Acknowledgements

This thesis was carried out to shed light on the available solar recourse, and potential for power production from a PV system oriented and fixed in optimal direction and tilt angle, in Ås, 30 km south of Oslo, Norway.

I would like to thank my supervisor, Muyiwa Samuel Adaramola, for his assistance through constructive discussions, assistance in search for relevant literature, through sharing his insight into the field of electricity production and distribution and furthermore for motivating a steady work effort throughout the semester.

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Emil Elias Traaholt Vågnes

Ås, 11th May 2014

Abstract

The Norwegian government is committed to increase the renewable energy share of the Norwegian primary energy consumption to 67.5%, and to increase the share of energy in transport to 10% renewable by 2020. In order to achieve these targets, investment in renewable energy resources such as wind and solar energy is essential. Even though observation of solar irradiation show that the solar resource in the south-eastern parts of Norway is better than earlier believed, less focus has been placed on utilization of solar energy resource in Norway. In this study, the results obtained from field monitoring the performance of a 2.07kW$_p$ photovoltaic grid-connected system installed at the Norwegian University of Life Sciences, Ås, Norway, is presented.

The PV-system is mounted on the flat section of the roof of a laboratory building at the Department of Mathematical Science and Technology of the University. Detailed performance measurement of the system started in February 2013, and still on going. However, the analysis presented in this study consists of the data recorded between March 2013 and February 2014. The electricity generated by the system is fed directly into the grid. The in-plane irradiance, array power output, system power output and other parameters are measured and averaged every 1-minute by a data logger integrated in the inverter. The measured data was utilized to estimate the reference yield, array yield and final yield, as well as other performance parameters of the system.

The specific yield of the system through to recording period was found to be 931.6kWh/kW-year. The monthly average array yield varied between 0.04kWh/kW$_p$-day in January and 4.8kWh/kW$_p$-day in July, with an overall average value of 2.73kWh/kW$_p$-day. The monthly average final yield was found to vary between 0.02kWh/kW$_p$-day in January and 4.5kWh/kW$_p$-day in July, with an overall average value of 2.54kWh/kW$_p$-day. The overall annual capacity factor, performance ratio and system efficiency are 11%, 83% and 13%, respectively. The findings from this study show that the performance of this system is comparable with similar systems installed in northern Europe.

Sammendrag

Norge har satt seg som mål å øke fornybarandelen av det primære energiforbruket med 9.5% i forhold til 2005 nivå, til 67.5% innen 2020. 10% av energien brukt i transportsektoren skal også være fornybar innen 2020. For å nå disse målene er det viktig å vurdere alle tilgjengelige fornybare energikilder som mulige satsningsområder.

Innstrålingsforholdene i de sør-østlige delene av Norge har nylig blitt funnet å være bedre enn tidligere antatt. Fram til nå har det vært lite fokus på sol som en potensiell kraftkilde her til lands, men dette er i ferd med å forandre seg.

I denne oppgaven presenteres resultater for produksjon og ytelse til ett 2.07 kW_p solcelleanlegg over en periode på 12 måneder. Solcelleanlegget er installert på et flatt område av taket til en bygning tilhørende Institutt for Mattemariske realfag og Teknologi (IMT), ved Norges Miljø- og Biovitenskapelige Universitet, NMBU. Detaljerte målinger av systemets ytelse startet i februar 2013 og pågår fremdeles, denne studien er basert på målinger gjort mellom 1. mars 2013 og 28. februar 2014. Målingene er gjennomsnittmålinger med minuttoppløsning logget av en integrert web server i vekselretteren/inverteren til systemet. Datasettet inkluderer målinger av innstråling i planet, kraft fra streng og kraft fra systemet som helhet, bl.a.. Elektrisiteten som produseres av anlegget blir overført direkte til det lokale distribusjonsnettet.

Anleggets spesifikke *yield* ble kalkulert til 931.6kWh/kW_p-år. Gjennomsnittlig energi produsert av systemet ble kalkulert til 2.55kWh/kW_p-dag, og varierte mellom et månedlig gjennomsnitt på 0.02kWh/kW_p-dag og 4.5kWh/kW_p-dag, i henholdsvis januar og juli. Gjennomsnittlig energi produsert av strengen ble kalkulert til 2.73kWh/kW_p-dag, og varierte mellom et månedlig gjennomsnitt på 0.04kWh/kW_p-dag og 4.8kWh/kW_p-dag, i henholdsvis januar og juli. Den årlige kapasitetsfaktoren, systemvirkningsgraden og samlet virkningsgrad viste seg å være henholdsvis 11%, 83% og 13%.

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Nomenclature

Parameter	Symbol	Equation	Unit
System Data			
Nominal power	P_0		W
STC* reference in plane irradiance	G_{STC}	1000	W/m^2
Temperature coefficient of power	λ	-0.46% per °C	% per °C
Module temperature	T_m		°C
Recorded Parameters			
In plane solar irradiation	G_i		W/m^2
Power from PV array	P_A		kW
Power to grid	P_{TU}		kW
Array area	A_A		m^2
Derived Parameters			
Energy to all loads	E_L	$E_{Lac} + E_{Ldc}$	kWh
Energy to grid	E_{TU}	$\tau_r \times \sum_{\tau} P_{TU}$	kWh
Reference Yield	Y_r	$\frac{\tau_r \times (\sum_d G_i)}{G_{STC}}$	[kWh/(kW-day)]
Corrected Reference Yield	Y_T	$Y_r(1 - \lambda(T_m - 25)$	[kWh/(kW-day)]
Array Yield	Y_A	$\frac{E_{A,d}}{P_0}$	[kWh/(kW-day)]
Final Yield	Y_f	$\frac{E_{use,PV,day}}{P_0}$	[kWh/(kW-day)]
Array capture loss	L_C	$Y_r - Y_A$	[kWh/(kW-day)]
Thermal capture losses	L_{Ct}	$Y_r - Y_T$	[kWh/(kW-day)]
Miscellaneous capture loss	L_{cm}	$L_C - L_{Ct}$	[kWh/(kW-day)]
Performance ratio	PR	$\frac{Y_F}{Y_r}$	[kWh/(kW-day)]
Capacity factor	CF		%
Mean array efficiency	$\eta_{pv,\tau}$	$\frac{E_{A,\tau}}{\int_{\tau} G_i A_A dt}$	%
Inverter efficiency	$\eta_{inv,\tau}$	$\frac{E_{IO}}{E_{II}}$	%
System efficiency	$\eta_{sys,\tau}$	$\eta_{pv,\tau} \times \eta_{inv,\tau}$	%
Useful energy from system	$E_{use,PV}$	$E_{TU}+E_L$	kWh

**Standard Test Conditions: air mass: 1.5, temperature: 25°*

INTRODUCTION

1.1. Background

In order to reduce climate gas emissions from energy end use in its member states, the European Union (EU) introduced “*DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL: on the promotion of the use of energy from renewable sources..*“, popularly referred to as the “renewable directive”, taken into effect 25/06/2009 (European Parliament 2009).

Norway, being an EFTA country and part of the European Economic Area (EEA), also adopted the Renewable energy directive composed by the EU in 2009. By implementing the directive, a nation is to establish an national action plan which sets the share renewable sources is to make up of that nation’s total energy consumption by 2020 (European Parliament 2009). Norway aims for a 67.5% renewable share by 2020 (Regjeringen 2011), a 9.5% increase compared to the country’s renewable share of 2005 (Regjeringen 2011).

Power production in Norway is for the most part based on hydropower. In 2011, 95% of power production in Norway was derived from hydro, the remaining 6% were provided by thermal power production (4%) and wind power (1%) (SSB 2013). In 2012, 50.2% of the energy consumed in Norway was electric power, while power derived from fossil sources (mostly petroleum products) provided about 42% (SSB 2013) (Figure 1.1).

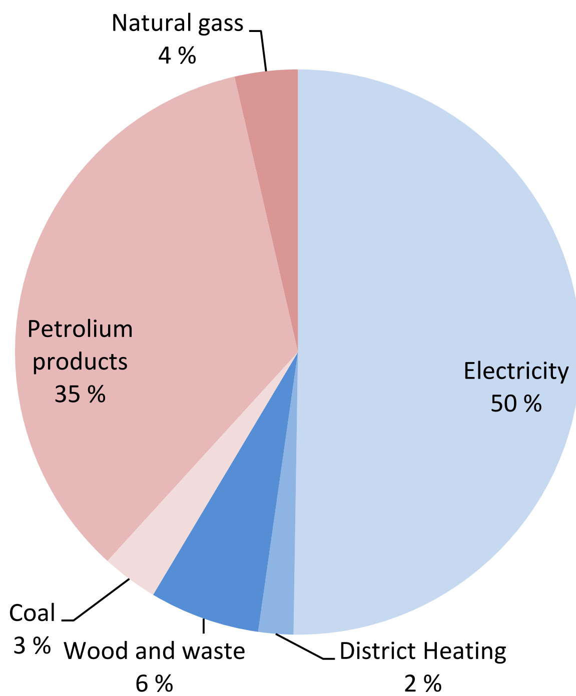

Figure 1.1: Total Energy end-use in 2014 by source in Norway (SSB 2013)

To increase the share of renewable energy to 67.5% of the Norwegian power mix, the government has created several economic incentives for power producers and consumers to consider utilizing renewable energy sources. In 2012, Norway and Sweden opened a common marked for trading of green certificates (OED 2012), which ensures the power producer an extra profit on every kWh of renewable energy sold. Also, the public enterprise ENOVA provides founding for projects, private or corporate, promoting more efficient energy consumption and increased production of “new” renewable energy (ENOVA 2014).

In similar efforts to increase renewable energy capacity in other European countries saw PV power production emerged as one of the favored technologies. This has not happened in Norway. Even though photovoltaic (PV) power production technology is well-known and readily used throughout Norway, the total contribution of PV power to the national energy system is as of May 2014 , negligible.

The PV-installations found in Norway can be characterized as follows: small, distributed and, for the most part, not grid connected. The largest market for PV-systems in Norway is the leisure market, where PV-systems supply cabins and recreational homes (as well as vehicles and boats) with electricity. By 2012, this *stand-alone domestic* segment represented 93% of the total PV-capacity in Norway, sporting 9250kW_p out of a 9952kW_p total capacity. The second largest market, the *stand-alone non-domestic* market segment (represented in most part by costal navigation infrastructure, but also several telecommunication- and weather stations) is estimated to have installed 510kW_p PV capacity between them. By 2012, the total of grid connected PV-capacity in Norway was 192kW(Bugge 2013).

Table 1.1: Cumulative installed PV power in four sub-markets (kW). Source: (Bugge 2013)

Sub-market	2004	2005	2006	2007	2008	2009	2010	2011	2012
Stand-alone domestic	6440	6800	7150	7450	7780	8080	8400	8800	9250
Stand-alone non-domestic	375	377	390	410	430	450	470	490	510
Grid-connected distributed	75	75	128	132	132	132	192	192	192
Grid-connected centralized	0	0	0	0	0	0	0	0	0
Total (kW)	6890	7252	7668	7992	8342	8662	9062	9482	9952

There are several reasons why the accumulated PV capacity in Norway is low. Low price of electric power, high capital cost of PV and limited experience with the technology on larger scale are some of them. Another important factor is the uncertainties in mapping of the solar resource in Norway.

A good comprehension of the solar resource is essential for planning PV power production at any location. Internationally, several software tools for solar resource mapping have been developed. However, in a recent screening to find and describe available data for mapping of the solar resource in Norway, the company Kjeller Vindeknikk found that several of these commonly used tools based their estimates on a very limited number of actual ground observations on Norwegian territory. This is expected to result in large uncertainties and biases for the estimates of the solar recourse in Norway (Berntsen 2013). Kjeller Vindteknikk suggests that these estimates should be compared to on-ground observations in order to better describe the Norwegian solar resource (Berntsen 2013).

Good knowledge of the solar resource is essential for investment in PV power systems in Norway. This paper aims to contribute to that knowledge.

1.2. Scope and Objectives

Performance assessments of real life PV system installation are the best way to determine the potential for PV power production in an area, and there is little information available in open literature on the actual operation and energy production form PV systems in Norway.

This paper describes the performance and power production of a 2.07kW_p PV-system located in Ås which is 30km south of Oslo. The assessment seeks to shed light on the potential for power production from PV-panels in this part of Norway through four objectives. The objectives of the thesis are to:

i. Collect PV performance and relevant meteorological data.
ii. Determine the weekly and monthly relevant performance indices for this system.
iii. Compare the performance of this system with similar studies (as found in open literature).
iv. Examine the effect of seasonal variations on the system performance.

LITERATURE REVIEW

2.1 *Published Documentation*

Case studies of PV system performance have been, and are being, conducted throughout the world. Conditions for PV power production may vary with geographic location, as climatic and seasonal changes in weather and irradiation conditions differ. By normalizing performance parameters to a PV systems rated power, we can compare conditions for PV power production in different geographical locations. The specific-, final yield, system efficiency and the performance ratio (PR) are the most readily compared performance parameters. These values reveal how much energy a PV system can be expect to produce in a specific location per kW installed capacity, and tell us what effect system losses have on the system efficiency. Table 2.1 contains the above mentioned performance parameters, as well as type of PV technology and rated capacity, for several PV systems located in different parts of Europe.

Table 2.1: System specifications, specific- and average final yield, system efficiencies and performance ratio of six related studies of photovoltaic systems.

Location	Rated Capacity (kW_p)	Type of PV technology	Specific Yield (kWh/kW_p)	Final Yield (kWh/kW_p-day)	System efficiency (%)	PR (%)	Ref.
Dublin, Ireland	1.72	Mono c-SI	885.1	2.4	12.6	81	(L.M. Ayompe 2009)
Germany*	35.7×10^6	-	909.6	2.49	-	-	(Bruno 2013)
Warsaw, Polen	1	Amorphous-Si	830	2.3	4.0-5.0	60-80	(S.M. Pietruszko 2003)
Nicosia, Cyprus	1.54	Multi c-Si	1582	4.3	-	79	(George Makrides 2007)
Arvika, Sverige	108	Multi c-Si	978	2.68	-	84	(GEC 2013)
Oslo, Norway**	7	-	922	2.53	-	82	(Berner 2013)

* Average values for the whole country based on total energy produced and total kW_p capacity in 2013.

** Simulation estimates by Multiconsult.

We notice the high values of specific- and final yield for the study in Cyprus, which have among the best conditions in Europe in terms of solar irradiance (Marcel Šúri, Thomas A. Huld et al. 2007), and low system efficiency for the study from Warsaw, Poland. The study from Poland is done on a system with amorphous silicon technology. The conversion efficiency of this type of PV technology is lower than those based on crystalline silicon (Chu 2011). The nameplate efficiency of the panels used in the study from Poland was 6% (STC) (S.M. Pietruszko 2003). The other case studies reviewed here are based on crystalline silicon technology. The values presented for Oslo, Norway are results of a simulation conducted by Multiconsult on the behalf of the Norwegian governmental enterprise of ENOVA. The simulation is based on global irradiation data from the metrological station Sørås in Ås. The simulation results compare well to the values found for Arvika, Sweden, located about 106 km W-SW of Oslo. Field performance assessments of PV systems in Norway are not available in open literature.

2.2 *Unpublished documentation*

The following data has not been published in form of literature, but are publicly available through the web page sunyportal.com, run by the German energy company SMA Solar Technology AG. Specifications for, as well as production from, PV installations around the world are available at this site. Specifications for 11 PV systems in Norway were available by May 2014, but production data for a period of one year or more were only available for five PV systems (Table 2.2): *sunypoertal.com -> Publicly available PV systems -> Norway -> Search.*

The specific- and average final yield for the five PV systems in Table 2.2 were calculated for the same period that recordings for the present study was done; March 2013 throughout February 2014. It is not possible to say how representative the yield values in Table 2.2 are for their respective regions of the country as there is little data available for orientation, tilt angle and operation of the systems. However, the yield values serve well as indicators of conditions for PV power production.

Table 2.2 Data for five PV systems that have been opperating for more than one year located in Norway (sunyportal.com 2014).

Location	**Rated Capacity (kW_p)**	**Type of PV technology**	**Spesific Yield (kWh/kW_p)**	**Final Yield (kWh/kW_p-day)**	**PV syst. Name**	**PV syst. Type**
Bergen	6.12	Multi c-SI	717.9	1.96	Sonne71	Roof top
Os	63.53	Mono c-SI	790.7	2.17	OSEANA	Facade
Oslo	7.7	Mono c-SI	684	1.87	1.Trond Home Manager	Roof top
Sandnes	1.28	-	774.7	2.2	ISOBO AKTIV	Roof Integrated
Trondheim	1.41	Multi c-SI	688.4	1.89	Charlottenlund VGS	Roof top

METHODOLOGY

3.1 Solar cell

Power production by means of photovoltaic technology involves the direct conversion of solar radiation into electricity by using solar cells. A solar cell is basically a specialized semiconductor diode with a large barrier layer that converts energy in light shone upon it to DC electricity (Haberlin 2012).

Photovoltaic solar cells are the basic building blocks of any PV system. Solar cells can consist of thin slices, called wafers, of crystalline silicon (Si), or of amorphous-silicon (or other photosensitive materials) deposited as thin layers on a low-cost backing material, such as glass, plastic or stainless steel (thin film) (Chu 2011). The wafer, or thin film, is rigged with conduction bands for leading electrons freed from the photosensitive material when exposed to sunlight (creating electric current). Solar cells are typically applied an anti-reflection coating for enhanced efficiency. In 2010 crystalline silicon (c-Si) solar modules represented 85-90% of the global marked (multi – and mono crystalline combined), while thin film technology represented 10-15% (IEA 2010). Figure 3.1 illustrates the predicted development in efficiency of five different PV technologies. CIGS (Copper indium gallium selenide) and CdTe (Cadmium telluride) are also thin-film technologies.

Solar cells can be interconnected to make a solar module or solar panel; the solar panels may be connected to make PV arrays (or strings). PV arrays may be joined into an even larger PV system. By interconnecting PV units, the power capacity of the system increases. If one interconnects four panels with a rated power of 200 W_p, the resulting string/array will have an accumulated *rated* power of 800 W_p. Today, single solar cells with a kW_p of a couple of watts are in use in appliances like mobile- and battery chargers. On the other end of the scale, large PV power plants may consist of several million solar panels, sporting an installed capacity of over 500 MW_p (Solar 2014).

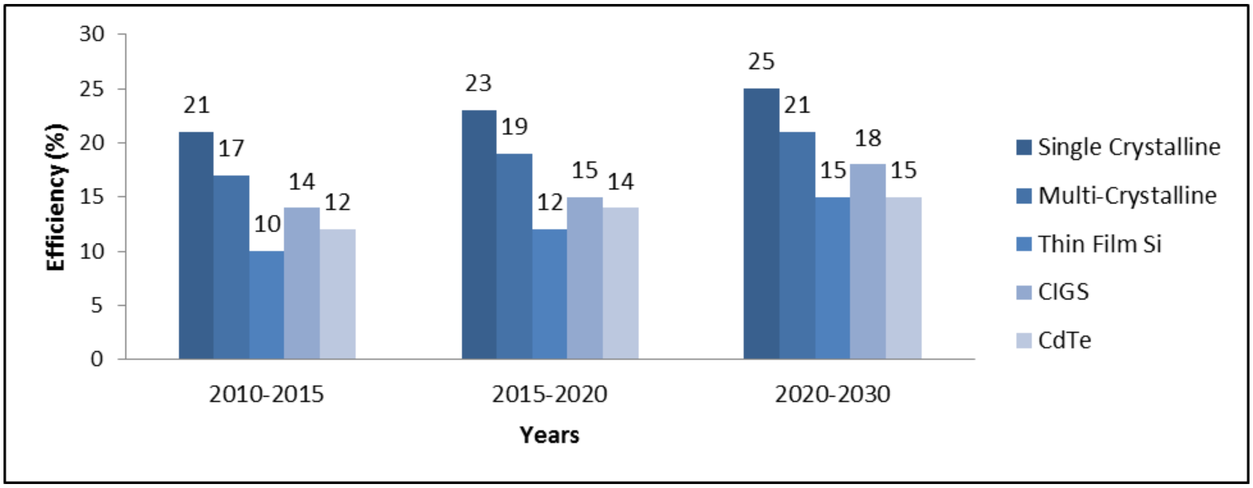

Figure 3.1 Thin film Si is expected to experience the largest relative increase of efficiency from 2010 to 2030, single crystalline Si will still be the most efficient by 2030 (Chu 2011).

3.2 Photovoltaic (PV) energy systems

PV energy systems can be divided in to three categories (figure 3.2): (1) Off-grid or stand-alone (not connected to electrical grid), (2) grid-connected with storage facilities (e.g. battery bank) and (3) grid connected without storage facilities (see Figure 3.2). In remote areas with no established electrical grid, stand-alone PV systems can provide a local source of energy, and with an integrated battery bank, it can provide stored surplus power at times of low primary PV power production.

A grid-connected system with storage facilities can be a good option for areas where the electrical system is established but is unreliable.

In areas with good infrastructure for distribution of power, it is possible to reduce the system cost for medium to large –sized PV systems by leaving out the battery bank and letting the produced energy evacuate directly to the electrical grid (Haberlin 2012). However, intermittent power poses challenges to the grid operators of electricity grids. Oftentimes, as is the case for in Norway, grid operators are obligated by law to keep a continuous balance between supply and demand (OED 1990). Sudden input of power to a power system will pose a challenge to maintaining its balance.

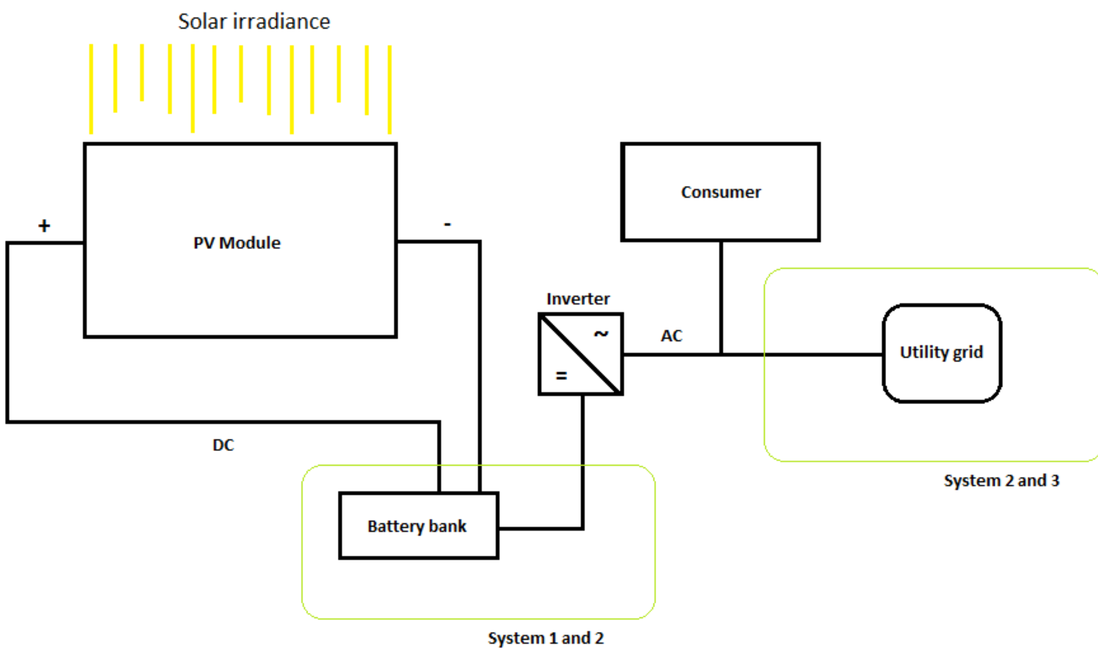

Figure 3.2: Energy collected by a PV system can be used instantaneously, stored in a battery bank or evacuated to the utility grid.

3.3 Specifications of the PV system at IMT

The subject of this study is a grid connected PV system without storage facilities (figure 3.3). It was installed by the Institute for Mathematical Science and Technology (IMT) for use in education, and recording of operation started in early 2013. The solar panels were donated to the university by the Norwegian solar cell producer REC, as they discontinued their production in Norway in 2012.

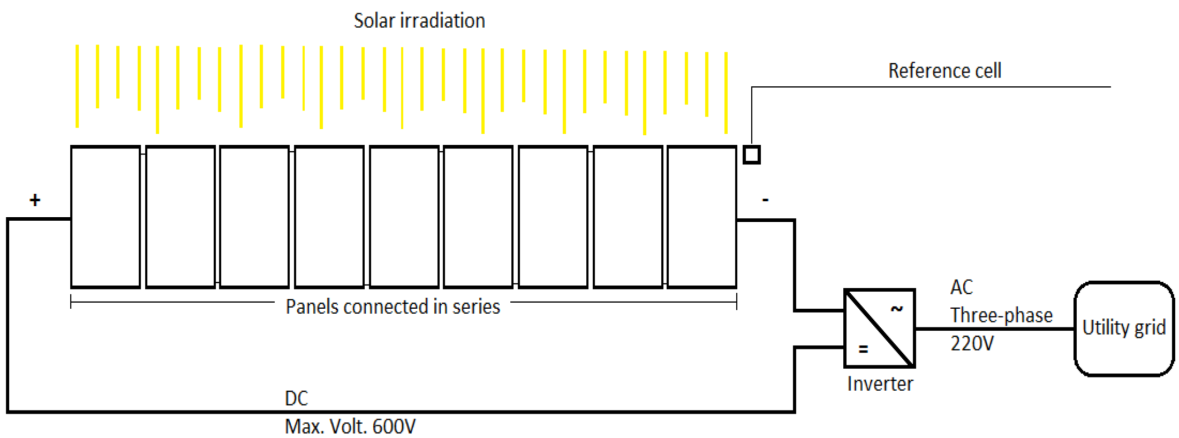

Figure 3.3: A schematic illustration of the PV system object of this study.

The PV system is located on the coordinates UTM32N 6615547, 600159 (or latitude 59.65^{o}N and longitude 10.76^{o}E), approximately 105 m above sea level, and is oriented southwards. It consists of nine multi-crystalline solar modules, connected in series, and covers a total area of 14.85 m^2. The accumulated installed capacity is 2.07 kW_p. The nine solar modules were placed on an unshaded flat section of the laboratory building on campus, at the Norwegian University of Life Science (NMBU), Ås. The modules were tilted and fixed at an angle of 37°. The reference cell is of the brand SolData: calibration factor of 886spc: 168mV/(kWm^2). The instrument currently used for recording global irradiation is an Eppley Precision pyrometer. Operational-and irradiance data was recorded by an integrated web server in the inverter, at one-minute intervals. For this study the recorded values for Date/Time, Input Power (W), Output Power (W) and in-plane irradiation (W) were utilized to calculate the performance of the PV system, through the period 1st of March 2013 to 28th of February 2014, according to the IEC 61724:1998 standard. Specific yield was calculated as well as annual, monthly and weekly average daily final-, array- and reference yields. System losses, system efficiencies, capacity factor and performance ratio for the recording period were also calculated. The calculations were done in Excel 2010.

Data for global irradiation (W) and air temperature (°C) were derived from a metrological field station operated by IMT, Sørås, and made available for this study by Signe Kroken at IMT. The field station is located 650m south of the PV system and records on hour intervals.

Being a grid connected system, the system comprises of PV module, inverter and utility grid (figure 3.3). These components are connected together by cables. Brief description of the inverter and PV module is provided is Sections 3.3.1 and 3.3.2. The placement of the PV module is showing in Figure 3.3. The inverter is placed inside the laboratory.

Figure 3.4: A panorama view of the southward facing PV module. More photographs in Appendix C.

3.3.1 Inverter specifications

The inverter is of the brand Eltec Valere, model THEIA HE-t 4.4kW. It operates with a max. DC voltage of 600V and a nominal input DC power of 4600 W. The main specifications of this inverter are presented in Table 3.1.

Table 3.1: Input-, Output-, and Performance data for the inverter used for this study. Further specifications are presented in Appendix I.

THEIA HE-t 4.4kW Specifications			
INPUT DATA			
Nominal DC power	Max. DC Voltage	Voltage range MPPT	Max. input current
4600 W	600 V	230-480 V	21.0 A
OUTPUT DATA			
Nominal output power		Nominal AC current	Max AC current
4400W		20.0 A	23.0 A
PERFORMANCE DATA			
Max. efficiency		EU efficiency	Power feed starts at
97.3%		96.9%	<7 W

3.3.2. Solar panel specifications

The PV system includes nine solar panels, assembled in one array. This gives the array a rated output power of 2.07 kW_p. The systems maximum voltage is 600V. The specifications for these panels vary, as listed in Table 3.2.

Table 3.2: Solar panel models and specifications. All solar panels are produced by REC, except for one that is produced by Jumao Photonic Co. Ltd.

Peak power (P_{mpp}), W	**SC Current (I_{sc}), A**	**OC Voltage (V_{OC}), V**	**Rated Voltage (V_{mmp}), V**	**Rated Current (I_{mpp}), A**	**Max.Syst.Volt., V**	**Model**
240	8.4	37.7	30.4	7.9	600	REC240PE
240	8.4	37.7	30.4	7.9	600	REC240PE
240	8.4	37.7	30.4	7.9	600	REC240PE
220	8.3	36.5	28.3	7.7	1000	REC215AJM
220	*7.9*	*36.7*	*29.8*	*7.4*	*1000*	*JMP-220W-M6-G*
220	8.3	36.5	28.3	7.7	1000	REC220A-JM
230	8.5	36.7	28.5	7.9	600	REC230PE
220	8.2	36.4	28.3	7.6	1000	
235	8.7	36.9	28.6	8	600	REC235PE

3.4 Grid connected PV system performance parameters

The performance of grid-connected system is generally examined by means of several parameters. The main parameters are shown in Table 3.3. The system yields and losses are normalized to the rated power of the PV module. As a result values acquired from different size PV systems, and from different geographical locations, can be compared. The energy quantities are referred to as yields.

The reduction in performance of a PV-grid system can be attributed to energy losses. Various energy losses occur under real life operation of a PV system. The main categories of losses are: PV array capture losses and system losses, which can be divided into thermal capture losses and miscellaneous capture losses. Thermal capture losses results from array operating temperatures other than 25°C as recorded under standard test conditions (STC). Miscellaneous capture losses may occur for one or several reasons, such as wiring losses in the cables between PV panels and inverter, losses due to soiling, diodes, shading and/or component failure. Capture losses occur at the DC side of the PV conversion chain (A. Chouder 2009). Losses at the AC side of the conversion, called system losses, are mainly occurring in the inverter, losses occurring in the transformer and/or losses occurring in the wiring carrying AC current (K. Padmavathi 2013). Losses are formulated as differences between yields and, and as the yields, they have units of [kWh/(kW-day)].

3.4.1 Reference yield (Y_r)

The reference yield tells us how many hours the in plane irradiation needs to be at reference irradiance in order to produce the same amount of energy as was recorded for any recording interval of interest.

Thus, the daily reference yield $Y_{r,d}$ is calculated by dividing total daily in plane irradiance by the reference irradiance. As the total daily in plane irradiance is in units of [kWh/(m^2-day)] and the reference irradiance is equal to 1 kW/m^2, the reference yield is in units of [kWh/(kW-day)], or in hours per day. The reference yield is a measure of the theoretical energy available at a specific location over a specified time period. It is given as:

$$Y_{r,d} = \frac{\tau_r \times \left(\sum_{day} G_i\right)}{G_{STC}} \quad \text{[kWh/(kW-day)]} \qquad \text{(Eq.1)}$$

3.4.2 Array yield (Y_f)

The array yield is the daily PV energy output (DC) from the array normalized to the array's rated capacity. The array yield represents the number of hours the PV array needs to operate at the rated PV capacity in order to produce the same amount of energy as was recorded. **Eq.2** formulates the daily array yield.

$$Y_{A,d} = \frac{E_{A,d}}{P_0} \quad \text{[kWh/(kW-day)]} \qquad \text{(Eq.2)}$$

3.4.3 Final Yield (Y_f)

The final yield is the PV system energy output (AC) normalized by the PV system rated installed capacity. The yield indicates how many hours a day the PV system must operate at its rated capacity in order to produce the same amount of energy as was recorded. **Eq.3** formulates the daily final yield.

$$Y_{f,d} = \frac{E_{use,PV,day}}{P_0} \quad \text{[kWh/(kW-day)]} \qquad \text{(Eq.3)}$$

3.4.4 System Losses

System losses equal the difference between the array yield and the final yield.

$$L_S = Y_A - Y_F \qquad \text{(Eq.4)}$$

3.4.5 Array capture losses (L_C)

The array capture losses are the difference between the reference yield and the array yield.

$$L_C = Y_r - Y_A \quad \text{[kWh/(kW-day)]} \qquad \text{(Eq.5)}$$

3.4.6 Thermal capture losses (L_{Ct})

The thermal capture loss is the difference between the reference yield and the corrected reference yield. *As the module temperature was not recorded, Eq.6, Eq.7 and Eq.8 were not utilized in this study.*

$$L_{Ct} = Y_r - Y_T \quad \text{[kWh/(kW-day)]} \qquad \text{(Eq.6)}$$

Where the corrected reference yield is given by the equation:

$$Y_T = Y_R(1 - \lambda(T_m - 25)) \text{ [kWh/(kW-day)]} \quad \text{(Eq.7)}$$

3.4.7 Miscellaneous capture losses (L_{cm})

The miscellaneous capture loss is the difference between array capture losses and thermal capture losses, given by the equation:

$$L_{cm} = L_C - L_{Ct} \text{ [kWh/(kW-day)]} \quad \text{(Eq.8)}$$

3.4.8 Performance ratio (PR)

The performance ratio compares the PV arrays actual performance with the arrays ideal performance under standard test conditions. The performance ratio describes the effects losses have on the PV system efficiency, and is found by dividing the final yield by the reference yield.

$$PR = \frac{Y_F}{Y_r} \quad \text{(Eq.9)}$$

3.4.9 Capacity factor(CF)

The yearly capacity factor for an energy producing unit (e.g. PV array) is defined as the useful energy produced by this unit during a one year period, divided by the amount of energy the unit would have produced if it was running at its rated power for 24h-day for 365 days (8760h during a normal year) (K. Padmavathi 2013). The annual capacity factor of the PV system is given as:

$$CF = \frac{Total\ E_{AC}}{P_{PV,rated} * 8760} \quad \text{(Eq.10)}$$

3.4.10 System efficiencies

The array efficiency (η_{pv}), inverter efficiency (η_{inv}) and overall system efficiency (η_{sys}) is found using the following equations:

$$\eta_{pv,\tau} = \frac{E_{A,\tau}}{\int_{\tau} G_i A_A dt} \quad \text{(Eq.11)}$$

To calculate the efficiency of the inverter, the energy output (E_{AC}) from the inverter is divided by the energy input (E_{DC}) to the inverter:

$$\eta_{\mathrm{inv},\tau} = \frac{E_{AC}}{E_{DC}} \quad \text{(Eq.12)}$$

$$\eta_{\mathrm{sys},\tau} = \eta_{pv,\tau} \times \eta_{\mathrm{inv},\tau} \quad \text{(Eq.13)}$$

3.4.11 Energy output

The energy output is defined as the amount of AC power produced by the system over a given period of time. The total daily and monthly energy produced can be determined respectively from equations 14 and 15.

$$E_{AC,daily} = \sum_{t=1}^{24} E_{AC,t} \quad \text{(Eq.14)}$$

$$E_{AC,monthly} = \sum_{d=1}^{N} E_{AC,d} \quad \text{(Eq.15)}$$

where $E_{AC,t}$ =AC energy output at hour t; $E_{AC,d}$ = daily AC energy output; $E_{AC,m}$ = monthly AC energy output; N = number of days in a month.

The equations for derived parameters used in calculation of the PV system performance assessment are as found in standard IEC 61724:1998 and as found in the work of K. Padmavathi (K. Padmavathi 2013). By applying the appropriate energy quantities, equations 1 through 15 can be utilized to find annual, monthly and weekly yields, losses, efficiencies and energy outputs.

RESULTS AND DISCUSSIONS

4.1 Energy output

Monthly average values from this study, show that the energy production from the PV system varies throughout the monitoring period (Figure 4.1). This is as expected, following the linear relationship between the photovoltaic system's power production and the amount of solar irradiation it collects (Figure 4.2). This observation is related to the daily position and movement of the sun. The sun is at its highest on 22nd of June, and at its lowest on 22nd of December (sees Appendix B). Therefore, it is as expected when the recorded values for produced power are at their highest during the summer months and lowest during the winter months.

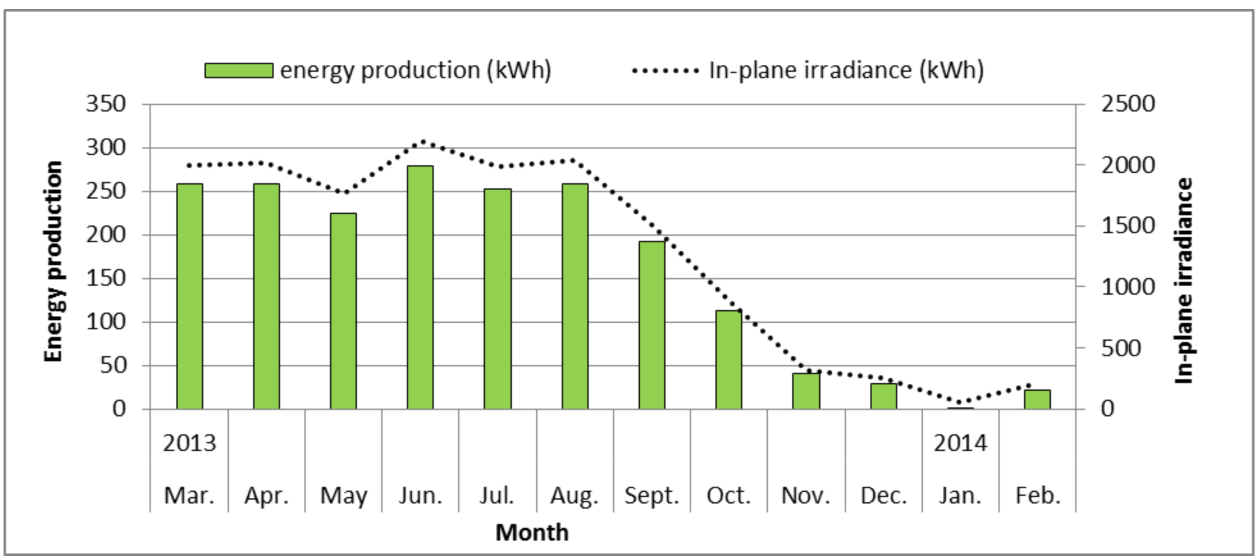

Figure 4.1: Energy produced by the PV system per month. The production varies as the amount of accumulated in-plane irradiance onto the PV modules per month varies.

The monthly average daily array yield varies between 0.06kWh/kW$_p$ (in January) and 5.53kWh/kW$_p$ (in July). The total annual energy output delivered to grid was found to be 1927.7kWh with an average energy output of 160.6kWh/month.

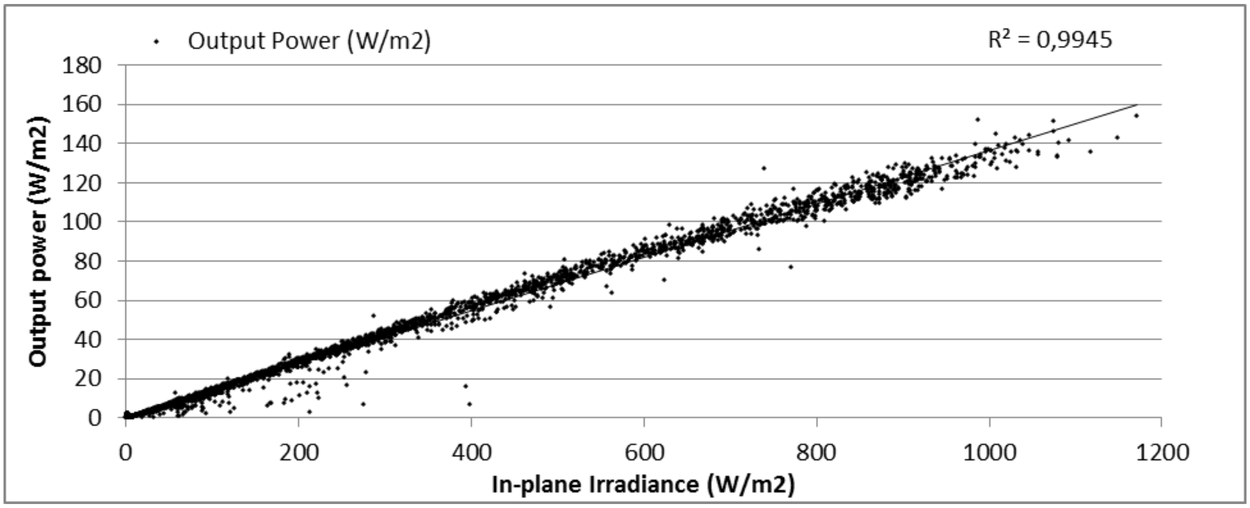

Figure 4.2: Relationship between in-plane irradiance and output power.

4.2 System Yields

The results show that the highest values for monthly average daily reference-, array-, and final yields were recorded in June, with values of 4.92 kWh/(kW$_p$-Day), 4.80 kWh/(kW$_p$-Day) and 4.50 kWh/(kW$_p$-Day) respectively. The lowest were recorded for January, with values of 0.13 kWh/(kW$_p$-Day), 0.04 kWh/(kW$_p$-Day) and 0.02 kWh/(kW$_p$-Day) respectively. The average daily reference-, array-, and final yields throughout the recording period were found to be 2.8 kWh/(kW$_p$-Day), 2.73 kWh/(kW$_p$-Day) and 2.54 kWh/(kW$_p$-Day) respectively .

The yields values for the months December through February are low, especially the values for January (Figure 4.3). The yield values from this period were affected by the decreasing number of sun hours per day as the seasons change from summer to winter, and by soiling losses (part of the array capture loss) due to snow and frost cover. Also, data missing from the dataset affects the yield values part of the recording period. This will be discussed later.

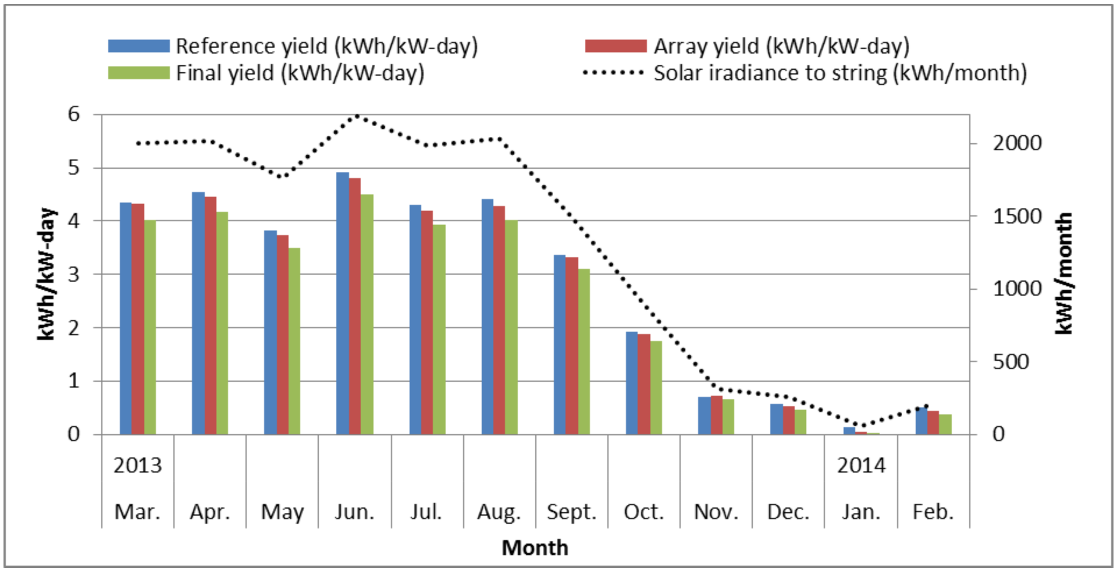

Figure 4.3: The variation of the monthly average daily reference-, final- and array yields through the recording period.

The values for specific yield of 927.7 kWh/kW$_p$ and average final yield of 2.55 kWh/kW$_p$-day found in this study (see Table 4.1) compare well to those recorded at Arvika, Sweden (specific yield: 978 kWh/kW$_p$; final yield: 2.68 kWh/kW$_p$-day), the closest of the locations listed in Table 2.1, 100 km east of Ås. It is also worth to note that the findings derived from simulations by Multiconsult (Berner 2013) compare well to the yield values of this study (specific yield: 922 kWh/kW$_p$; final yield: 2.53 kWh/kWp-day).

Table 4.1: System specifications, specific- and average final yield, system efficiencies and performance ratio found in the present study.

Location	Rated Capacity (kW$_p$)	Type of PV technology	Specific Yield (kWh/kW$_p$)	Final Yield (kWh/kW$_p$-day)	System efficiency (%)	PR (%)
Ås, Norway	**2.07**	**Multi c-Si**	**927.7**	**2.55**	**13**	**83**

4.3 Losses

The annual average daily system loss for the PV system was found to be 0,19h/day, varying between 0,32h/day in March and 0,02h/day in January. The annual average daily array capture loss for the PV system was found to be 0,05h/day. The losses varied between 0.18h/day in March and 0.04h/day in October and December. In November a *negative* system loss of 0.01h/day was recorded. To reveal what months the system- and capture losses had the largest impact on the final yield, we examine the losses relative to the reference yield (Figure 4.3).

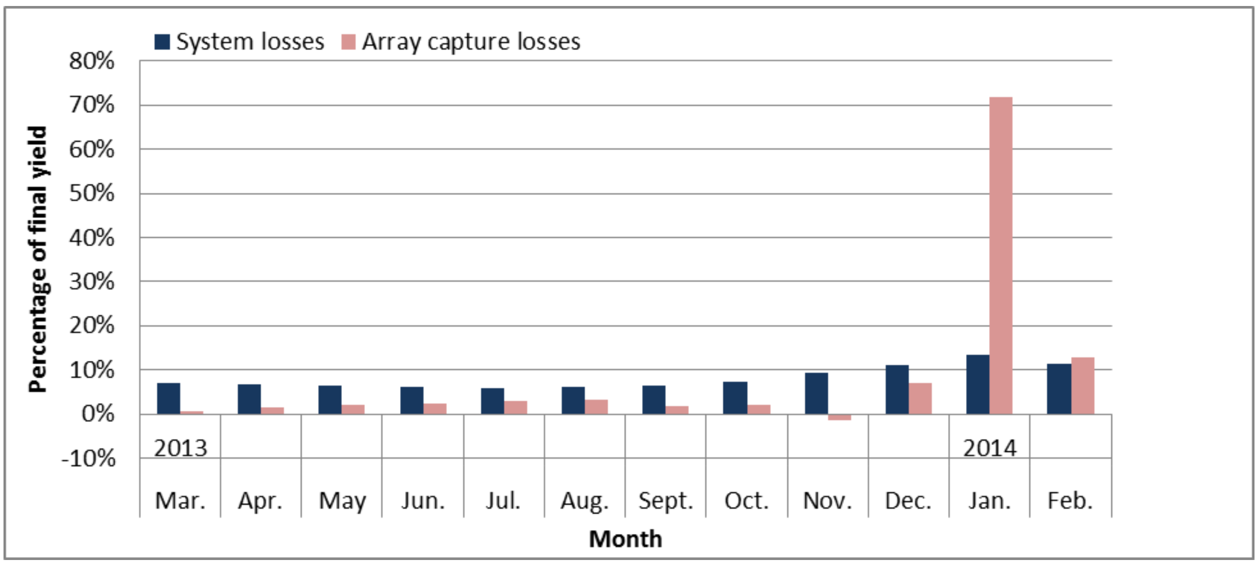

Figure 4.4: Monthly average daily array capture- and system losses relative to reference yield per month. The system loss is lower in the summer than in winter because lower values of array output power reduce the inverter efficiency. In November the array capture loss is negative. This is most likely a result of enhanced array efficiency due to low operating temperatures and no soiling losses from snow or frost.

Soiling losses could not been quantified in this paper as recordings for module temperature was not available. Snow cover is known to decreases the productivity of a photovoltaic system by decreasing the amount of irradiance received by the solar panels (Rob W. Andrewsa, Andrew

Pollarda et al. 2013). The data reveal two strong indicators that snow caused the reduced yields observed in December, January and February:

(1) The solar panels were observed to be covered with snow for extended periods during January and February, but there were no recordings made for when or for how long the solar panels were covered by snow. However the online tool seNorge.no, developed by the Norwegian waterway- and energy directorate, the Norwegian institute of meteorology and Kartverket, provides interpolated data on when and how much snow was covering *the terrain* in throughout Norway. Although the uncertainty of the snow cover data from seNorge.no (±25cm, areal resolution (km^2)) is large, it does indicate in what periods of time there was snow in the terrain, and thereby what periods snow cover could have affected the power PV production. According to seNorge.no there was a 0-25 cm snow cover in the period 8th – 16th of December, a 25-50cm snow cover 14th of January to the 3rd of February and a 0-25cm snow cover 4th – 15th of February (NVE 2014). These periods fall within the weeks 50, 3-5 and 6-7 respectively. The figure 4.5 displays the energy production per week from week 49 of 2013 to week 9 of 2014.

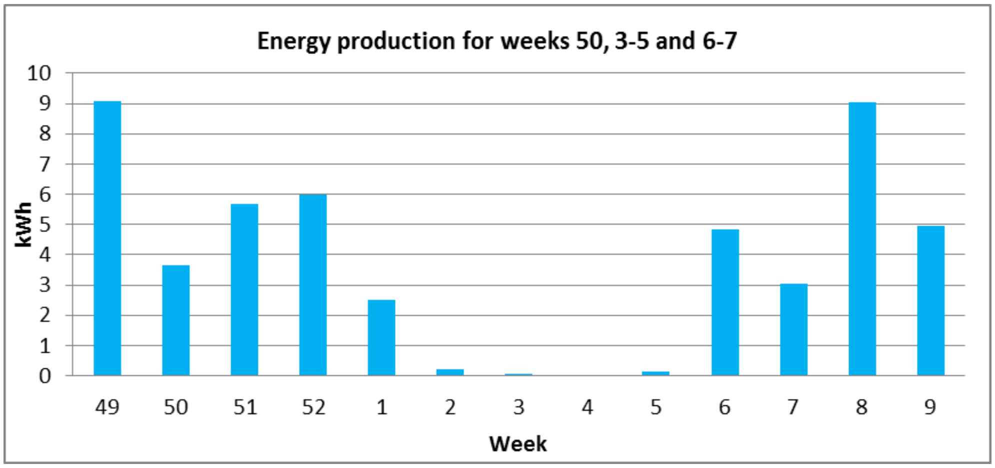

Figure 4.5: Energy produced during the weeks of 50, 3-5 and 6-7. The terrain snow cower was reported to be 0-25cm, 25-50cm and 0-25cm for these periods respectively (NVE 2014).

One cannot perceive a clear negative impact on production in weeks 50 and 6-7, when the snow cover was calculated to 0-25cm. However, in the period when terrain snow cover was reported to be 25-50 cm, week 3-5, production is close to nothing. The recorded production for week 2 is also very low, even though there was no reported snow cover. The reason for this is that, due to logger malfunctioning, 78% operation this week was not logged. About 7% and 2% of operational data is missing for the week 3 and 4 respectively. Weeks 50, 6 and 7 are not missing data.

(2) As previously mentioned the array capture loss can be divided into two categories, thermal capture loss and miscellaneous capture loss (M. Drif, P.J. Pérez et al. 2007). Because the efficiency of the solar panels increases as the temperature decreases, we cannot expect an increase in thermal losses during the coldest months of the recording period, namely December, January and February. But the array capture loss does increase relative to the

reference yield in this period (Figure 4.6). The relative increase in the array capture loss for December, January and February must therefore be derived from the miscellaneous loss category. Miscellaneous losses include losses in wiring between PV array and inverter, losses due to diodes, shading, mismatched operation, non-ideal maximum power point tracking (not relevant for this study), component failure and soiling losses (K. Padmavathi 2013). In this list, loss from soiling (due to snow and frost cover) is the most likely cause, as it is the only loss which will recede by itself without any altering to the technical system, which was not done during this period of recording. This assumption is strengthened by the fact that the relative size of the array capture loss to reference yield is largest for the same weeks that had the largest reported amount of terrain snow cover (Figure 4.6).

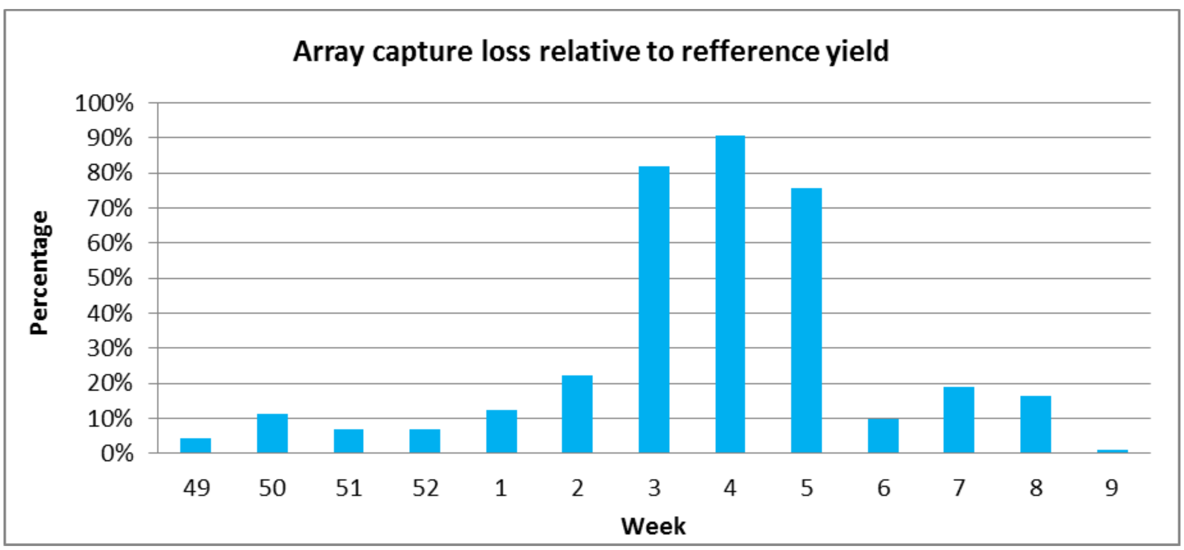

Figure 4.6: The weekly array capture loss is 82%, 91% and 76% relative to the reference yield in week 3, 4 and 5 respectively, the same weeks that the terrain snow cover was reported to be the deepest.

4.4 Efficiencies

The monthly estimated average efficiencies for the PV system were found to be consistent for all the months expect November, December, January and February (Figure 4.7). The monthly average inverter efficiencies were found to be 91%, 88%, 53% and 87% for the months of November, December, January and February respectively. For all other months this value varied only between 93% and 94%.

The monthly average array efficiency was calculated to be 14% for all months but for December, January and February, when values of 13%, 4% and 12% were calculated, respectively.

Following Eq. 13, the system efficiency equals the product of the array- and inverter efficiencies. The monthly average system efficiency was found to be 13% for all months except for December, January and February, when the system efficiency fell to 11%, 2% and 11% respectively.

The main reason for the reduced system efficiency in December, January and February is that the inverter efficiency is reduced at low levels of input power from the PV array (Figure 4.8). The average input power from the PV array to the inverter for recordings where *Output array power* > 0, was 15.36W for January, while being recorded to 145.41W and 73,49W for December and February respectively. Over the whole recording period, the average was 432.4W.

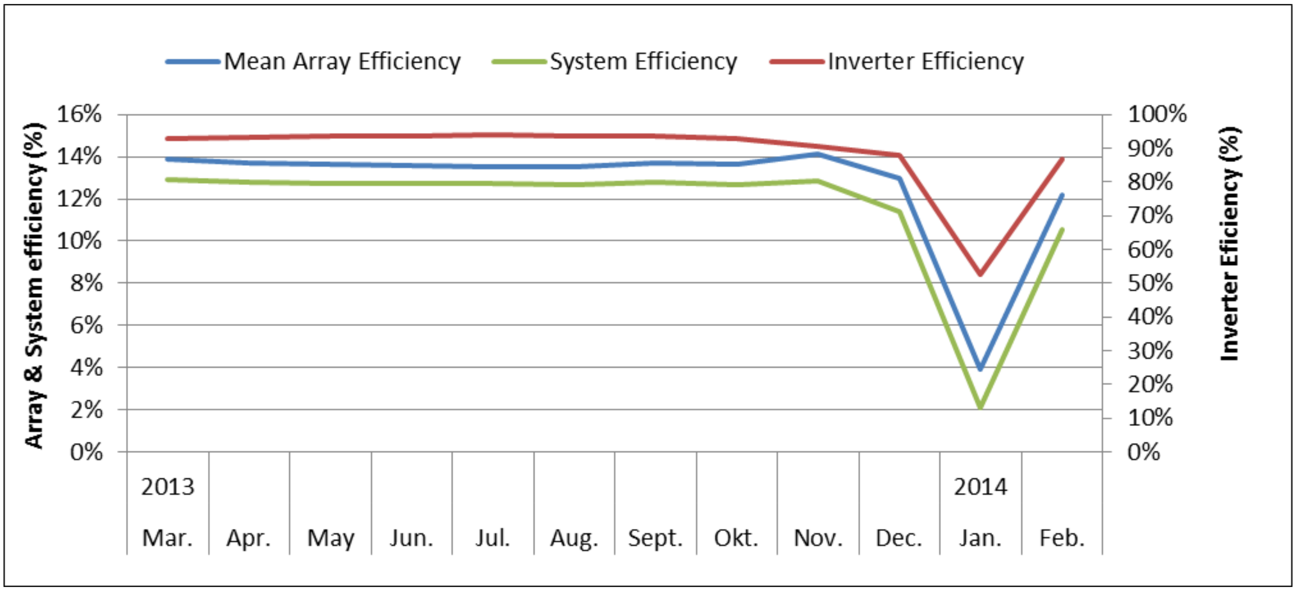

Figure 4.7: Monthly average inverter-, array-, and system efficiencies through the recording period.

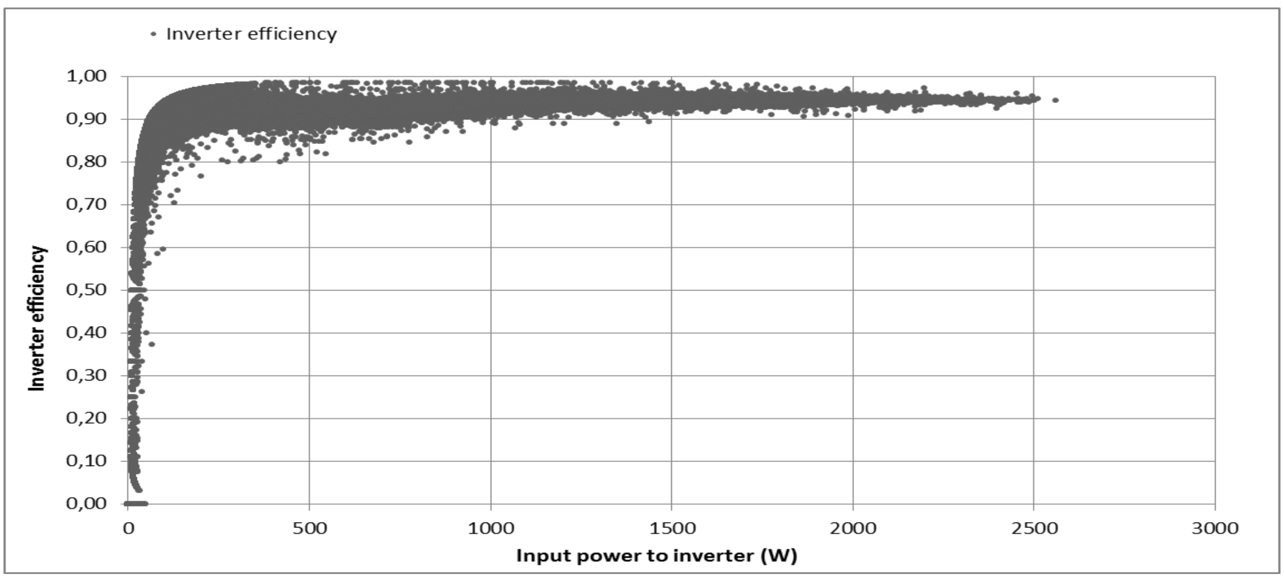

Figure 4.8: The effect of input power magnitude on inverter efficiency.

As a result of the above mentioned factor, the performance ratio too was reduced in the winter months, and especially so in January. The annual average system performance ratio (Eq.9) was fund to be 83% throughout the recording period. Monthly averages varied between the minimum of 15% in January and the maximum of 93% in March (Figure 4.9).

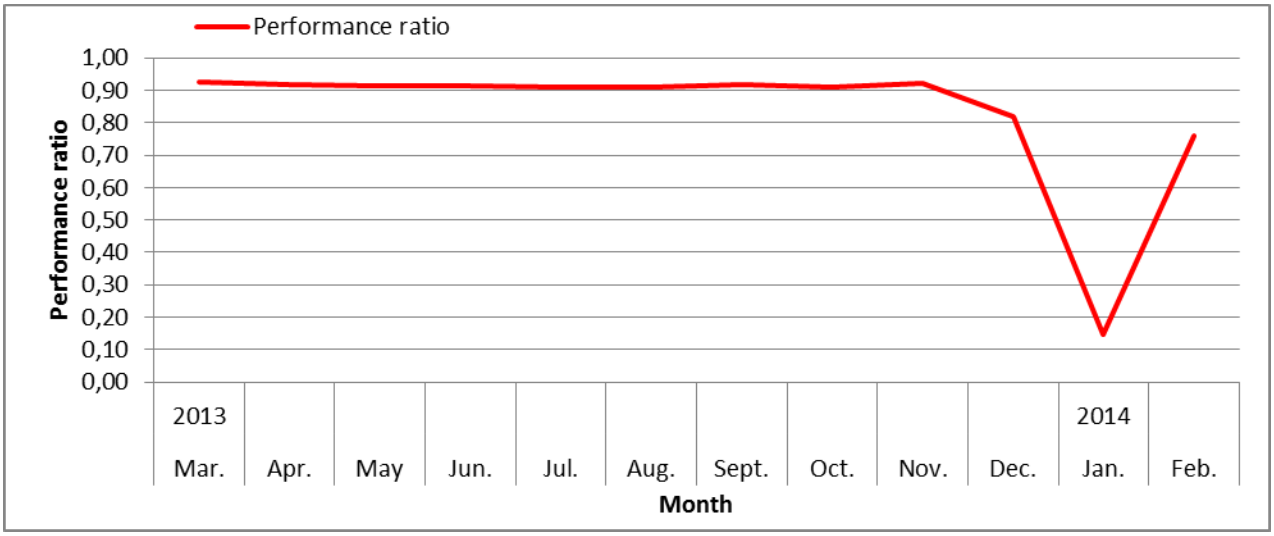

Figure 4.9: Monthly variation of the system performance ratio.

If we leave out the values for January, the annual average system efficiency, performance ratio and capacity factor increases from 11.6% to 12%, and 83% to 89%, respectively.

In the period March through November, during which 97% of the total energy production from the PV system took place, the average system efficiency and performance ratio was recorded to be 13% and 91% respectively.

The recorded monthly average values of yields, losses efficiencies and performance ratio reveal the negative impact snow cover, and low array output power, has on the operation of a PV system.

As previously mentioned and illustrated in Figure 4.10, the dataset of this study is missing 3, 23, 2, 50 and 20 percent of the data for the months March, July, August, November and January respectively (figure 4.10). This amounts to a total of 8% missing data throughout the recording period. In this paper the missing data is treated as production losses due to PV system- or grid dysfunction. The actual reason for the missing data resulted from logger dysfunction following grid failure, as it does not turn on automatically after the grid is up and running again.

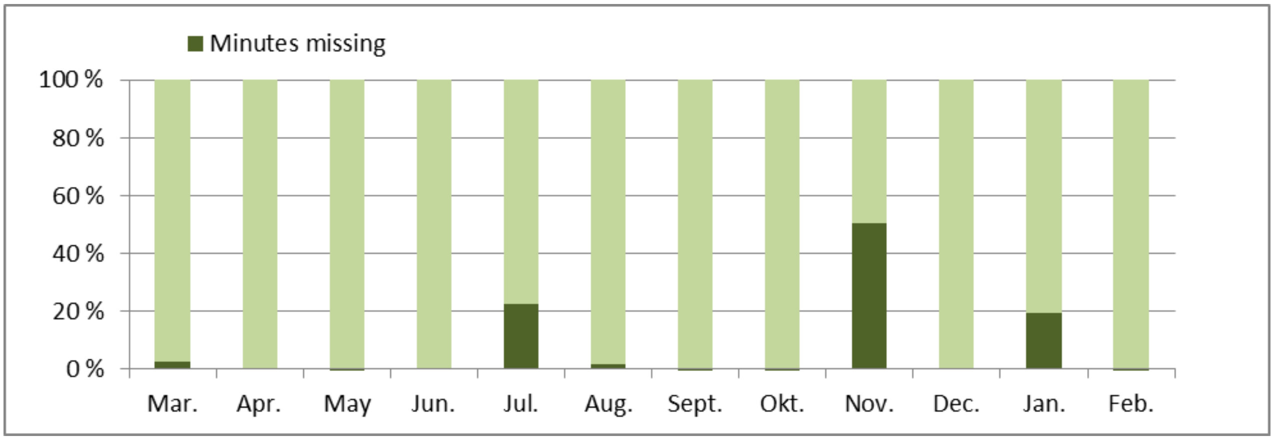

Figure 4.10: Distribution of missing data as percentage of time for the respective months.

According to the local grid operator, the average capacity factor of the utility grid in Ås has been 99.98-99.99% the six years preceding 2013 (Arild Olsbu, Gunn Spikkeland Hansen et al. 2013). At time of writing, data for 2013 is not available. The average annual capacity factor for the whole Norwegian utility grid was in the range of 98% - 99% during the years 2001 to 2012 (NVE 2013). Data for 2013 and 2014 are not available at the time of writing.

Considering this information, 8% of missing data is far higher than the value one would expect to find for the average annual down time of the utility grid in Ås, or in Norway as a whole. This means that the observed energy production for the recording period most probably would have been higher than what was derived from the available dataset. We can make a suggestion as of what the actual energy production could have been by making three assumptions (figure 4.11):

1. The actual downtime for the local utility grid in Ås was at the national average of 2% during the recording period.
2. The missing data is evenly spread throughout the day.
3. The missing data would not affect the average yield values if included in the calculations.

Given the above mentioned assumption, the total energy production during the recording period was 2015.7 kWh, 4.6% higher than recorded. The assumed average daily final yield and specific energy yield would then be 2.71kWh/kW_p-day and 989.2 kWh/kW_p, respectively.

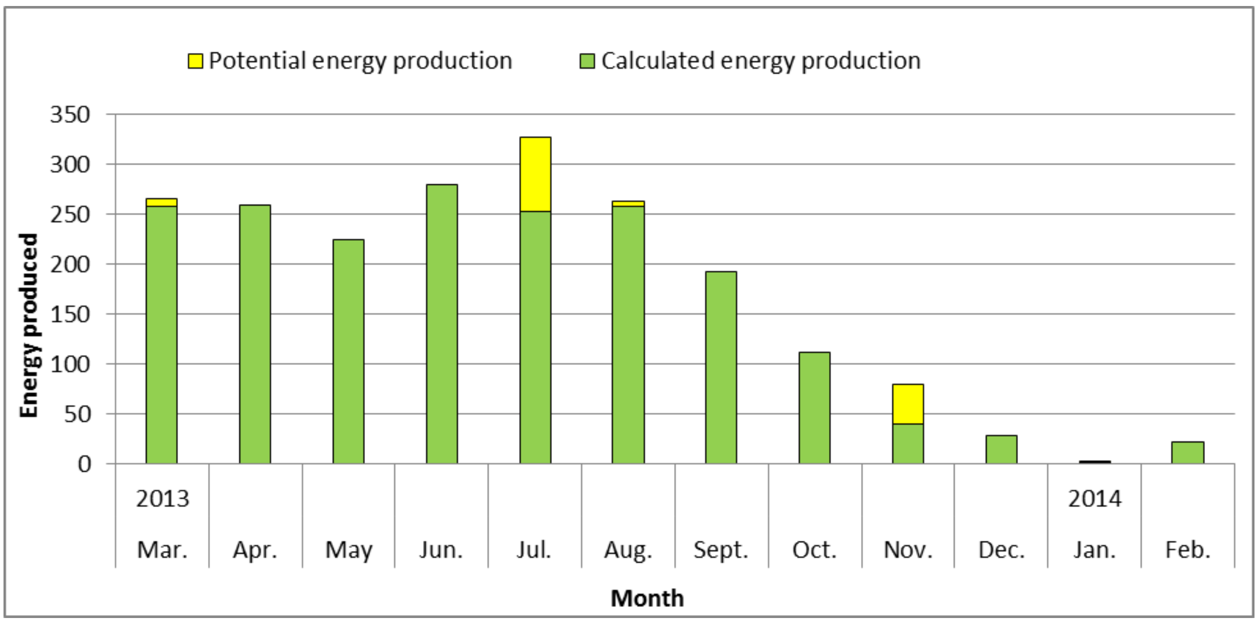

Figure 4.11: The amount of energy produced as calculated, and the amount of energy that might actually have been produced but not recorded, following the above mentioned assumptions.

The results from this study are derived from one year of recorded data, similar calculations for the same PV system will vary as irradiance and climatic conditions vary in the future. However, average global irradiation and temperature through the 12 months of recording were similar to the yearly average for the last thirteen years in this area. This implies that the availability of the most important factor for determining conditions for PV power production, solar energy, was representative through the recording period. It is not known how representative the loss due snow cover on the panels was. This is a factor that will vary from year to year, and which has potential of affecting the annual performance of a PV power system. This said, 97% of the energy production took place during a period not expected to be significantly affected by soiling losses due to snow and frost (March-November). One can therefore assume that the findings from this study are representative for this type of PV system in this area of Norway.

CONCLUSIONS AND SUGGESTIONS

5.1 Conclusions

The normalized energy production from a 2.07 kWp PV system in Ås, measured through 12 months recording period, was found to be slightly higher compared to similar studies from Warsaw, Dublin and an estimated average for Germany, and slightly lower compared to a study from Arvika, Sweden. Holes in the dataset indicate that the actual energy production during the recording period could be higher than the observed energy production.

The performance of the PV system was affected by changing number of sun hours per day through the recording period and by soiling losses due to snow and frost during the winter months. The relatively low average temperature at this latitude is believed to have a positive effect on the system performance, although this effect could not be quantified in this study.

5.2 Suggestions for further study

Data describing the solar resource and potential for production of power by means of PV systems in Norway is sought for by both state and private enterprises in Norway.

In order to better describe solar irradiation conditions and PV production potential in Norway, observations of irradiation from around the country should be collected and used to calibrate software commonly used to estimate such values. This work has been initiated by Kjeller

Vindteknikk. Also, more case studies of PV system performance should be conducted throughout the country, and the results made publicly available.

Already established PV systems should be identified, and their respective specifications and performance data made available.

5.3 Suggestions for further research on the subject PV system in Ås

The performance assessment of the PV system in Ås should be continued, and the issue of logger malfunctioning following grid failure should be sorted out. Data accumulated over time will give a more representative description of the conditions for PV power production in this area.

In order to better describe the effects of climatic conditions on the PV system performance, it would be beneficial to start logging module temperature, as well as ambient temperature and global irradiation in immediate vicinity of the PV array.

In addition, performance assessment of PV-grid system with uniform PV modules of similar technical specifications from the same producer should be studied. Furthermore, economic assessment of these proposed and current PV system installations should be carried out.

Recording of snow cover in terrain and on panels should also start.

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Appendix A: Detailed specifications of THEIA HE-t inverter

THEIA HE-t

SOLAR INVERTERS: 2.0KW – 4.4KW

ELTEK VALERE
always on

TECHNICAL SPECIFICATIONS

Model	2.0HE-t [1]	2.9HE-t [1]	3.8HE-t	4.4HE-t
INPUT DATA				
Nominal DC power	2100 W	3000 W	4000 W	4600 W
Max. Recommended PV Power	2625 W	3750 W	5000 W	5750 W
Max. DC voltage	600 Vdc	600 Vdc	600 Vdc	600 Vdc
Voltage range MPPT	230 to 480 Vdc	230 to 480 Vdc	230 to 480 Vdc	230 to 480 Vdc
Max. input current	9.5 A	13.5 A	18.0 A	21.0 A
Number of PV string inputs	3			
Number of MPP trackers	1			
Input features	Reverse polarity protection, Ground fault monitoring, Integral DC switch disconnector (optional), Integral DC fuses for string inputs (optional) Field configurable for positive or negative grounding, or ungrounded			
OUTPUT DATA				
Nominal output power	2000 W	2900 W	3800 W	4400 W
Nominal AC current	9.0 A	13.0 A	17.0 A	20.0 A
Max. AC current	10.5 A	15.2 A	19.7 A	23.0 A
Mains output voltage	184Vac to 276Vac single or split phase [2]			
Mains frequency:	50Hz / 60Hz (+/- 5Hz) [2]			
Power factor (cos φ)	1			
PERFORMANCE DATA				
Maximum efficiency:	96.9 %	97.0 %	97.2 %	97.3 %
CEC efficiency:	96.1 %	96.4 %	96.9 %	97.0 %
EU efficiency:	96.0 %	96.2 %	96.6 %	96.9 %
Power feed starts at	< 7 W			
Night mode power	< 1 W			
MECHANICAL DATA				
Protection degree	IP 65 / NEMA 4X			
Dimensions	610H x 353W x 154D mm / 24.02H x 13.90W x 6.06D inches			
Weight	19kg / 42lbs	19kg / 42lbs	21kg / 46lbs	21kg / 46lbs
Cable access	Bottom and Sides			
Input cable connection	MC3, MC4, Tyco, Screw terminals, Cable clamp, Others on request			
Output cable connection	Screw terminals, Cable clamp			
DESIGN STANDARDS				
EM compatibility:	EN 61000-6-2, EN 61000-6-3, FCC Level B			
CE / UL marking:	Yes			
Other standards:	UL 1741, DIN VDE V 0126-1-1, G83/1, EN 50438, AS 4777, ENEL Guidelines (DK 5940), EN 61000-3-2, EN 61000-3-3, EN 61000-3-11, EN 61000-3-12			
ENVIRONMENTAL DATA				
Operating temperature:	-25 to +65 °C / -13 to +149 °F (possible power derating above +45°C / +113°F)			
Storage temperature:	-30 to +80 °C / -22 to +176 °F			
Ventilation	Convection cooling			
ADDITIONAL FEATURES				
Topology	High frequency transformer, galvanic isolation			
Noise Emission	≤ 40 dB (A)			
Communication	Graphical, color display with touch sense buttons, Embedded web-server, Ethernet, CAN and RS485 bus interface, 3x LEDs for visual status indication			
Warranty	5 years, 10 years, 15 years, and 20 years options			

1) Preliminary data for THEIA models
2) Voltage and frequency range adjustable to specific grid settings

357115.DS3 rev6 - Specifications subject to change without notice

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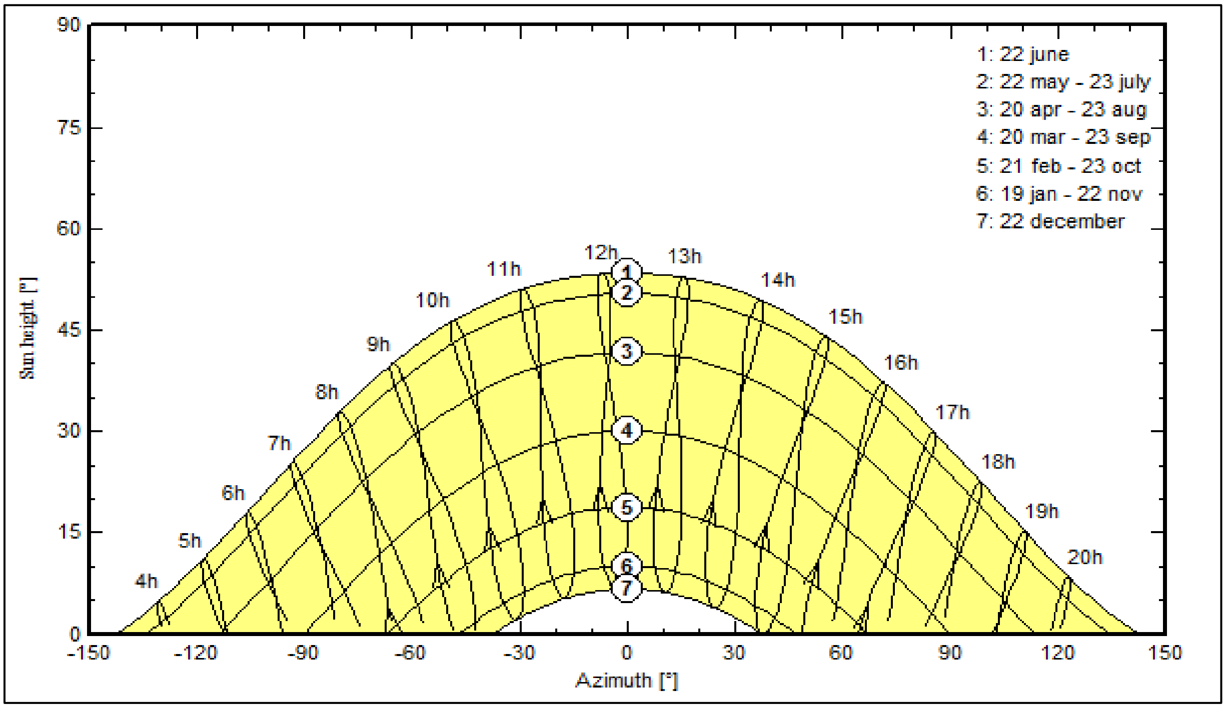
Appendix B: Sun position over Oslo



(Berner 2013)

Appendix C: Photographs of PV system

Clockwise, from top left: PV array and reference cell, PV array, PV array on top of laboratory building and PV array installation.