

If electricity is used for generating thermal energy, the most efficient way to utilise it would be to use a heat pump. The heat pump will operate more efficiently with less difference in temperatures (see Figure 1.2). Since the average temperature of Trondheim from June 2015 to May 2016 (from yr.no) was 6,26 °C, and the average indoor temperature is about 20 to 25 °C, a heat pump would be a good alternative for domestic heating. It is , however, less efficient during the cold winter, and less needed during the warm summer. A solution may be to let a PV/T or a DX-SAHP produce electrical and thermal energy during the warm months (June, July, August, September), and storing it for the colder months (December, January, February, Mars). The remaining months (October, November, April and May) could be heated by a heat pump with the electrical energy produced on sunny days.

Another alternative is illustrated in Figure 2.10 b). In Hesaraki et al. (2014), the combination of PV/T, heat pump and seasonal thermal energy storage is reviewed. *The problem with seasonal storage, however, is heat loss. This can be reduced by low-temperature storage but a heat pump is then recommended to adjust temperatures as needed by buildings in use.* The heat pump can also be used between the collector and storage tank for enhanced thermal energy extraction from the solar collectors. The main factors indicating the overall performance of a seasonal thermal energy storage is the COP of the heat pump and the solar fraction (SF);

$$SF = \frac{q_c - Q_{loss}}{Q_{hd}} \tag{2.6}$$

where q_c is average amount of heat produced by a solar collector, Q_{loss} is the thermal loss from the system, and Q_{hd} is the heating demand in the building. These factors increase with increasing solar collector area and storage volume.

The energy conservation for a thermal energy storage system is

$$q_c + W_{hp} = Q_{hd} + Q_{loss} + Q_{tank} \tag{2.7}$$

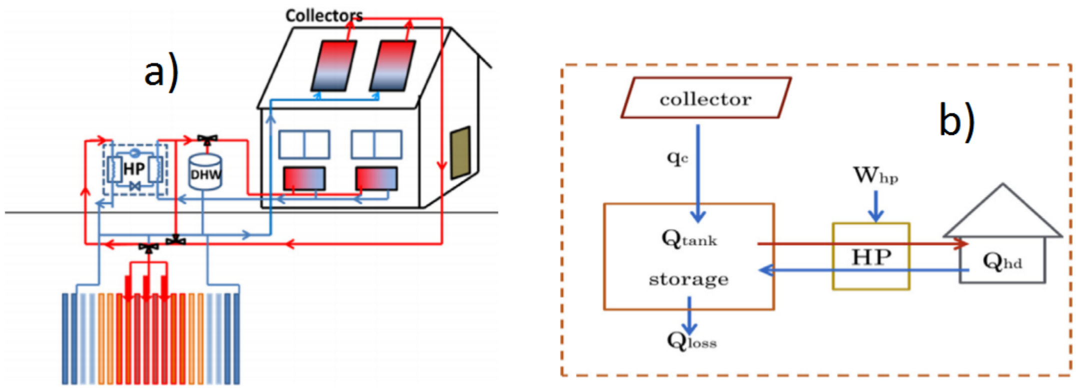

Figure 2.10: From Hesaraki et al. (2014). a) Borehole thermal energy storage with a heat pump and solar collectors. b) Energy conservation for thermal energy storage with heat pump.

where W_{hp} is electricity input to the heat pump and Q_{tank} is the stored energy in the tank.

2.4.3 Choice of refrigerant for the heat pump

When choosing the refrigerant for the heat pump, several factors must be considered. Optimizing electrical energy consumption and efficiency is important regarding environmental aspects, but not if using the refrigerant itself results in disposal of other harmful chemicals to the atmosphere. Hydrofluorcarbons, such as R134a have a high global warming potential (GWP) Bengtsson and Eikevik (2016) . Leaking will therefore result in an undesirable increase of global warming, especially for large scale systems. Other refrigerants with low GWPs are therefore a better alternative. As ammonia (R717) is incompatible with copper and the system will operate beyond the critical temperature for carbon dioxide (R744), refrigerants such as propane (R290) and the widely used isobutene (R600a) are to be recommended. *The hydrocarbon (HC) refrigerants R290 and R600a are strong candidates and have many benefits: they are cheap, non-toxic, chemically stable, compatible with many materials, and miscible with mineral oils [8,9]. The drawback is their flammability [12], which makes it important to have a low charge of refrigerant, a completely sealed system, and good ventilation around the heat pump system* Bengtsson and Eikevik (2016).

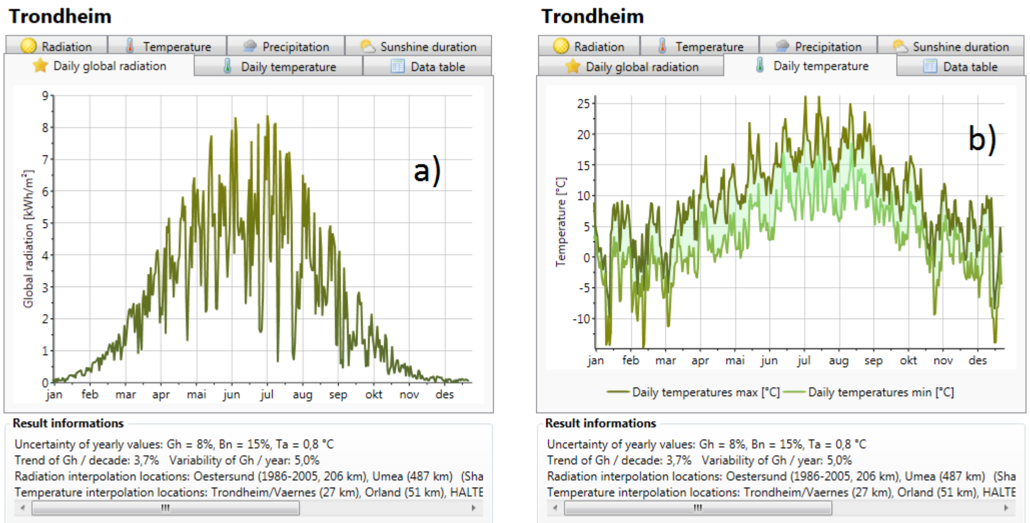

Figure 2.11: Output data from meteonorm 7. a) Daily solar radiation in KWh/m^2 on coordinates: latitude 63,416419 longitude 10,410864 (IPM, NTNU Trondheim). b) Average temperatures.

2.4.4 Estimations on the use of a combined PV, heat pump and thermal energy storage system implemented in a Norwegian climate (Trondheim)

A rough estimate will be given here, on the use of combined PV/T, heat pump, and thermal energy storage systems. This system will be complex and multidisciplinary, with many different variables. The calculations and simplifications done here will not be an accurate analysis, but a suggested calculation, using existing renewable energy production and storing techniques.

From SSB (2012) we have that the average total energy consumption in households in Norway is about 25000 KWh per year. About 5000 KWh is from fuelwood, oil firing and other fuel based energy sources. From SINTEF (2008) we have that around 80 % of all the electric energy is also used for heating. We therefore have that

$$P_{tot} = 25000KWh \tag{2.8}$$

$$Q_{hd} = 20000 \cdot 0,8 + 5000 = 21000KWh \tag{2.9}$$

$$E_{el} = P_{tot} - Q_{hd} = 4000KWh \tag{2.10}$$

where E_{tot} is total energy consumption for one household per year, Q_{hd} is the heating demand

Trondheim

Radiation | Temperature | Precipitation | Sunshine duration | Daily global radiation | Daily temperature | Data table

	Gh kWh/m²	Gh hor kWh/m²	Dh kWh/m²	Bn kWh/m²	Ta °C	Td °C	FF m/s
January	6	0	4	22	-0,2	-4	5,1
February	23	0	12	57	-0,9	-5	4,6
March	65	0	29	110	0,8	-4,4	4,2
April	111	0	46	156	5,9	-0,5	3,9
May	153	0	71	168	9,4	3,1	4,1
June	158	0	83	150	12,4	6,9	4,1
July	154	0	60	188	15,3	10	3,6
August	112	0	62	111	14,7	9,8	3,4
September	67	0	30	98	11	6,7	4
October	30	0	17	52	6,2	1,8	4
November	8	0	6	17	2,6	-1,6	4,6
December	3	0	2	12	-0,2	-4	4,6
Year	885	0	421	1141	6,4	1,6	4,2

Result informations

Uncertainty of yearly values: Gh = 8%, Bn = 15%, Ta = 0,8 °C
Trend of Gh / decade: 3,7% Variability of Gh / year: 5,0%
Radiation interpolation locations: Oestersund (1986-2005, 206 km), Umea (487 km) (Sha
Temperature interpolation locations: Trondheim/Vaernes (27 km), Orland (51 km), HALTE

Figure 2.12: Table from meteonorm 7. Monthly solar radiation and average temperatures.

and E_{el} is electrical energy. From Figure 2.11 and Figure 2.12 we have that March through October gives a total of 696 KWh/m^2 in solar radiation. In November through February the solar energy will be less reliable due to the inclination angle of the sun and snow covering the panels. In this period the solar panels will produce about

$$E_{SP} = S_R \cdot \eta_{sp} = 696 \cdot 0,15 = 104,4 KWh/m^2 \tag{2.11}$$

where S_R is solar radiation and η_{SP} is the efficiency of the solar panel (here simplified to 15%). The thermal energy collected by regular solar collectors will have efficiencies of about 40-70%. Combining this with PV gives various efficiencies with different configurations. Here, we will simplify the thermal energy extraction to 30% of the solar radiation. The thermal energy extracted is therefore

$$q_c = S_R \cdot \eta_{sc} = 696 \cdot 0,30 = 208,8 KWh/m^2 \tag{2.12}$$

where q_c is thermal energy produced and η_{SC} is the efficiency of the solar thermal collector. Thermal energy extracted from the solar cells will also result in 5-15% increase in electric energy production, but is not taken into account in this calculation. It now comes down to how much area is covered with PV/T. If we use the ZEB Living Lab as a reference, the roof of the house holds

48 units of REC260PE solar panels. This equals

$$E_{prod} = 48 \cdot A_{REC} \cdot E_{SP} \approx 8000KWh \tag{2.13}$$

and

$$q_c = 48 \cdot A_{REC} \cdot Q_c \approx 16000KWh \tag{2.14}$$

where $A_{REC} = 1,6m^2$ is the area of the REC260PE solar panels. Using the energy conservation for thermal energy from equation 2.7 gives

$$16000KWh + W_{hp} = 21000KWh + 16000KWh \cdot 0,3 + 16000 \cdot 0,10 \tag{2.15}$$

$$W_{hp} = 11400KWh \tag{2.16}$$

Where Q_{loss} is simplidfied to 30% of q_c, and Q_{tank} is simplified to 10% of q_c. Bear in mind that this is an equation for combined STES and heat pump. Its still possible to generate thermal energy with regular PV/T, but in many cases a heat pump will be necessary. The remaining thermal energy need can therefore be covered by a air-to-air or STES heat pump. The solar fraction is

$$SF = \frac{16000KWh - 16000 \cdot 0,3}{21000KWh} \approx 53\% \tag{2.17}$$

which gives

$$Q_{tot} = 21000KWh - 0,53 \cdot 21000KWh = 9870KWh \tag{2.18}$$

and

$$E_{tot} = 8000KWh - 4000KWh = 4000KWh \tag{2.19}$$

that shows that the electrical energy production will be capable of covering both electrical consumption, and the remaining of the thermal energy need with a heat pump system with COP of at least 2,5. In total, these calculations suggests that a regular Norwegian family house can be more or less self-sufficient on energy, and therefore save about 20 000 NOK, or 2400 USD annually on energy spendings (these figures will vary. Here the sum of power, grid rent and taxes are assumed to be 0,80 NOK/KWh). The investment cost of such a system therefore needs to be carefully considered. As mentioned, the advantages of using combined PV/T, heat pump and thermal energy storage will increase and relative cost will decrease with increasing size.

2.5 Other Concepts and Ideas

2.5.1 Concentrated Photovoltaics (CPV)

For other parts of the world with more sunlight then Norway, there are other alternatives in converting solar irradiation to electrical power than the most commonly used single crystalline silicon photovoltaic solar panels. A variety of different solar panels and their improving efficiencies can be seen on Figure 2.13. Figure 2.14 shows how the light spectrum from the sun is absorbed by different cells. Today, solar panels with multijunction cells can produce electricity with an efficiency of 46 % from concentrated solar irradiation. These solar panels however, use concentrated photovoltaics (CPV) and the concentration needs equal 400 suns or more. This gives the need for adequate cooling of the solar cells, and further leads to an obvious potential for thermal energy extraction. Examples of companies working on this concept is Zenith Solar from Israel (see Figure 2.15 and Figure 2.16) and Absolicon AB from Sweden (see Figure 2.17). Operating in areas with high level of Direct Normal Irradiance (DNI), Zenith Solar claims to achieve efficiencies of up to 72 % with their combined heat and power (CHP) units.

2.5.2 A comment on Direct Normal Irradiation

Figure 2.17 shows the level of DNI across the world. DNI is the amount of solar irradiation per area that would hit a plate oriented normal to the sun, at any time of the day. The most important affecting parameters are latitudinal position and weather conditions. Comparing the map on Figure 2.17 to a regular map of the world (Figure 2.18) reveals a correlation between DNI and organic life (this is outside the writer of this thesis competence, but a comment is given nevertheless). Areas with around 2,5 kWh/m^2 (daily) seems to be covered with fertile land, while areas with more then 6,5 kWh/m^2 seems to consist of deserts or bedrock. When placing the CPV-CHP units, it would seem a good idea to select areas with as high level of DNI as possible. Further, if the CPV-CHP was placed so that the rest of the ground was exposed to around 2,5 kWh/m^2, this might contribute to convert a more or less "dead area" to fertile land for agri-

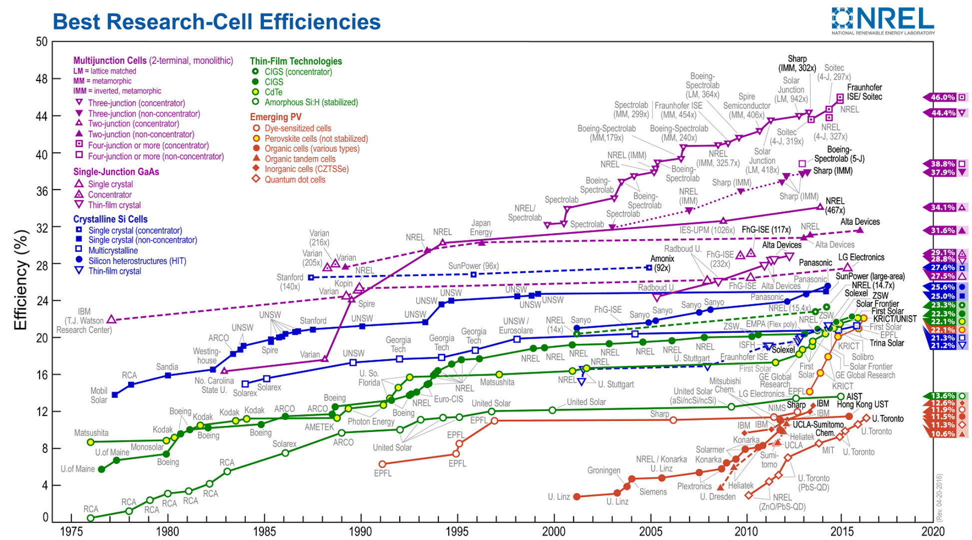

Figure 2.13: From NREL (2016), An overview of how efficiencies of different solar panels are evolving. As seen on the graph, multijunction cells with concentrated solar power currently have the highest efficiencies.

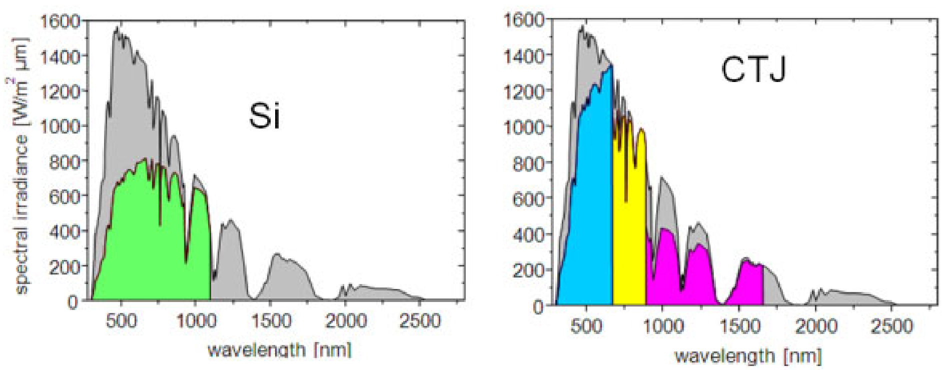

Figure 2.14: From Suncore (2016), showing how a triple junction cell (to the right) absorbs a larger portion of the sun's lights spectrum than the conventional single junction crystalline silicon cells (to the left).

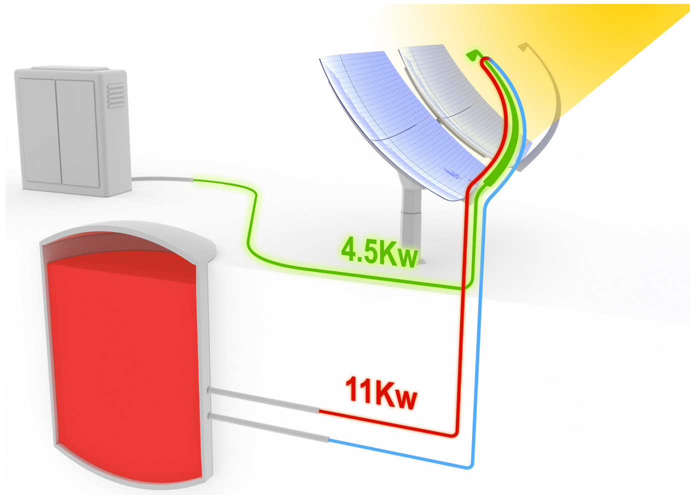

Figure 2.15: From Zenith (2006), illustration of how the Zenith Solar Concentrated Photovoltaics (CPV) Combined Heat and Power (CHP) unit converts solar power to electricity and heat.

Figure 2.16: Zenith Solar collectors operating in Israel. The area of the collectors covers 22 m^2 and the orientation follows the sun (From Zenith (2006)).

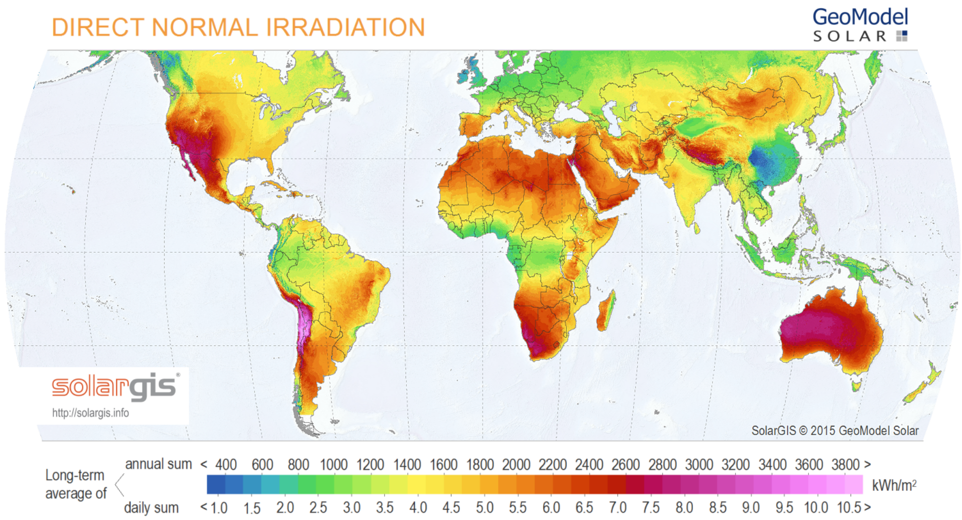

Figure 2.17: From SolarGis (2016), level of Direct Normal Irradiation (DNI) across the world.

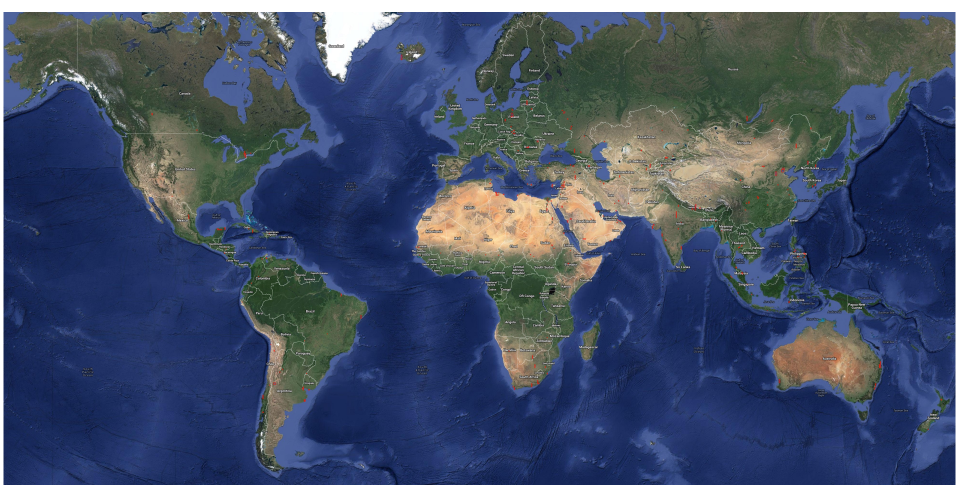

Figure 2.18: From GoogleEarth (2015), a satellite picture of the world. Notice the correlation between level of DNI on Figure 2.17 with desert/bedrock and green areas on the world map.

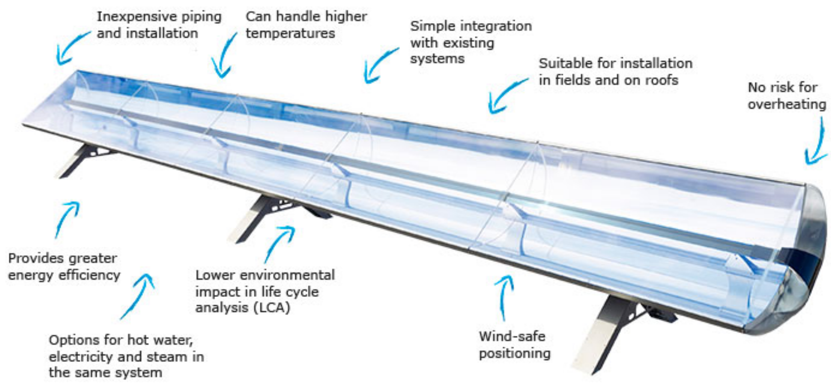

Figure 2.19: From Byström (2016), another CPV product, showing how the Absolicon X10 PVT collects solar power to produce high-grade electrical energy and low-grade thermal energy.

culture. Alternatively, large amounts of distilled clean water could be provided by the CPV-CHP units, covering even bigger areas with fertile land. A "CPV-CHP-farm" could potentially therefore produce electrical power, hydrogen gas, clean water, salt and fertile soil from solar power and seawater. This concept could also be used on platforms out in the open sea. Although this might not be economically feasible, about 40 % of the worlds total land surface is already used for agriculture, representing most of the arable land available on earth. It is therefore reasonable to be looking for other alternatives. If a "dead area" was provided with accessible energy, water, giving green terrain and employment opportunities, this would probably increase value of real estate and the growing life in general within a region.

Chapter 3

Summary and Recommendations for Further Work

3.1 Summary and Conclusions

This master thesis have reviewed the possibility of enhancing renewable energy production by combining electric and thermal energy extraction from solar power. A test rig has been constructed to explore the concept. The test rig was however not completed as originally planned. A fully operational PV/T-HP turned out to be difficult to construct for one person during one semester as time and budget did not suffice. The rig was constructed so that other students easily can take over, and continue similar projects. A simplified PV/T experiment were conducted, and the data presented. Calculations regarding combined PV, heat pump and seasonal thermal energy storage regarding Norwegian climate were presented. The results show that Norway have considerable potential regarding such a system. Installation costs should be carefully considered, however. Other ideas and concepts on solar power in areas with a higher level of solar irradiation have also been presented.

3.2 Discussion

A simplified PV/T experiment were conducted in order to evaluate potential unfavorable designs revealed in the COMSOL-simulations. Both the simulations and experiment showed that the temperature difference between the backplate (thermal collector) and PV-panel was higher then optimal. This is due to the low thermal conductivity of the double layer polyester on the back of the REC260PE solar panel. This problem may be difficult to solve. The material needs to be both thermal conductive and electrical resistant, which is a rare combination. One example of such a material is tungsten. This is an expensive material however, and it might interfere with the voltage in the solar cells.

3.3 Recommendations for Further Work

The writer of this thesis again agrees with Kjellsen (2016) that; *By having a team working on these problems consistently over time focusing on specific tasks, it can more easily be carried out and pace of development can improve.* As the concept is multidisciplinary it should also be considered to use students from specific fields of study for the different tasks. Access to laboratories, materials and mechanical workshops/personnel are also important factors for a successful project. A draft of continued work on a DX-SAHP can be seen on Figure 3.1.

When it comes to optimizing a PV/T or a DX-SAHP it might be easier to start with a solar collector, and then adding a thin layer of PV-cells on top of the collector. This way, the development process can focus on optimizing the evaporator and the system as a whole, rather then making a new collecor that already exists. The cost of adding PV-elements to solar collectors is assumed to be low. It would be interesting to see if such a system generates more total exergy (can be calculated from equation 2.5). If not, the need for electrical and/or thermal energy should determine if an installation should choose such system, and how much should be produced from thermal/electrical.

After working with renewable energy for six months, the writer of this thesis is confident that the future energy sector will have a dominant proportion of solar energy.

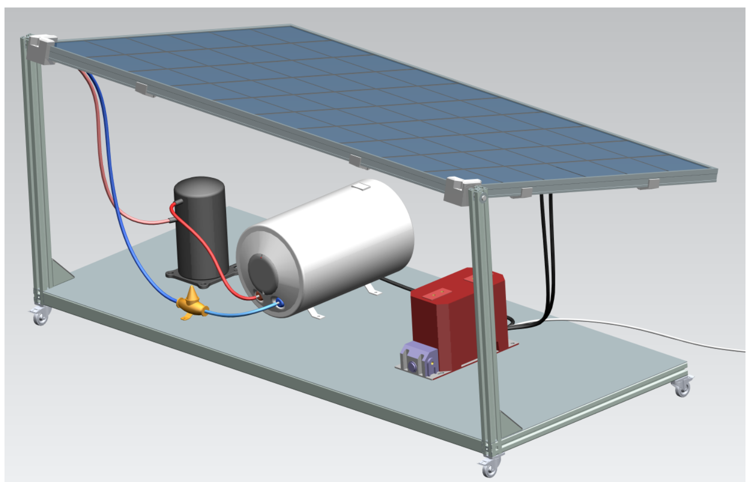

Figure 3.1: A draft of continued work on the DX-SAHP test rig.

Appendix A

Acronyms

CAD Computer aided design

COP Coefficient of performance

CPV Concentrated photovoltaics

CPV-CHP Concentrated photovoltaics - combined heat and power

DNI Direct normal irradiation

DX-SAHP Direct expansion solar assisted heat pump

GWP Global warming potential

PLA Polylactic acid

PV/T Photovoltaic/thermal solar panel

PVTA-HPWH Photovoltaic thermal hybrid solar collector assisted heat pump water heater

PV/T-HP Photovoltaic thermal heat pump

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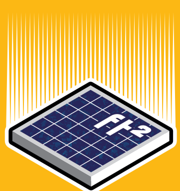
ENERGIZING LIFE TOGETHER

REC

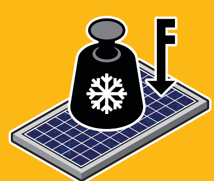
HIGH PERFORMANCE SOLAR PANELS

REC PEAK ENERGY BLK SERIES

REC Peak Energy BLK Series panels are the perfect choice for building solar systems that combine long lasting product quality with reliable power output. REC combines high quality design and manufacturing standards to produce high-performance solar panels with uncompromising quality.

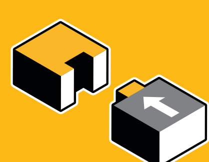


MORE POWER PER FT²



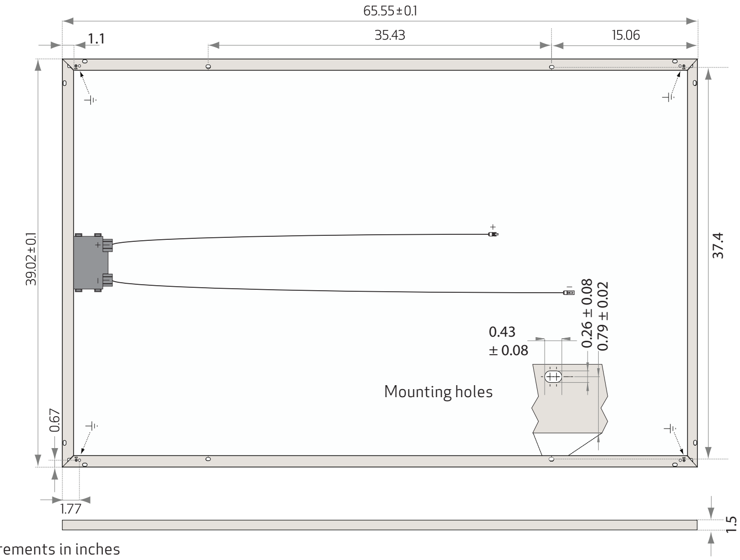
ROBUST AND DURABLE DESIGN

ENERGY PAYBACK TIME OF ONE YEAR



EASY TO INSTALL

REC PEAK ENERGY BLK SERIES



All measurements in inches

ELECTRICAL DATA @ STC	REC240PE BLK	REC245PE BLK	REC250PE BLK	REC255PE BLK	REC260PE BLK	REC265PE BLK
Nominal Power - P_{MPP} (Wp)	240	245	250	255	260	265
Watt Class Sorting - (W)	0/+5	0/+5	0/+5	0/+5	0/+5	0/+5
Nominal Power Voltage - V_{MPP} (V)	29.7	30.1	30.2	30.5	30.7	30.9
Nominal Power Current - I_{MPP} (A)	8.17	8.23	8.30	8.42	8.50	8.58
Open Circuit Voltage - V_{OC} (V)	36.8	37.1	37.4	37.6	37.8	38.1
Short Circuit Current - I_{SC} (A)	8.75	8.80	8.86	8.95	9.01	9.08
Panel Efficiency (%)	14.5	14.8	15.1	15.5	15.8	16.1

Analysed data demonstrates that 99.7% of panels produced have current and voltage tolerance of ±3% from nominal values.
Values at standard test conditions STC (airmass AM 1.5, irradiance 1000 W/m², cell temperature 25°C).
At low irradiance of 200 W/m² (AM 1.5 and cell temperature 25°C) at least 97% of the STC panel efficiency will be achieved.

ELECTRICAL DATA @ NOCT	REC240PE BLK	REC245PE BLK	REC250PE BLK	REC255PE BLK	REC260PE BLK	REC265PE BLK
Nominal Power - P_{MPP} (Wp)	183	187	189	193	197	202
Nominal Power Voltage - V_{MPP} (V)	27.7	28.1	28.3	28.5	29.0	29.4
Nominal Power Current - I_{MPP} (A)	6.58	6.64	6.68	6.77	6.81	6.90
Open Circuit Voltage - V_{OC} (V)	34.4	34.7	35.0	35.3	35.7	36.0
Short Circuit Current - I_{SC} (A)	7.03	7.08	7.12	7.21	7.24	7.30

Nominal operating cell temperature NOCT (800 W/m², AM 1.5, windspeed 1 m/s, ambient temperature 20°C).

CERTIFICATION

c UL us LISTED

UL 1703, IEC 62716 (ammonia resistance) & IEC 61701 (salt mist corrosion - severity level 6).

WARRANTY

10 year product warranty.
25 year linear power output warranty
(max. degression in performance of 0.7% p.a.).

16.1%	EFFICIENCY
10	YEAR PRODUCT WARRANTY
25	YEAR LINEAR POWER OUTPUT WARRANTY
DUTY★FREE	US IMPORT DUTY FREE

TEMPERATURE RATINGS

Nominal Operating Cell Temperature (NOCT)	45.7°C (±2°C)
Temperature Coefficient of P_{MPP}	-0.40 %/°C
Temperature Coefficient of V_{OC}	-0.27 %/°C
Temperature Coefficient of I_{SC}	0.024 %/°C

GENERAL DATA

Cell Type:	60 REC PE multi-crystalline 3 strings of 20 cells with bypass diodes
Glass:	1/8" mm solar glass with anti-reflection surface treatment
Back Sheet:	Double layer highly resistant polyester
Frame:	Anodized aluminum (black)
Junction Box:	IP67 rated 4 mm² solar cable, 35" + 47"
Connectors:	Multi-Contact MC4 (4 mm²)
Origin:	Made in Singapore

MAXIMUM RATINGS

Operational Temperature:	-40 ... +85°C
Maximum System Voltage:	600 V
Design Load:	75.2 lbs/ft² (3600 Pa)* 33.4 lbs/ft² (1600 Pa)* *Refer to installation manual
Max Series Fuse Rating:	15 A
Max Reverse Current:	15 A

MECHANICAL DATA

Dimensions:	65 1/2 x 39 x 1 1/2 in
Area:	17.76 ft²
Weight:	39.6 lbs

Note! All given specifications are provisional data only and subject to change without notice at any time.

Ref: NE-05-05-04-R. 12.13

REC is a leading global provider of solar energy solutions. With more than 15 years of experience, we offer sustainable, high performing products, services and investments for the solar industry. Together with our partners, we create value by providing solutions that better meet the world's growing energy needs. Founded in Norway, REC is listed on the Oslo Stock Exchange (ticker: RECSOL) and headquartered in Singapore. Our 1,500 employees worldwide generated revenues of NOK 4.1 billion in 2012.

REC

www.recgroup.com

NTNU
Det skapende universitet

MASTERKONTRAKT

- uttak av masteroppgave

1. Studentens personalia

Etternavn, fornavn **Lund, Magnus Størdal**	Fødselsdato **19. apr 1991**
E-post **magnusstordallund@gmail.com**	Telefon **95272555**

2. Studieopplysninger

Fakultet **Fakultet for ingeniørvitenskap og teknologi**	
Institutt **Institutt for produktutvikling og materialer**	
Studieprogram **Master i produktutvikling og produksjon**	Studieretning **Produktutvikling og materialer**

3. Masteroppgave

Oppstartsdato **15. jan 2016**	Innleveringsfrist **10. jun 2016**
Oppgavens (foreløpige) tittel **Energiproduksjon med kombinert bruk av solceller og varme/kjøle krets**	
Oppgavetekst/Problembeskrivelse Oppgaven har hensikt å undersøke effekten av å kjøle ned solceller for å øke gi økt strømproduksjon i kombinasjon med produksjon av lavverdig varmeenergi. Målet er å lage en testrigg hvor variabler som kjølesystem, produsert elektrisk energi og varme kan måles og evalueres. Målinger skal sammenlignes med teoretisk modeller og beregnede verdier. Arbeidet søker å kartlegge nye muligheter til å optimalisere fornybar energiproduksjon for å styrke dennes konkurransedyktighet.	
Hovedveileder ved institutt **Førsteamanuensis Bjørn Haugen**	Medveileder(e) ved institutt
Ekstern bedrift/institusjon **EPT**	Ekstern veileder ved bedrift/instutisjon **Trygve Magne Eikevik**
Merknader **1 uke ekstra p.g.a påske.**	

4. Underskrift

Student: Jeg erklærer herved at jeg har satt meg inn i gjeldende bestemmelser for mastergradsstudiet og at jeg oppfyller kravene for adgang til å påbegynne oppgaven, herunder eventuelle praksiskrav.

Partene er gjort kjent med avtalens vilkår, samt kapitlene i studiehåndboken om generelle regler og aktuell studieplan for masterstudiet.

Trondheim 3/2-2016

Sted og dato

Student

Hovedveileder

Originalen lagres i NTNUs elektroniske arkiv. Kopi av avtalen sendes til instituttet og studenten.

NTNU	Kartlegging av risikofylt aktivitet	Utarbeidet av	Nummer	Dato
HMS		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av		Erstatter
		Rektor		01.12.2006

Enhet: Institutt for Produktutvikling og materialer **Dato: 09.09.2015**

Linjeleder:

Deltakere ved kartleggingen (m/ funksjon): **Magnus Størdal Lund – student, Bjørn Haugen – veileder, Trygve Magne Eikevåk – medveileder**

Kort beskrivelse av hovedaktivitet/hovedprosess: Oppgaven har hensikt å undersøke effekten av å kjøle ned solceller for å øke gi økt strømproduksjon i kombinasjon med produksjon av lavverdig varmeenergi. Målet er å lage en testrigg hvor variabler som kjølesystem, produsert elektrisk energi og varme kan måles og evalueres.

Student: Magnus Størdal Lund   Masteroppgave: Energy production with solar panels in combination with cooling/heating system

Er oppgaven rent teoretisk? NEI

Signaturer: *Ansvarlig veileder:* Bjørn Haugen   *Student:* Magnus Størdal Lund

ID nr.	Aktivitet/prosess	Ansvarlig	Eksisterende dokumentasjon	Eksisterende sikringstiltak	Lov, forskrift o.l.	Kommentar
1	Bruk av verksted	MSL	HMS-kurs tilknyttet	Spørre mekanikerne hvis usikker på aktivitet		
1a	Bruk av roterende maskineri	MSL	Brukermanual, HMS ved dreiing osv.	Spørre mekanikere		Ikke bruk hansker ved roterende maskiner
1b	Bruk av kappeverktøy	MSL	Brukermanual, HMS ved kapping/skjæring	Spørre mekanikere		
1c	Sammenføyning (sveis, lim og lignende)	MSL	Datablad	Spørre Lab-ansvarlig		
1d	Test med sol/lab-sol	MSL	EPT-retningslinjer	Høre med relevant personnel. Bruke solkrem, solbriller		

				og dekkende hodeplagg og klær.		
1e	Bruk av plastikk dyse 3D-printer	MSL	3D-printer manual	Bruke hansker		

ID nr.	Aktivitet/prosess	Ansvarlig	Eksisterende dokumentasjon	Eksisterende sikringstiltak	Lov, forskrift o.l.	Kommentar
2	Montering	MSL	HMS-kurs tilknyttet	Kontrollere at spenningen/koblingen med solcellene		
3	Tester/eksperimenter	MSL		Lage små testeksemplarer slik at strøm og spenning blir tilstrekkelig lav		
3a	Kobling av rigg	MSL	EL-kurs	Bruke gummihansker, alltid kontrollere spenning/strøm, bruke sperringer for at andre ikke skal røre systemet		

NTNU HMS	Risikovurdering	Utarbeidet av	Nummer	Dato
		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av		Erstatter
		Rektor		01.12.2006

Enhet: Institutt for Produktutvikling og materialer **Dato:**

Linjeleder:

Deltakere ved kartleggingen (m/ funksjon): Magnus Størdal Lund – student, Bjørn Haugen – veileder, Trygve Magne Eikevik – medveileder

Risikovurderingen gjelder hovedaktivitet: Bruk av verksted, eksperimenell testing

Prosjektoppgave student: Magnus Størdal Lund   Tittel på oppgaven: Energy production with solar panels in combination with cooling/heating system

Signaturer: *Ansvarlig veileder:* Bjørn Haugen   *Student:* Magnus Størdal Lund

ID nr	Aktivitet fra kartleggings-skjemaet	Mulig uønsket hendelse/ belastning	Vurdering av sannsyn-lighet	Vurdering av konsekvens:				Risiko-Verdi (menn-eske)	Kommentarer/status Forslag til tiltak
			(1-5)	Menneske (A-E)	Ytre miljø (A-E)	Øk/ materiell (A-E)	Om-dømme (A-E)		
1	Bruk av verksted								
1a-i	Bruk av roterende maskineri	Roterende klemskade	2	D	A	B	D	D2	Ikke bruk hansker, hettegenser og lignende som kan sette seg fast i roterende maskin
1a-ii		Flyvende gjenstander, Spon som treffer uønsket område	3	C	A	B	B	C3	Bruke briller! Bruk kjølevæske og riktige kuttdata
1a-iii		Feilbruk -> ødelagt verktøy og/eller maskin	4	B	A	A	A	B4	Ha riktig opplæring, få assistanse før bruk av maskin og ved bytting av verktøy
1b-i	Bruk av kappeverktøy	Kuttskade	2	D	A	B	D	D2	Passe fingra! Bruk maskinen riktig, spør hvis usikker
1c	Bruk av samenføyningsmidler (lim og lignende)	Brannskade, skade på hud og øyne	2	C	B	B	C	C2	Lese datablad nøye! God lab-skikk. Spør hvis usikker
2-i	Montering	Små klemskader	4	A	A	A	A	A4	Passe fingra! Spørre om bistand

									til større sammenstillinger
2-ii	Montering	Elektrisk støt	3	A	A	A	A	A3	Så lenge strøm og spenning holdes lav er det liten fare
3-i	Tester/eksperimenter	Andre tukler med riggen	3	B	B	B	B	B3	Lav strøm + spenning og oppsatt hindring/gjerde gir liten risiko
3-ii	Tester/eksperimenter	Lekkasje i varme/kjølekrets	3	B	B	B	B	B3	Bruke kjølemedium som er ufarlig for omgivelser og miljø
3-iii	Tester/eksperimenter	Solbrenning	4	B	B	B	B	B4	Forholde seg fornuftig til solstråling. Bruke solkrem, hodeplagg, dekkende bekledning

Sannsynlighet vurderes etter følgende kriterier:

Svært liten 1	Liten 2	Middels 3	Stor 4	Svært stor 5
1 gang pr 50 år eller sjeldnere	1 gang pr 10 år eller sjeldnere	1 gang pr år eller sjeldnere	1 gang pr måned eller sjeldnere	Skjer ukentlig

Konsekvens vurderes etter følgende kriterier:

Gradering	Menneske	Ytre miljø Vann, jord og luft	Øk/materiell	Omdømme
E Svært Alvorlig	Død	Svært langvarig og ikke reversibel skade	Drifts- eller aktivitetsstans >1 år.	Troverdighet og respekt betydelig og varig svekket
D Alvorlig	Alvorlig personskade. Mulig uførhet.	Langvarig skade. Lang restitusjonstid	Driftsstans > ½ år Aktivitetsstans i opp til 1 år	Troverdighet og respekt betydelig svekket
C Moderat	Alvorlig personskade.	Mindre skade og lang restitusjonstid	Drifts- eller aktivitetsstans < 1 mnd	Troverdighet og respekt svekket
B Liten	Skade som krever medisinsk behandling	Mindre skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1uke	Negativ påvirkning på troverdighet og respekt
A Svært liten	Skade som krever førstehjelp	Ubetydelig skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1dag	Liten påvirkning på troverdighet og respekt

Risikoverdi = Sannsynlighet x Konsekvens
Beregn risikoverdi for Menneske. Enheten vurderer selv om de i tillegg vil beregne risikoverdi for Ytre miljø, Økonomi/materiell og Omdømme. I så fall beregnes disse hver for seg.

Til kolonnen "Kommentarer/status, forslag til forebyggende og korrigerende tiltak":
Tiltak kan påvirke både sannsynlighet og konsekvens. Prioriter tiltak som kan forhindre at hendelsen inntreffer, dvs. sannsynlighetsreduserende tiltak foran skjerpet beredskap, dvs. konsekvensreduserende tiltak.

MATRISE FOR RISIKOVURDERINGER ved NTNU

KONSEKVENS						
	Svært alvorlig	E1	E2	E3	E4	E5
	Alvorlig	D1	D2	D3	D4	D5
	Moderat	C1	C2	C3	C4	C5
	Liten	B1	B2	B3	B4	B5
	Svært liten	A1	A2	A3	A4	A5
		Svært liten	Liten	Middels	Stor	Svært stor
		SANNSYNLIGHET				

Prinsipp over akseptkriterium. Forklaring av fargene som er brukt i risikomatrisen.

Farge	Beskrivelse
Rød	Uakseptabel risiko. Tiltak skal gjennomføres for å redusere risikoen.
Gul	Vurderingsområde. Tiltak skal vurderes.
Grønn	Akseptabel risiko. Tiltak kan vurderes ut fra andre hensyn.