Design of an off-grid Photovoltaic system

With supplementing energy from Wind and Diesel

ANTON ØRBÆK S091870, JOHANNES DAHL S091251, CARLO ALBERTO AMADEI S102087
DEPARTMENT OF CIVIL ENGINEERING, TECHNICAL UNIVERSITY OF DENMARK
DK 2800, KGS. LYNGBY, DENMARK

Course: 11128 Team: 11 Handed in to: Bengt Perers

Abstract

With increasing electricity prices and the need to minimize environmental impact, two young men have decided to see if it's possible to live in a capital city completely off the main grid. The combination of a number of sustainable energy technologies were considered in order to help them reach their goal. In order to completely go off the grid enough electricity needs to be generated by either photovoltaic solar panels or wind turbines to cover their electrical requirements. Two different simulation programs, HOMER and PVSUN3, were used in order to determine the required size of the solar collector array and components. Both simulation programs showed that it's not economical to cover the electrical requirement only by solar PV for all year operation. A hybrid system consisting of a wind turbine, solar collectors, controller, invertor and a backup generator is required in order to meet the cabins electrical demand.

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Introduction

With the ever growing concerns of global warming, international interests have increased the research and development into sustainable energy systems. The costs of many different technologies have steadily decreased while the systems themselves have improved. Combining this with steadily growing electricity prices the market for sustainable, efficient energy technologies has opened up to a large user group of home owners. It's not necessarily expensive to be disconnected from the main grid anymore; local resources can even give conditions that are better economically. All it takes is a little effort.

The aim of this project is to investigate and design a solar PV and wind turbine system for a standalone house in the outskirts of Copenhagen, Denmark. In order to correctly size the system two different simulation programs, HOMER and PVSUN3, will be used. With these programs a number of different solar PV and wind turbine arrays can be simulated in order to determine the cheapest and best system configuration.

1. Scenario description and load

1.1 Location

The small scenario house, in size compared to a cabin, is located on the outskirts of Copenhagen, at the GPS coordinates N55°40'52.32", E12°36'38.88". The building is facing directly south and benefits from not having any buildings or trees close by, blocking the sun.

1.2 Occupants

There are two people living full time in the building. One of the occupants is a full-time student. The time spent at home is generally limited to early mornings and late evenings, the rest of the time is spent in school. During weekends the approximate time spent at home is 50 %, but large variations occur throughout the year. The second person living in the residence is a full-time employed carpenter. The weekday schedule is similar to the student with a five workday's but he might occasionally work during the weekends. Work starts later in the morning however and like the student he uses a number of appliances in the morning. He returns home for lunch for approximately one hour.

Between morning and evening, except lunch, the cabin stands empty. This means that the only electrical usage in this period of the day is for appliances such as fridge and clock radio.

1.3 Heating requirements

The building is heated by a wood burning stove with a back boiler. The back boiler heats up the domestic hot water for the home when the fire is on. There is a solar air heater installed on the south facing wall which provides sufficient amount of heat to cover the day time heating requirement from early spring until late autumn. There is also a flat plate solar water collector on the roof to heat the water during the summer periods and help pre-warm the water during the winter months. A large expected amount of electricity for heating requirements can therefore be neglected.

2. Scenarios

Two different scenarios off electrical appliance usage have been drawn up. This is done so that it is possible to simulate how the system would operate under summer and winter conditions.

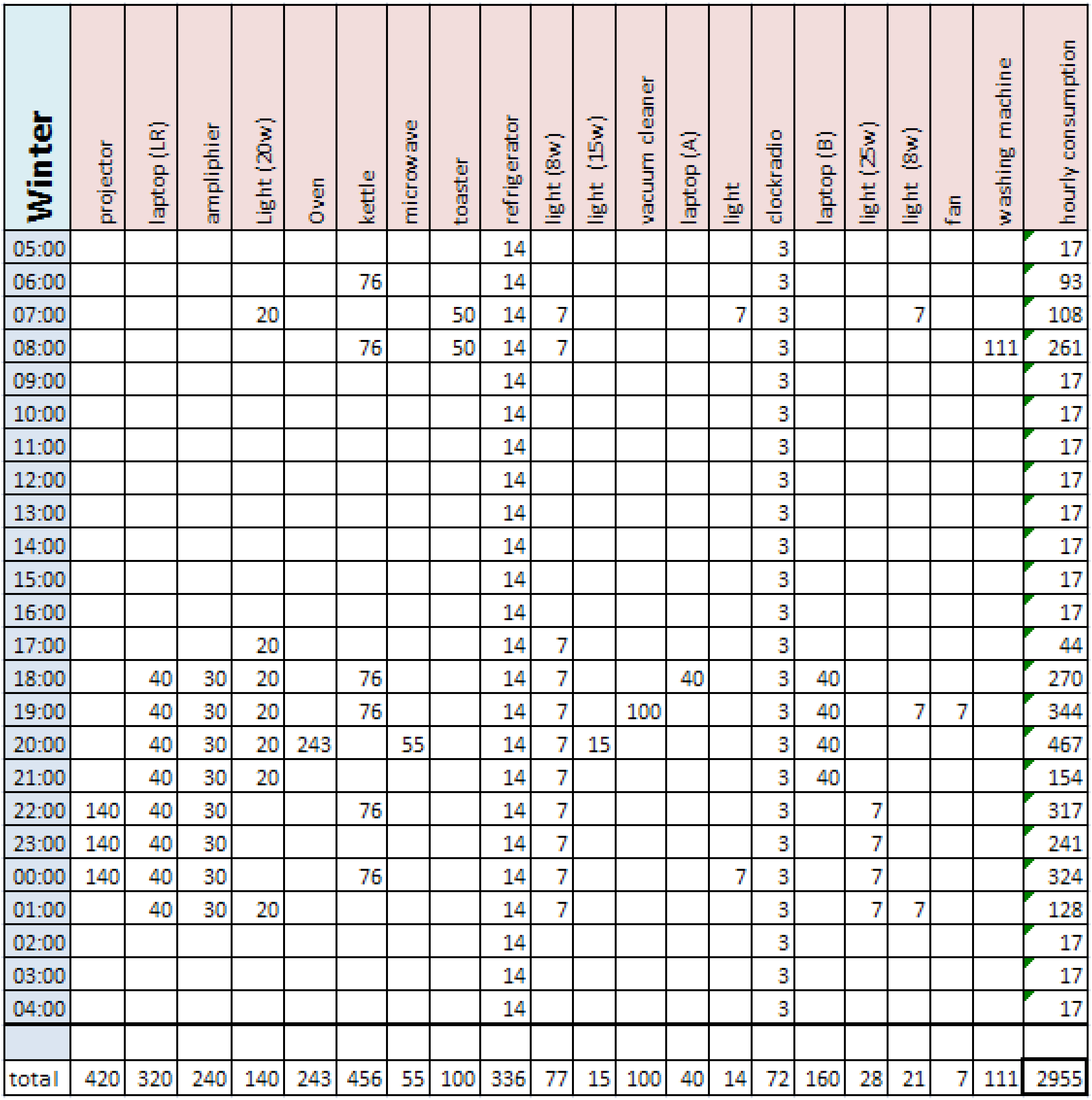
The winter time has a high daily load. This is due to the fact that the days are shorter, so the lights will be in use for longer periods. Also the occupants spend more time indoors, making the operational period of a number of appliances higher, such as projector, laptops and kettle. The summer period is naturally lower with lower operational periods due to time being spent outdoors and on vacation. There is also more natural light, making the operational period of the indoor lights less.

The scenarios are based upon the occupant's lifestyle during the year. An interview with the two occupants was carried out in order to get an understanding of their requirements and hourly time table. The solar system can then be designed to directly meet their needs and electrical consumption. The results from this meeting are compiled in Table 1 below and Table 12 in Appendix A. These tables are later used in the computer simulation programs, HOMER and PVSUN3.

2.1 Determination of the daily consumption

In order to determine the daily consumption of the dwelling a table including all the appliances with an hourly time step was constructed. The table was then given to the occupants of the building so marks could be made when an appliance was used and in which time step it was used. They were asked to fill one out for a summer scenario and a winter scenario. This gave a good understanding of how often the appliances are used during the two different periods of the year. The recorded electrical consumption of each appliance was then inserted into these cells in order to quantify the amount of electricity used during each hourly time step, see Table 1.

TABLE 1: WINTER CONSUMPTION



Winter	projector	laptop (LR)	ampliphier	Light (20w)	Oven	kettle	microwave	toaster	refrigerator	light (8w)	light (15w)	vacuum cleaner	laptop (A)	light	clockradio	laptop (B)	light (25w)	light (8w)	fan	washing machine	hourly consumption
05:00									14						3						17
06:00						76			14						3						93
07:00				20				50	14	7				7	3			7			108
08:00						76		50	14	7					3					111	261
09:00									14						3						17
10:00									14						3						17
11:00									14						3						17
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13:00									14						3						17
14:00									14						3						17
15:00									14						3						17
16:00									14						3						17
17:00				20					14	7					3						44
18:00		40	30	20		76			14	7			40		3	40					270
19:00		40	30	20		76			14	7		100			3	40		7	7		344
20:00		40	30	20	243		55		14	7	15				3	40					467
21:00		40	30	20					14	7					3	40					154
22:00	140	40	30			76			14	7					3		7				317
23:00	140	40	30						14	7					3		7				241
00:00	140	40	30			76			14	7				7	3		7				324
01:00		40	30	20					14	7					3		7	7			128
02:00									14						3						17
03:00									14						3						17
04:00									14						3						17
total	420	320	240	140	243	456	55	100	336	77	15	100	40	14	72	160	28	21	7	111	2955

At the end of each time step the sum of consumption is shown in the column to the right. By adding the hourly consumptions together the total daily consumption was reached. This daily consumption is based on the highest electrical consuming day of the week. For example the oven, vacuum cleaner and the washing machine will only be used once a week, and not every day.

The solar PV system is then designed on this high daily consumption so it can meet this load in case all the appliances are actually used on the same day.

2.2 Real consumption of electrical devices

In order to size the solar PV system correctly, it is required to determine the total consumption of the dwelling.

The first step was to find out what type and how many electrical appliances are in the cabin. Then a list with their rated power was constructed. This rated power is the max power that the appliances use though they will generally use less during actual operation. For example the electric cooker is rated at 2.2 kW but it will only consume that power when heating up the oven. When the oven is warm it will stop using electricity because it keeps the heat while continuing to cook the food. Only when the temperature drops will it start to consume electricity again. Experiments were therefore conducted with every appliance in order to determine the real consumption of the building so that the PV system could be sized correctly. The experiment procedure can be found in the Appendix A.

The results of these experiments can be found in the Table 2 below. Notice that by adding the consumption of each appliance there is a decrease from 10 kW to 7.7 kW. By discovering this real consumption, the PV system can be correctly sized. This will save on the initial investment needed by decreasing the quantity of solar PV panels and batteries required in order to meet the demand.

TABLE 2: REAL CONSUMPTION

Rooms:	**Devices:**	**Rated power [W]:**	**Real consumption [W]:**
Living Room	video projector	288	140
	laptop	90	40
	amplifier	140	30
	light 1	10	9
	light 2	10	9
Kitchen	oven	2200	1700
	kettle	2200	2105
	microwave	2300	1260
	toaster	1000	899
	refrigerator+freezer	70	70
	light 1	8	8
	light 2	15	14
	vacuum cleaner	1200	1015
room1	laptop	72	40
	light	10	10
room2	clockradio	3	3
	laptop	90	40
	light 1	25	23
bathroom	light 1	10	10
	Fan	7	7
	washing machine	260	260
	TOTAL:	**10008**	**7692**

3. System Components

An off-grid system is a system that is not connected to the main power grid and must therefore be able to supply energy by itself at all times. An off-grid house needs to provide the same comforts of heat and electricity with use of energy sources available at the sight. It is a necessity to provide the system with enough power and back-up power so that if one source is not available the others can take up the load. The designed system will consist of many components that need choosing. Solar panels, batteries, wind turbine, diesel generator, inverter and controller. Every component is selected and explained in the paragraphs below.

3.1 Solar panels

The main focus of the project and the main power supply for the off-grid house is the solar panel. The panel must be dimensioned in cooperation with the batteries to supply enough power to run the system operation throughout the year. There are many ways of providing electricity from the sun, but the most common is PV from monocrystalline and polycrystalline.

Monocrystalline are uniform cells with high efficiencies of up to 20 % and have good market availability. They are one of the oldest and most reliable types of solar cells and have been known to last for up to 50 years, although 25 years is the average expected life time. They are however quite expensive.

Polycrystalline cells consist of none-uninform cells and have a lower efficiency around 10-15 %. It will therefore be necessary to install a larger area of panels to reach the same need power output. They are on the other hand cheaper to buy than monocrystalline.

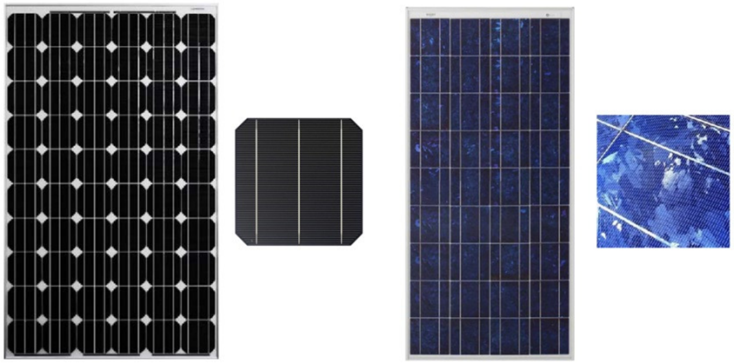


FIGURE 1: MONO VS POLYCRYSTALLINE (BLIMPBY, 2010)

With the choice of solar panel also comes the issue of the voltage they are running on. Depending on the size of the system it’s normal to run it on 12, 24 or 48 V. In this project the batteries, wind turbine and diesel generators are all running at 12 V and in DC. The solar panel will need to run at similar voltage and in DC as well. The voltage will in reality be higher, which is beneficial because batteries need to be charged by a slightly higher voltage. Low voltage does however limit the possible power output, around

140 W with today's technologies (Blimpby, 2010). To meet the energy demand it will be necessary to connect several panels in parallel. It is possible to install panels with a higher voltage and buy a controller which can operate the voltage down. This opens up a lot of possibilities in products, but increases costs and decreases efficiency in total. Resistance in the cables is also an issue to take into consideration, making it a priority to make the cable distance short and the cables thick to limit losses.

TABLE 3: SOLAR PANEL COMPARISON (WORLD, 2010) (RVWORLD, 2010) (SUNTECH, 2010)

Solar panels:	Sungrid 140	Moser Baer	Suntech-STP140D
Type:	Monocrystalline	Polycrystalline	Polycrystalline
Price [DKK]:	5232	2334	3963
Efficiency [%]:	13.8	-	-
Rated power [W]:	140	80	140
Dimensions [m^2]:	0.98	0.68	1.00

In Table 3 some solar panel modules that fit the criteria of 12 V and still being big enough to be of use are displayed. Efficiency is an important factor for simulations and for dimensioning the system, but none where found for polycrystalline. The monocrystalline is therefore chosen as it's a better choice in terms of efficiency, costs are not that much higher and dimensions are smaller. The quantity of collectors is chosen based on the results from the simulations.

3.2 Batteries

The choice of battery is a very important factor for the total operation of the system as all produced and withdrawn energy has to come via the batteries. Small off-grid PV systems today consist in general of open lead acid batteries as they are the most commonly available and the cheapest. Major factors that influence the battery lifetime are deep discharge, overcharge, low electrolyte level and high battery temperature. A battery is considered to have reached the end of its life when the capacity has reached 80 % of the nominal value (the guaranteed capacity from the manufacturer). An extra margin of safety for the batteries is that normal discharge should not be more than 50 % and only in very short periods of time should it get drop as far as 20 % of its capacity (IEA Task III, 1999). Attention to this will help extend the lifetime of the battery significantly.

The calculated design energy content of a battery is based on Voltage and Ampere hours. For a battery of 6 V and 250 Ah a total capacity of 6 V*250 Ah= 1500 Wh is found if the battery is fully discharged. Battery capacity at the end of lifetime is however expected to be 80 % and furthermore it has been decided that normal discharge shouldn't be below 50 %. The content of the battery is therefore reduced to 80 %*50 %= 40 % of the nominal value. In this case 40 %*1500 Wh= 600 Wh.

For a normal PV system the batteries should be able to provide enough energy for 3-7 days of operation without sun, or around 100 hours or normal energy consumption. The off-grid system in this report however will have support from both wind energy and a diesel generator so the rule is not that binding. The final simulations will provide battery capacity enough to meet the general load.

Depending on the choice of battery it might be necessary to connect the batteries in series and parallel to reach the required system voltage and capacity of 12 V and operation of 100 hours. Batteries are connected in parallel to increase the voltage, two 6 V batteries in parallel gives 12 V. When connected in series they increase battery capacity. Two 250 Ah batteries in series gives 500 Ah. In parallel the capacity will be the same but the energy content will of course increase, Wh= V*Ah.

One last important factor is the rated hours specified to drain the battery completely. If for example a 200 Ah battery is specified for a 20 hour rate it means that 10 Amps will be given over a 20 hour period. If however a 4 hour rate and 50 Amps are desired the capacity is no longer 200 Ah.

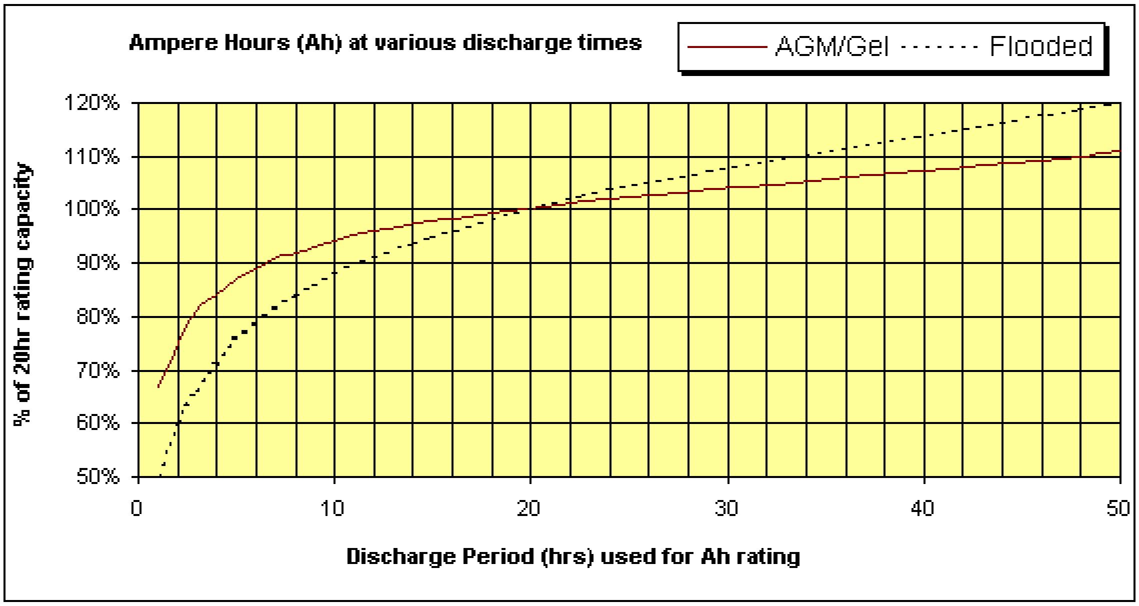


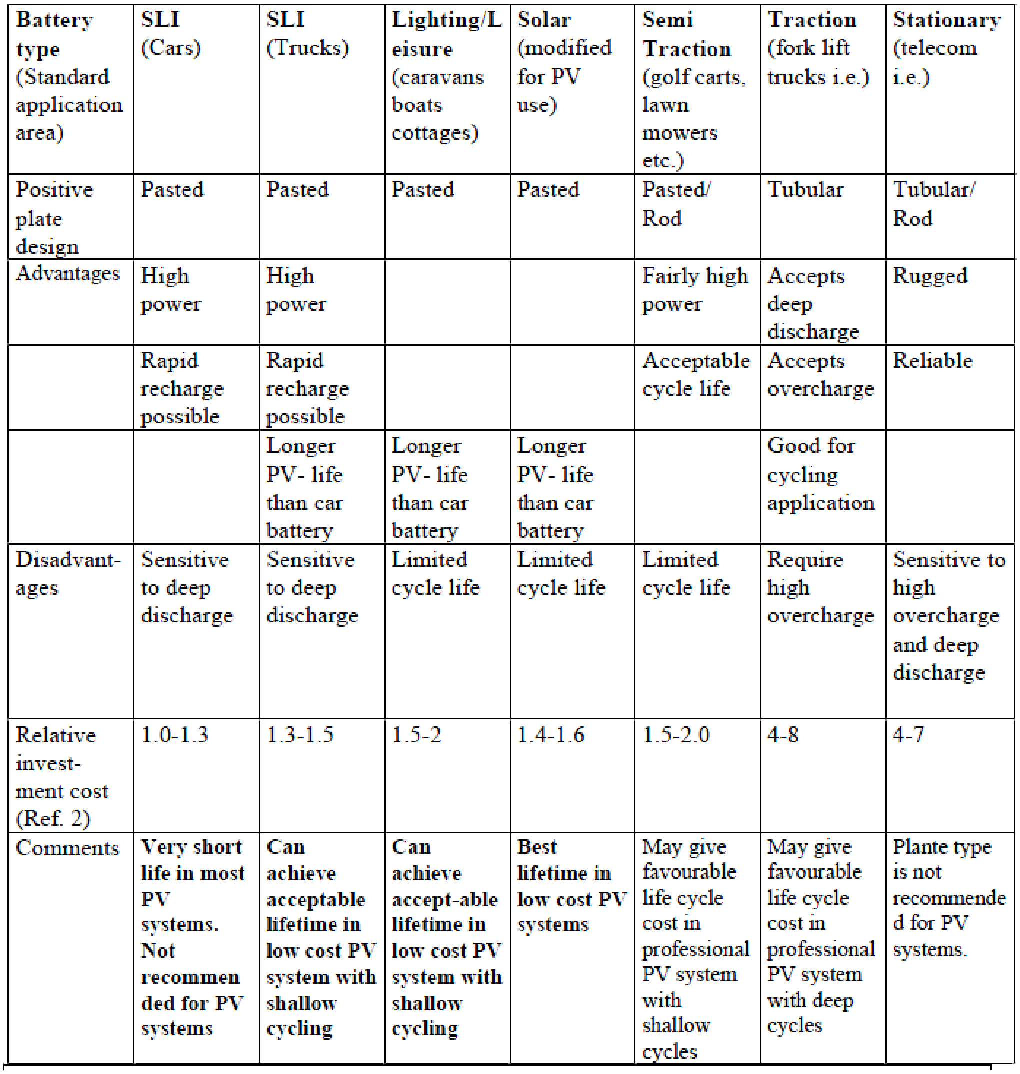
FIGURE 2: AMP HOURS FOR DIFFERENT DISCHARGE PERIODS (PETERSON)

From Figure 2 one can see that the Ah rating has gone down to 70 % of nominal capacity or 140 Ah. It will not be possible to drain 50 amps but only 35 amps. If the battery is given with a 100 hour rate the battery capacity can be 25-40 % larger than the given capacity at 20 hours.

The system amps are important as it's the current needed in the house. Small applications (such as a light) might need less than 1 amp, while a vacuum cleaner might need 12 amps. Estimations of the load of the house for 100 hours are around 12 kWh. With batteries running at 12 V the average electricity would be supplied at 10 Amps. The capacities of the battery needs to be 10 Amps*100 hours= 1000 Ah. Because of the actual possible system draw-off of 40 % of nominal capacity it's going to be 1000 Ah/0.40= 2500 Ah and 25 Amps.

Table 4 gives a good comparison of some lead batteries that are available on the market and could be used in a PV system.

TABLE 4: DIFFERENT BATTERIES - ADVATAGES AND DISADVANTAGES (IEA TASK III, 1999)



Battery type (Standard application area)	**SLI** (Cars)	**SLI** (Trucks)	**Lighting/Leisure** (caravans boats cottages)	**Solar** (modified for PV use)	**Semi Traction** (golf carts, lawn mowers etc.)	**Traction** (fork lift trucks i.e.)	**Stationary** (telecom i.e.)
Positive plate design	Pasted	Pasted	Pasted	Pasted	Pasted/ Rod	Tubular	Tubular/ Rod
Advantages	High power	High power			Fairly high power	Accepts deep discharge	Rugged
	Rapid recharge possible	Rapid recharge possible			Acceptable cycle life	Accepts overcharge	Reliable
		Longer PV- life than car battery	Longer PV- life than car battery	Longer PV- life than car battery		Good for cycling application	
Disadvant-ages	Sensitive to deep discharge	Sensitive to deep discharge	Limited cycle life	Limited cycle life	Limited cycle life	Require high overcharge	Sensitive to high overcharge and deep discharge
Relative invest-ment cost (Ref. 2)	1.0-1.3	1.3-1.5	1.5-2	1.4-1.6	1.5-2.0	4-8	4-7
Comments	**Very short life in most PV systems. Not recommended for PV systems**	**Can achieve acceptable lifetime in low cost PV system with shallow cycling**	**Can achieve accept-able lifetime in low cost PV system with shallow cycling**	**Best lifetime in low cost PV systems**	May give favourable life cycle cost in professional PV system with shallow cycles	May give favourable life cycle cost in professional PV system with deep cycles	Plante type is not recommended for PV systems.

As the system will not be a professional PV system and the system will be designed for deep cycle draw-off, a solar battery seems the most sensible course for investment.

Battery sizing is estimated for 12 kWh, approximately 4 days for our system. The voltage needs to be 12 V. Four different batteries with different sizes and voltages have been considered for simulation and all the batteries are able to run in deep cycle.

TABLE 5: BATTERY OPTIONS (DMSOLAR) (SHENZHEN CENTER POWER TECH. CO) (HOPPECKE BATTERIEN GMBH AND CO) (PMA SOLAR)

Batteries:	**Trojan T-105**	**Trojan L16P**	**Vision 6FM200D**	**Hoppecke 24OpzS**
Price [DKK]:	901	1599	4100	5870
Voltage [V]:	6	6	12	2
Nominal hour rate and nominal operating temperature [h and ^oC]:	20 hr	20 hr	10 hr and 25^{o}C	10 hr
Nominal capacity [Ah]:	225	325	200	3219
Nominal energy content [Wh]:	1350	1950	2400	6438
Actual energy content [Wh]:	540	780	960	2575
Efficiency [%]:	85	85	80	86
Nominal lifetime [years]:	8	8	10	20

The nominal hour rate is given for either 10 or 20 hours so for comparison purposes they are more or less equal in rated capacity. With voltages there is only one that runs in 12 V so the others need to be connected in parallel. For the most expensive battery with the lowest voltage, 6 batteries are required to be connected together. From a first glance it's hard to see what the best choice is. When looking at the table providing an actual energy content of approximately 12 kWh it's clearer.

TABLE 6: BATTERY OPTIONS PROVIDING 12 KWH

Batteries:	**Trojan T-105**	**Trojan L16P**	**Vision 6FM200D**	**Hoppecke 24OpzS**
Number of batteries needed to reach 12 kWh:	24	16	13	6
Price [DKK]:	21 636	25 585	53 295	35 222
Voltage [V]:	6	6	12	2
Nominal hour rate and nominal operating temperature [h and ^oC]:	20 hr	20 hr	10 hr and 25^{o}C	10 hr
Nominal capacity [Ah]:	2700	2600	2600	3219
Nominal energy content [Wh]:	32 400	31 200	31 200	38 628
Actual energy content [Wh]:	12 960	12 480	12 480	15 451
Nominal lifetime [years]:	8	8	10	20

The Hoppecke stands out as the best choice in this case. Not only is it the cheapest option when looking at the lifetime, it also has the highest actual energy content of 15 451 Wh. It's also easier to handle and clean 6 batteries compared to Trojan's 24.

In the end though, this is the best choice based on theoretical calculations for the off-grid solar powered system. Simulations will probably show that less battery power is needed when wind is introduced and the Hoppecke cannot be dimensioned smaller as this is the minimum voltage.

3.3 Wind turbine

A small wind turbine can be a cheap and efficient way to provide more power to the system as an alternative of installing another solar panel. In Danish conditions it could even turn into the main source of power during the winter months. It's also able to provide power during night time. The power output of a wind turbine is exponential; meaning that from just one extra m/s in wind speed the power output is that much higher. As a separate renewable back-up system to the PV, it is meant supplement the battery in combination and will therefore be designed small. There are many different sizes and shapes with different power outputs. Two wind turbines are compared in this section.

TABLE 7: COMPARISON OF "AIR" WIND TURBINES (SOUTHWEST WINDPOWER, 2010)

Wind Turbines:	**Air Breeze**	**Air X whisper 100**
Rated power (at 12.5 m/s) [W]:	200	400
Price [DKK]:	5017	3488
Cut in speed [m/s]:	2.68	3.58
Diameter [m]:	1.17	1.15
KWh/month (at 5.4 m/s):	38	38

The two wind turbines give a little curious case when looking at the monthly produced energy. They give the same average output of 38 kWh per month (at 5.4 m/s) even though one turbine has twice the amount of capacity installed. The reason this is true is because the Air Breeze is able to work at lower cut in speed and because the energy output for wind speeds around 6-8 m/s is more or less the same, regardless if it's 200 or 400 W installed.

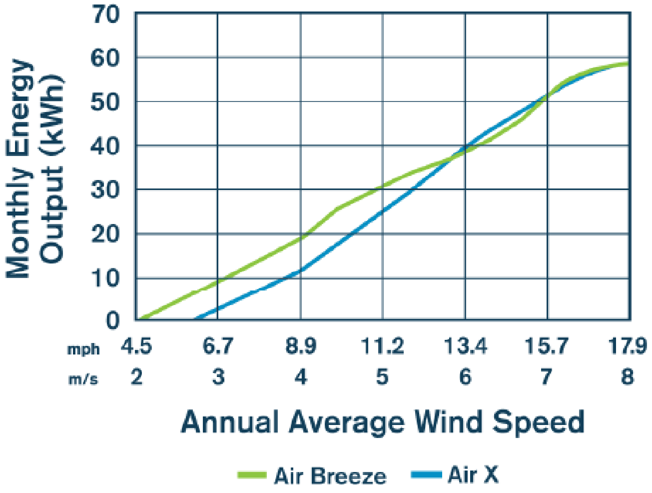


FIGURE 3: ENERGY OUTPUT OF WIND TURBINES (SOUTHWEST WINDPOWER, 2010)

The Air X is chosen as it's the cheapest wind turbine and has the largest capacity. When choosing the wind turbine for simulations it's necessary to provide the wind production per m/s of wind speed curve to the computer program. This ensures the program can simulate out of production capacity and not the rated capacity. Lifetime is not mentioned in any of the technical sheets from Southwest, but with care they should be able to operate for at least 20 years.

3.4 Generators

If all renewable energy sources fail, the system must have a backup energy source to take over. In a grid connected household this would be the backup, but in a stand-alone system a generator needs to be installed. These generators are run by traditional fuels such as gasoline, diesel and gas. Gasoline generators have a high cost of fuel and the lifetime of the generator is short, around 10 000 hours (Stafford, 2010). There is also a higher risk in storing gasoline because it's more volatile than e.g. diesel. The reason a gasoline generator is considered at all is because of the reduced noise compared to a diesel generator. If the generator was to be placed inside a house this factor could well outweigh the negatives. Propane and natural gas have good performance, low emissions and the fuel costs are low. It does however require a grid connection as it's hard to store large enough amounts of natural gas for longer operation periods.

A diesel generator is the most appropriate generator in a stand-alone system. Fuel and maintenance costs are low and the lifetime of a diesel generator is three times longer than that of a gasoline generator (around 30 000 hours) (Stafford, 2010). Since the location for the project has a large outside area where there is more than enough room to place the generator, noise pollution is not a large problem.

The question then comes to the size of the generator and type. A normal back-up generator designed to provide energy for full load would be installed with maximum capacity, 8-10 kW in our case, and in AC current to deliver electricity directly. Full load hours are rarely if ever realized and fuel consumption of a large generator is high at 3-4 l/h. It's also more expensive and it's bigger. For this case a small DC current diesel generator is used. It will provide energy to the solar batteries in DC current and the Inverter will draw power from the batteries to the house in AC current. The advantage of such a generator is the low fuel consumption and the possibility of running the generator in combination with wind and solar to fill the batteries.

TABLE 8: DIESEL GENERATOR FACTS (ALTEN| BATTERY CHARGERS, 2009)

Generator:	**Duke 120**
Maximum Power output [kW]:	3.4
Price [DKK]:	17375
Fuel Consumption at full load [L/h]:	0.95
Sound level, full load at 7 meters [dB]:	78

Table 8 shows some specific information about the chosen generator for this project. The rated maximum power is 3.4 kW and down which should be enough by itself for covering basic load on the system. It is also in the right range for providing extra power to the batteries when needed and the fuel consumption is less than 1 l/h. Sound level is 74 dB at 7 meters in open air, which can be compared to a loud conversation. Sound is going to be significantly reduced when generator is placed in a shed or something equivalent so it is not considered a problem. The integrated fuel tank is 17 l though, which is around 17 hours of operation or 57.8 kWh.

3.5 Inverter/Charger

Normal electrical appliances require power to come in AC, or alternating current, at 230 V while the energy sources create power in DC, direct current, at 12 V. To get the voltage right between the battery side and the household an inverter is needed. Sizing the inverter is however a challenge as it’s difficult to know how much energy is need in a maximum hour. If everything in the system was turned on at the same time the power consumption would be 7692 W.

Almost all the load comes from five devices: electric kettle, oven, microwave, toaster and vacuum cleaner. While these are all loads that are run over a short period and are therefore not that influential on a total consumption they do require a lot of power at one specific moment. It is not impossible that several of these appliances are turned on at the same time so as not to crash the system an inverter close to the maximum load should be chosen. Inverts are however able to supply loads above their rated capacity for a short period of time, perfect for short operating appliances with high power consumption.

An invert, like the battery and solar collector, is limited by how much energy can be sent at 12 volts. The limit seems to be around 4000 W, not quite enough to meet the maximum load. Peak power can reach up to 8000 W in short periods though and 4000 is more than enough for an average load. The amperage output is also limited. Two possible inverters from Victron energy is compared in Table 9.

TABLE 9: INVERTERS (VICTRON ENERGY) (PETER KENNEDY YACHT SERVICES)

Inverters:	**Quattro 5kVA**	**Quattro 3kVA**
Price [DKK]:	19522	12315
Voltage [V]:	12	12
Maximum Amperage [A]:	30	30
Continuous power output [W]:	4000	2500
Peak power [W]:	8000	6000
peak power operation time [min]:	-	-
Efficiency [%]:	92	93
Nominal lifetime [years]:	-	-

In most cases the Quattro 3kVa will be able to supply the load, but to be on the safe side the Quattro 5kVa is chosen. Even with this there might be incidences where the load will be higher than is possible, so operation of the five mentioned appliances at the same time should be considered before use.

3.6 Controller/Charger

The controller is a voltage regulator for the different power inputs going to the battery. Even though the solar panel has a rated voltage of 12 V the actual voltage is around 17 V. If there is no controller in place to make sure that the voltage is around 14.4 V the battery could get damaged from overcharging. Two types of controllers dominate the market today, 3 stage charge cycle and MPPT.

The 3 stage charger works in Bulk, Absorption and Float.

- Bulk: When a PV panel starts up it starts in a phase called Bulk. Here the voltage is gradually increasing to 14.4-14.6 Volts while the batteries draw maximum current.
- Absorption: Once the wanted voltage is achieved the controller stabilizes the voltage for a specific time while the current gradually decreases as the batteries charge up.
- Float: When the batteries have absorbed wanted current the voltage is lowered to what is called the float level (13.4 to 13.7 V). Here the batteries draw-off a small maintenance current until the next cycle is initiated. (Free sun power)

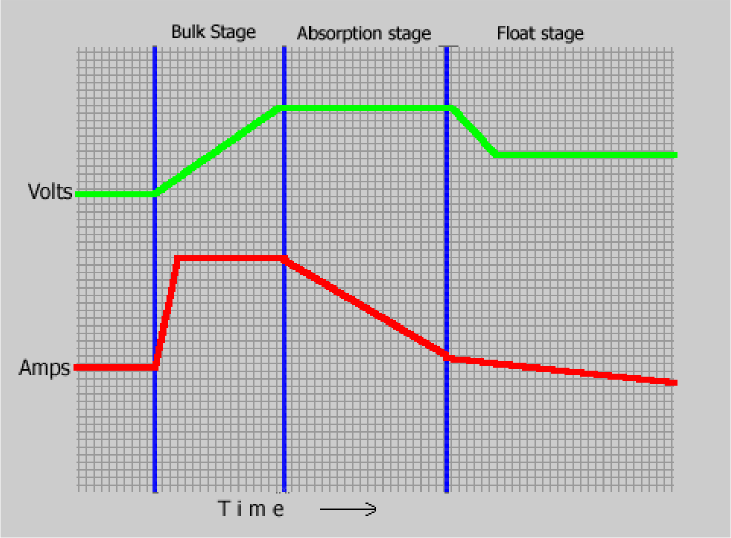


FIGURE 4: RELATIONS OF THE THREE PHASES (FREE SUN POWER)

MPPT or Maximum Power Point Tracking is the more advanced, but more expensive type of controller. A MPPT controller works with matching the output of the solar collector to the output of the batteries. The power output of a solar collector can be given as Power= Voltage*Ampere. Taking the Suntech polycrystalline discussed earlier which had a rated power of 140 W as an example. The optimum voltage and ampere for that collector was 17.6 V and 7.95 A = 140 W. If the battery is running at low voltage one day, 12.4 V, the collector could only supply 12.4 V*7.95 A = 98.58 W. The system would produce 30 % less power than what it’s supposed to. The MPPT corrects this by increasing the ampere to still reach the power output, from 7.95 to 11.3 A.

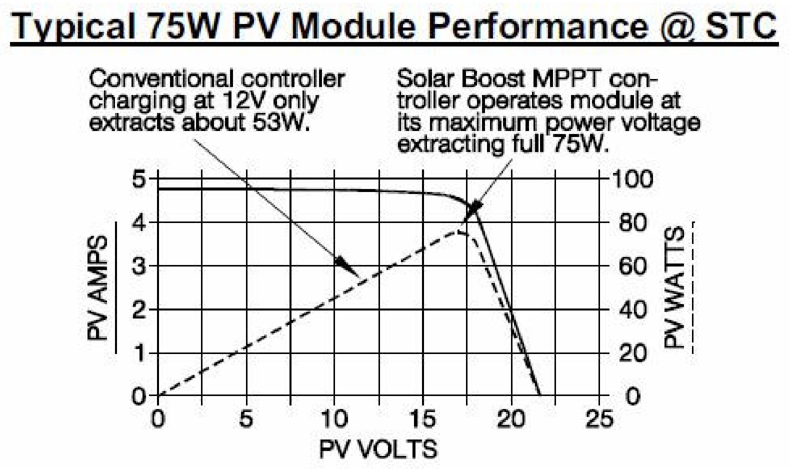


FIGURE 5: EXAMPLE OF TYPICAL MODULE PERFORMANCE

Apart from this correction in ampere it works in the same ways as the 3 stage charger. The system has two power producing units that needs controllers, wind and solar. Both would benefit highly from using a MPPT to maximize the energy output. Both systems can use the same controller.

TABLE 10: CONTROLLER/CHARGER (BLUE SKY ENERGY, 2010) (ALTE STORE)

Controller/Charger:	**1524iX**	**Flexmax 60**	**Tristar**
Type:	MPPT	MPPT	MPPT
Price [DKK]:	1336	3204	2388
Maximum output [A]:	20	60	45
Maximum power [W]:	900	900	600
Temperature compensation:	Yes	Yes	Unknown
Efficiency [%]:	97	98.1	99

The best controller in terms of highest efficiency is the Tristar. It also has a high maximum power output with possibilities of expansion and the cost is fairly cheap. Two of these controllers need to be bought.

4. Simulations

It can be very expensive to buy all the components for a solar PV system. It is therefore important to know that the configuration of the different components is optimal and that it will supply the required amount of electricity to meet the demand. This can be difficult to do because it is not possible to predict when the sun will shine.

Simulation software's such as PVSUN3 or HOMER can use an average of previous weather data to estimate the yearly solar radiation in a location. These programs can save a lot of time and money when designing a solar PV system. Using programs it's easy to see what the effect is of changes in system components to the total system performance. This way the most optimal and cost effective configuration can be designed and tested before spending any money on the actual components.

As a starting point a system was designed with supply from PV panels only. These simulations were carried out in PVSUN3, a program based on solar energy only. This way it's possible to run tests of the PV panels and battery bank configuration of the off-grid system.

Then the system was simulated again in HOMER, but this time in integration with wind turbine and diesel generator. HOMER is a more advanced and complicated program, but allows a wider range of inputs and will therefore give more accurate results to the project case. Explanation of how to simulate and what inputs have been used for the two programs can be found in the Appendix B and C.

4.1 PVSUN3

Simulating for all the different configurations with a period of two years is advised. When simulations start the batteries have full energy content, loading and unloading as they are used. When second year is started the energy content of the battery will be lower than it was in the beginning, since it's only been powered by the sun. Simulating over a two year period will therefore give a more accurate view of how the system is going to operate over its lifetime.

In the figures showing the results:

- The blue line, Pout_DC, is the electricity being generated by the solar panels
- The pink line, Pload, is the energy consumption of the house.
- The orange line, Pbat/gri, gives an indication of when the battery is charging.
- The red line, SOCbatt, is the State Of Charge in the battery, showing what the energy content is at all times during the year.

4.1.1 Results

The first simulation was carried out with 24 Trojan batteries as they were sized in the battery section and two sungrid monocrystalline solar panels. The Hoppecke batteries are not practical for simulations since further increases in the size of the battery have to be doubled every time (securing the voltage). Figure 6 gives a detailed analysis of the system operation over the two years.

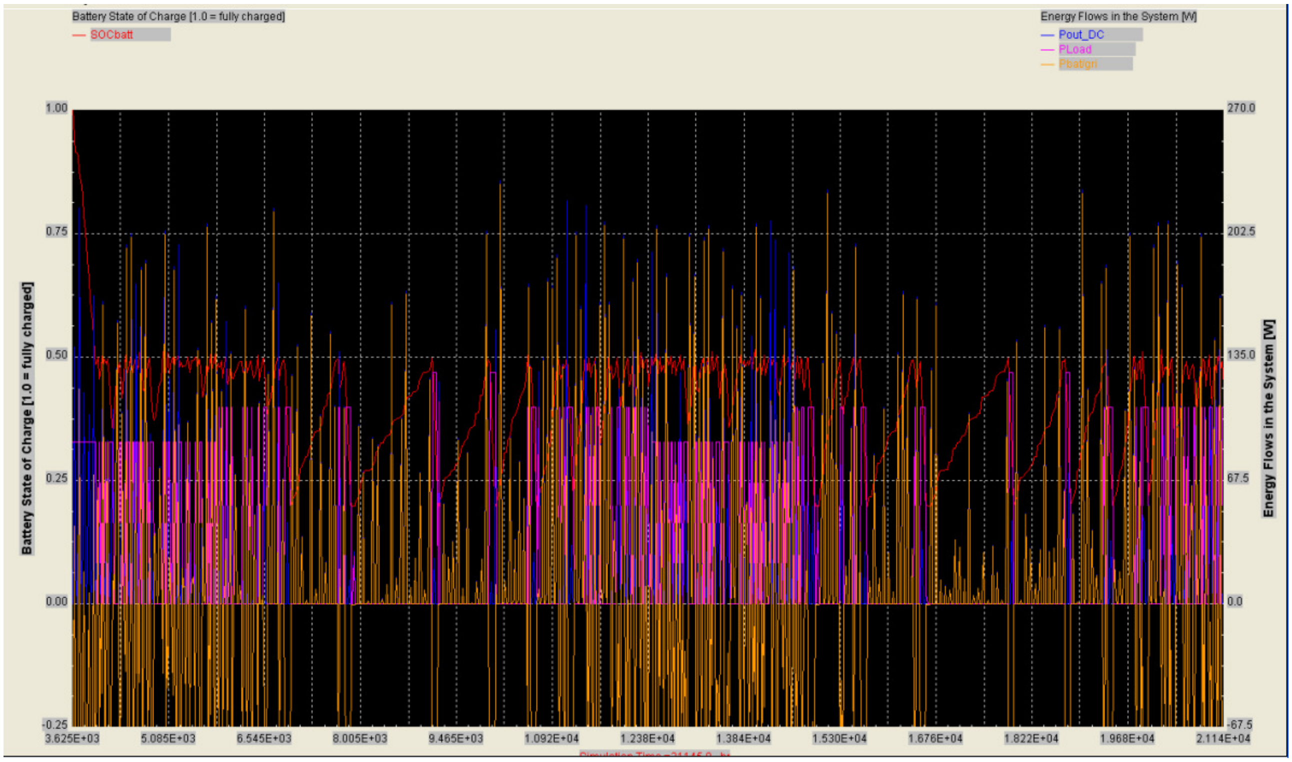


FIGURE 6: FIRST PVSUN3 SIMULATION, 2 COLLECTOR 24 BATTERIES

The x-axis is the period of time with the dotted vertical lines marking months. The left y-axis gives an indication of the battery state of charge, from 0 to 1. The right y-axis gives an indication of the energy flows in the system, from energy consumption to the produced solar energy.

The first thing that needs to be remembered is that the consumption, the pink line, is given as an average load of 123 Wh every hour for every day for every year. This means that for the system to be able to supply energy at all times the pink line has to be continuous over the two years. There are 3 different phases with different loads for summer, fall and winter each using 75, 85 and 100 % of the average load. For summer operation the load is supplied most of the time while in the two winters from December to March it's only met three times.

It's easy to see that the system dimensions are two small, too few batteries and too few solar panels. Second it's possible to see from the winter operation when the load is only met three times that the batteries will only supply energy once it's above 45-50 %, as it's specified in battery operation. What is not clear though is how long the batteries are discharged to. Even in the summer periods there is discharge below 50 % but due to solar availability the discharge is not that large, around 5-10 %. So when the SOC reaches 50 % winter time the program has a built in function telling that it's now possible to discharge for a certain amount of time. In the winter times this discharge continues until it reaches the bottom limit of 20 %. From 50 % capacity to 20 % there is 9720 W. With the average load of 123 W for winter this would amount to 80 hours. When the bottom capacity is reached the system is not operating again before it comes close to 50 %.

The blue line, the electricity production from the solar panels, can only be seen if there is production and draw-off at the same time. Either the solar production is higher than the consumption or it's possible to see the production between the consumption lines. Otherwise the production is covered up by the orange line as this indicates the battery bank charging and will be equal. So the battery is almost always providing power, but usually less than 50 W.

Summer operation is usually designed to provide a 100 hour load from the battery bank, meaning 12 kWh for our system. For all year operation the PVSUN3 manual suggest to install a battery bank which can provide average load for a full 1000 hours, slightly over 40 days. This equals a capacity of 120 kWh or 90 Trojan batteries in a battery bank.

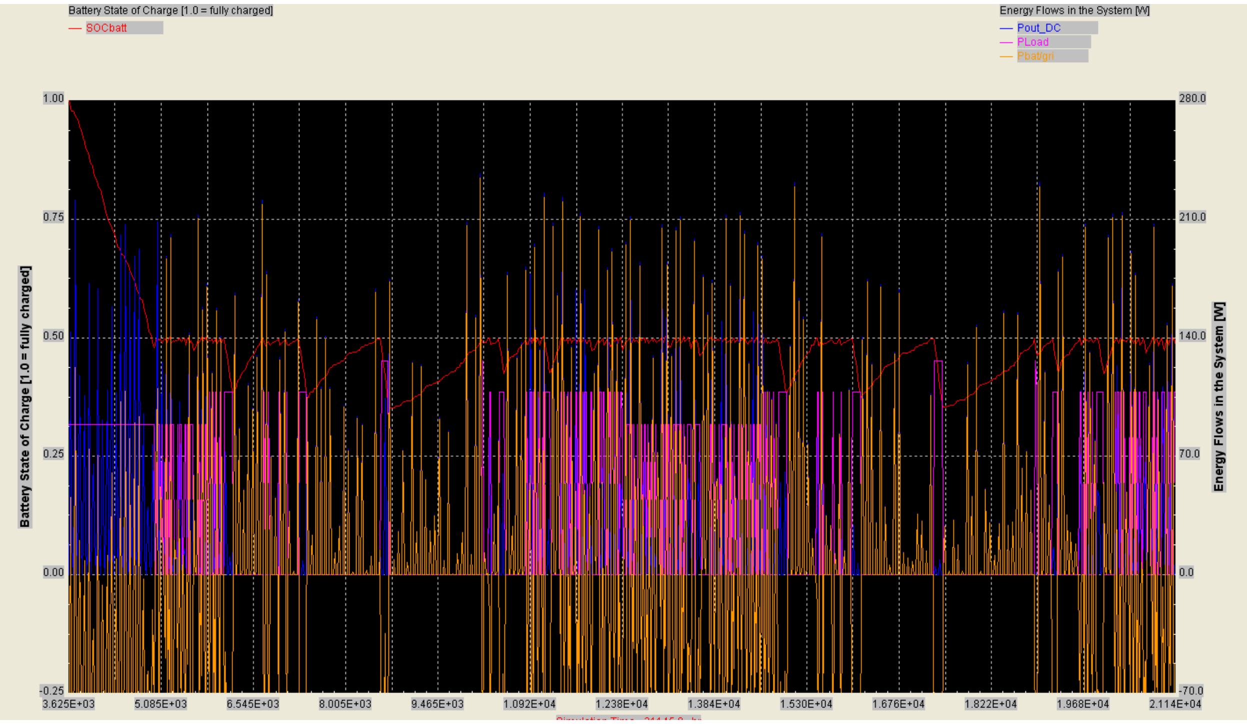


FIGURE 7: SECOND PVSUN3 SIMULATION, 2 COLLECTORS 90 BATTERIES

Even when the capacity is increased by a tenfold the production is still not able to keep up with consumption. The batteries help to smooth out the state of charge simply by being larger and making it impossible for the system to be drained in one cycle. Recharging the battery to 50 % takes a long time so in the end it's hard to see if the system has benefited at all except the initial supply from the charged batteries.

Simulating the system with the recommended battery bank at 1000 hours and increasing the number of solar collectors a sensitivity analysis was carried out. To be able to maintain power at all times throughout the whole year from batteries and sun 23 PV panels, close to 23 m^2, have to be installed, see Figure 8.

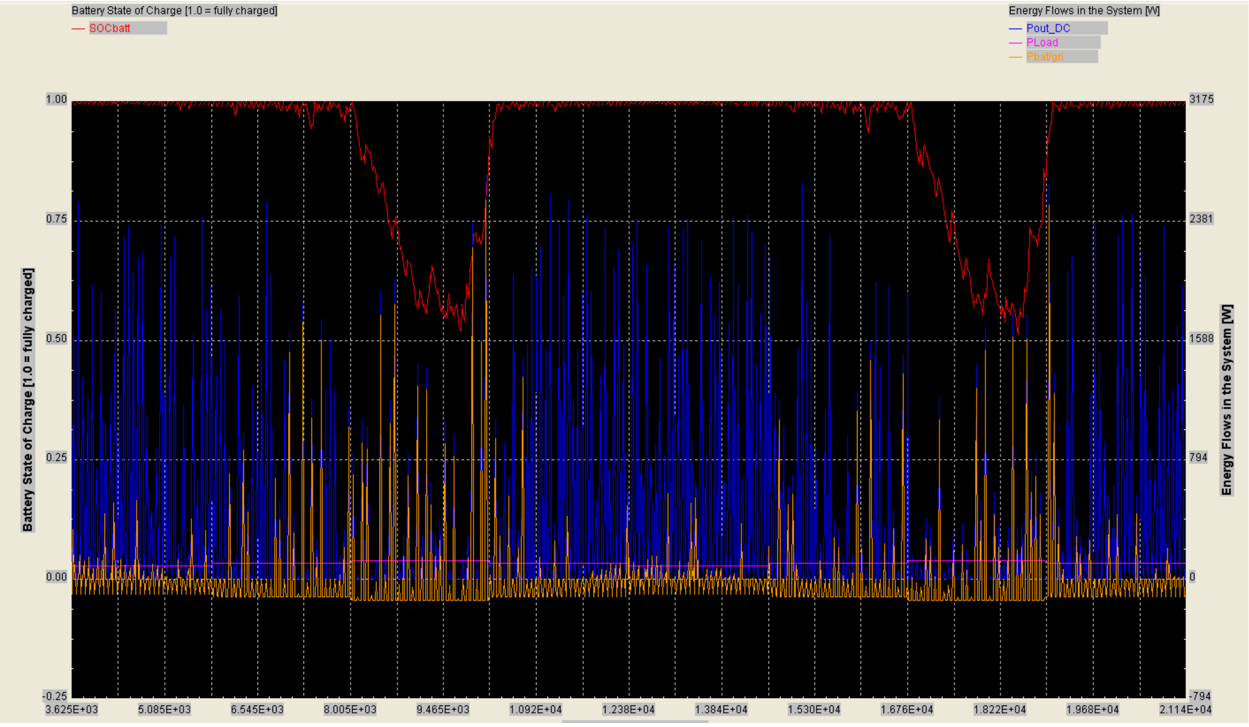


FIGURE 8: FINAL PVSUN3 SIMULATION, 23 COLLECTORS 90 BATTERIES

The system is now vastly over dimensioned for summer operation while in winter it's able to stay above 50 % discharge. The final cost just in batteries and solar panels surmount to 241 836 DKK, totally unrealistic and infeasible.

4.1.2 PVSUN3 conclusion

PVSUN3 is a simple solar calculating simulation tool that finds its uses, but is unpractical for all year systems. For simulating a summer-operation-only scenario it can give reasonable values and will be able to design a system. If users of the off-grid system are willing to reduce some loads in operation periods with less sun, e.g. not use the microwave or vacuum cleaner, and accept short periods without electricity, pure solar systems can be designed cheap and efficient. This system would also benefit from increasing operating voltage of batteries and panels. Physical size of system components would be massively decreased while power size would increase. Costs would not necessarily be lowered but the need for space and wires etc. would be a lot less.

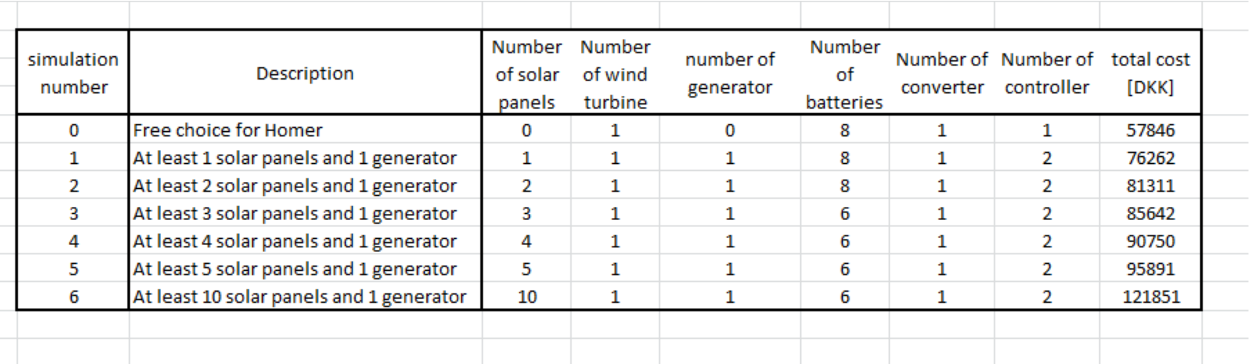
Back-up power or grid connection is still strongly advised if the possibility exists.

4.2 HOMER simulations

When simulating in HOMER more energy inputs can be chosen and designed. Components were selected and chosen in chapter 3. Solar panels, batteries, wind turbines, generators, inverters and controllers are all important figures for the HOMER simulation and they all require inputs which are detailed in Appendix C.

The first simulation in HOMER is to implement resources and costs, but not forcing the program to include anything. This means that the program is given free range of choice in panels, turbines, batteries and generator and it can choose any size of the system component. The only criteria are that the load is met. See Table 11 for simulation results.

TABLE 11: DIFFERENT SIMULATIONS WITH HOMER



simulation number	Description	Number of solar panels	Number of wind turbine	number of generator	Number of batteries	Number of converter	Number of controller	total cost [DKK]
0	Free choice for Homer	0	1	0	8	1	1	57846
1	At least 1 solar panels and 1 generator	1	1	1	8	1	2	76262
2	At least 2 solar panels and 1 generator	2	1	1	8	1	2	81311
3	At least 3 solar panels and 1 generator	3	1	1	6	1	2	85642
4	At least 4 solar panels and 1 generator	4	1	1	6	1	2	90750
5	At least 5 solar panels and 1 generator	5	1	1	6	1	2	95891
6	At least 10 solar panels and 1 generator	10	1	1	6	1	2	121851

With free choice HOMER creates a system with one wind turbine, one converter, one controller and eight batteries. Total system cost is 58 000 DKK. It’s apparent that choosing a solar is less cost effective than adding more batteries and supplying needed power with wind only. This is probably due to good wind speeds for the Copenhagen area while a solar PV panel is not able to help out much during most of the yearly operation. The generator is not chosen either since the costs are high the efficiency is poor and the fuel is expensive.

An off-grid system does however need a back-up generator for emergency uses so for simulation one the system is forced to have one. The possible number of wind turbines that can fit in the area is also restricted to one. This is done because the area is not that large and to keep a good non-turbulent wind profile at six meters for the first turbine. It’s also for esthetical reasons. Lastly one solar panel is chosen to secure energy supply and to see the influence on the system. As seen in Table 11 the total system cost increases by 20 000 DKK.

To further see the actual influence of solar panels on the system simulations are done with two, three, four, five and ten PV panels. The number of batteries are changed only once from eight to six when three solar panels are installed. Cost wise though it seems to have very little effect in reduction when the number of panels are increased. For every new solar panel increased the total system cost rises with 5000 DKK, looking at Figure 9 the cost is a linear function.

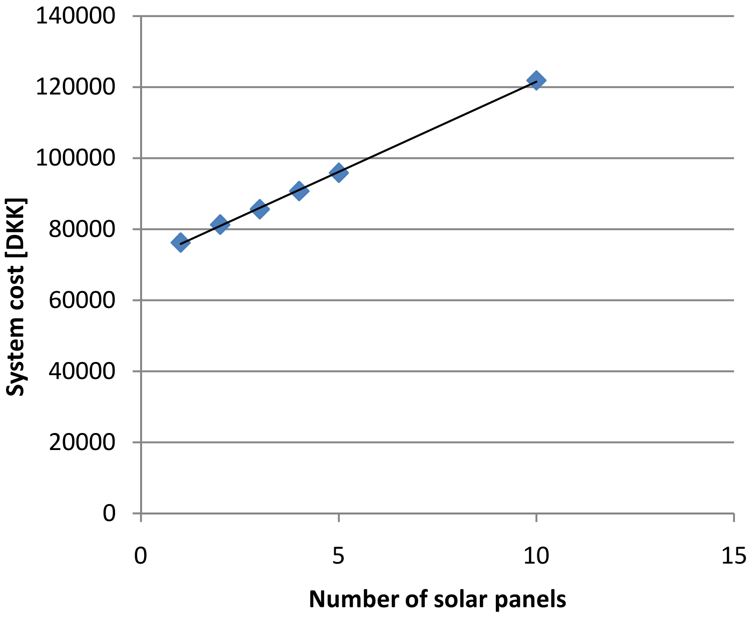
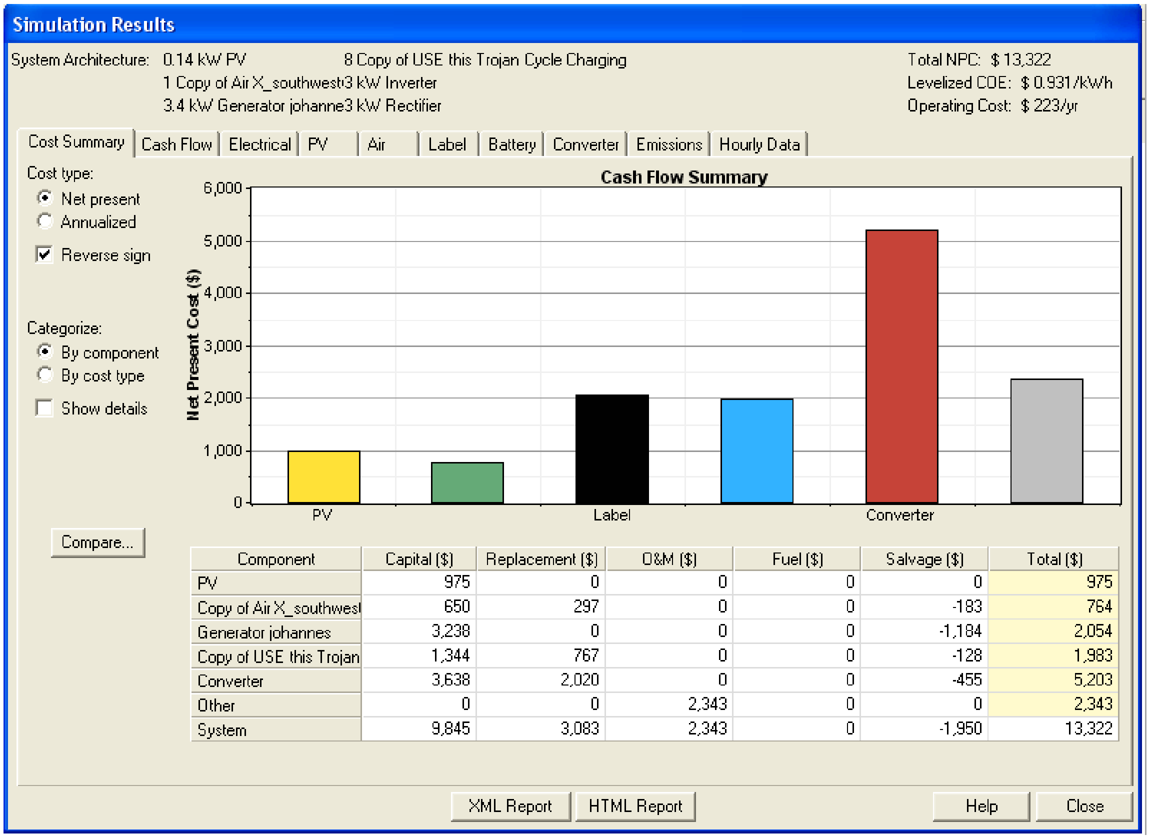


FIGURE 9: SYSTEM COST CURVE

The cheapest feasible hybrid layout is represented in simulation one.

If simulation one is analysed the answer to why it doesn't pay off should be clearer. Looking at investment costs the inverter is the most expensive part of the system. This is especially true considering the short lifetime (15 years) and the fact that two have to be installed over the 25 year lifetime of the system. O&M costs are fixed to be 840 DKK/year (about 1.2 % of the total investment) (Naji, 2009).



System Architecture: 0.14 kW PV
1 Copy of Air X_southwest
3.4 kW Generator johanne
8 Copy of USE this Trojan Cycle Charging
3 kW Inverter
3 kW Rectifier

Total NPC: $ 13,322
Levelized COE: $ 0.931/kWh
Operating Cost: $ 223/yr

Cost type:
● Net present
○ Annualized
☑ Reverse sign

Categorize:
● By component
○ By cost type
☐ Show details

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	975	0	0	0	0	975
Copy of Air X_southwest	650	297	0	0	-183	764
Generator johannes	3,238	0	0	0	-1,184	2,054
Copy of USE this Trojan	1,344	767	0	0	-128	1,983
Converter	3,638	2,020	0	0	-455	5,203
Other	0	0	2,343	0	0	2,343
System	9,845	3,083	2,343	0	-1,950	13,322

FIGURE 10: SIMULATION RESULTS

Wind energy, shown in green in Figure 10, is the cheapest component available, even cheaper than the PV given in yellow. This especially true considering the fact that one wind turbine has a rated power of 400 W while the slightly more expensive PV has a rated power of 140 W. The yearly output of the two resources is shown in Figure 11.

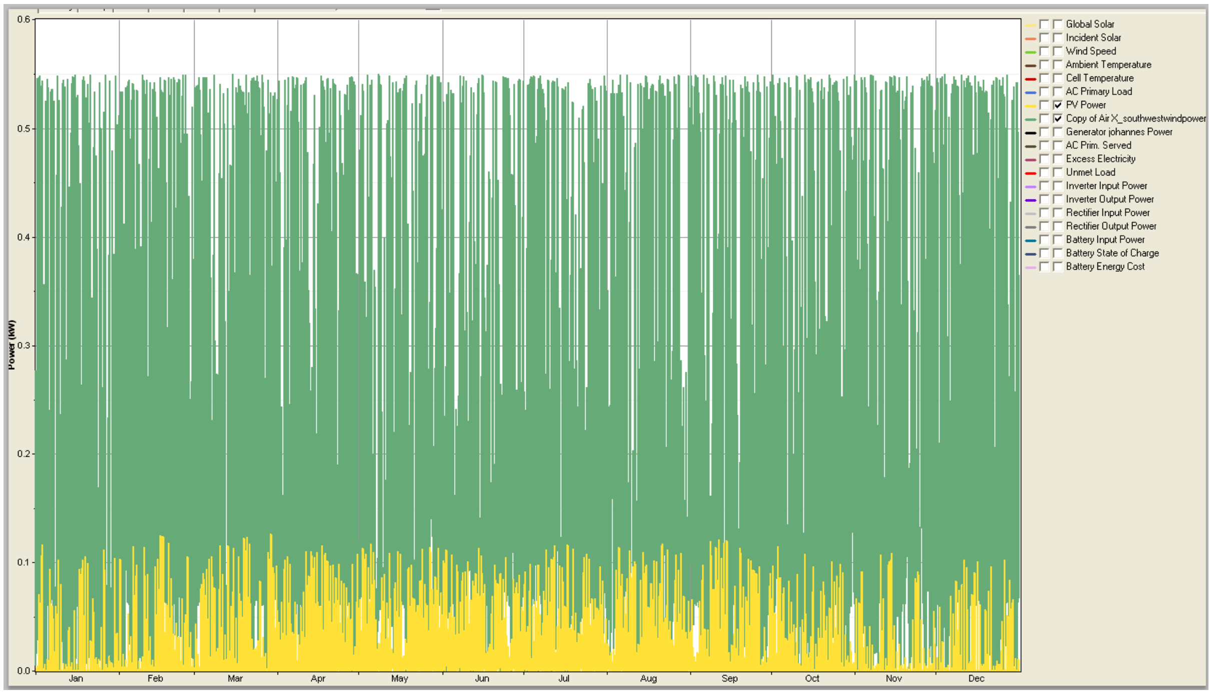


FIGURE 11: WIND AND SOLAR ENERGY OUTPUT

The battery bank of 8 batteries is also able to maintain a discharge level of over 50 % almost the whole year, meaning that lifespan of the batteries can be significantly improved.

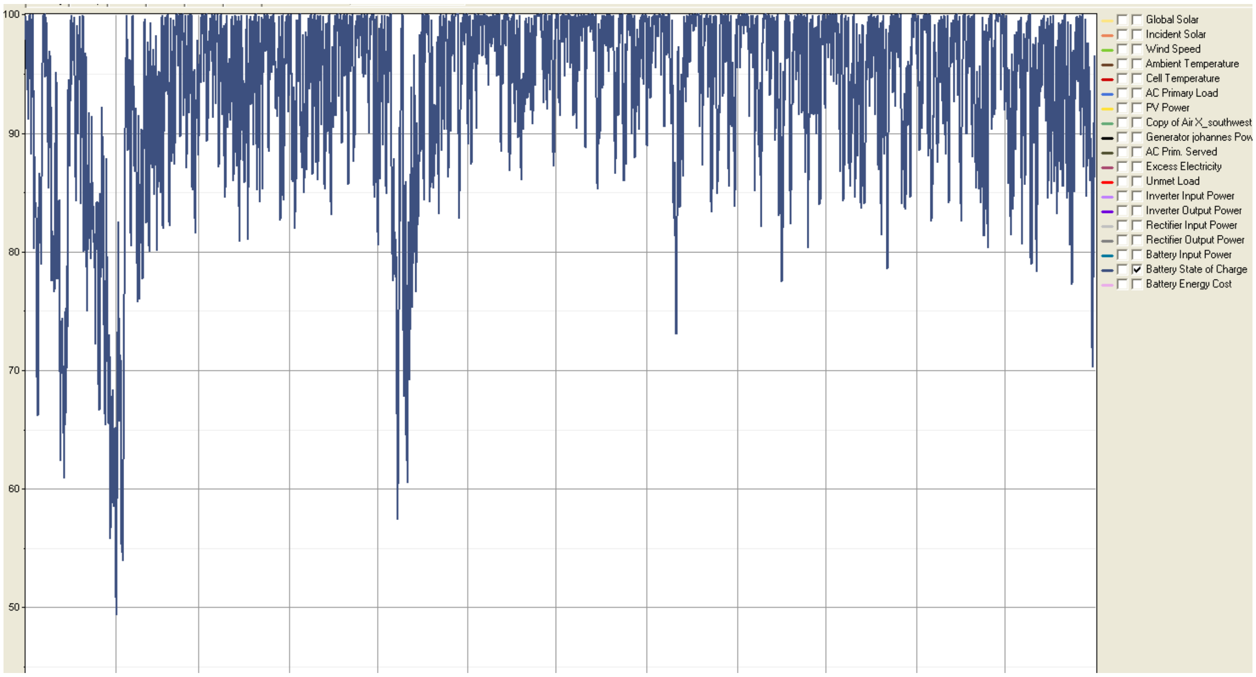


FIGURE 12: STATE OF CHARGE IN BATTERIES

If the system is designed for solar power only, how many panels and batteries are then needed to supply the full load. Simulating different inputs the system says that it’s able to supply enough electricity with

44 batteries and 15 PV panels, a lot less than 23 collectors and 90 batteries in PVSUN3. Looking at the state of charge in the battery bank however shows that the system is only modeling for one year operation, ending the SOC at 30 %. Even if the batteries are increased to the 90 used in PVSUN3 the effect is small, still ending operation with a low state of charge.

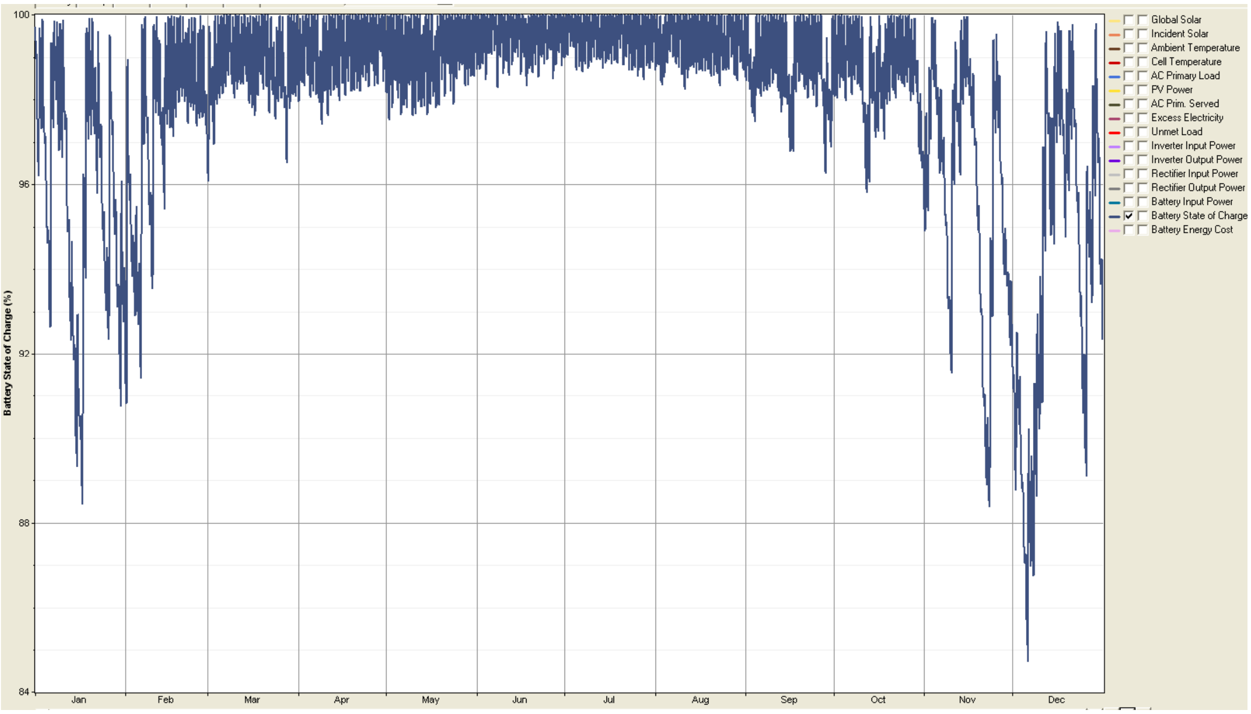


FIGURE 13: STATE OF CHARGE, 23 PANELS 90 BATTERIES

There are large differences between the two simulation programs though. If HOMER is configured with 90 batteries and 23 panels, as was the limit in PVSUN3, the state of charge never goes below 86 %, this can be seen in Figure 13. This is a lot higher than in PVSUN3 where the SOC reached down to 50 %. This is again influenced by the fact that HOMER cannot simulate for more than one year at a time, but SOC ends quite high in the simulation so there's no problem. There's also the fact that there are just more possible variables in HOMER. An example is the weather data which in HOMER has been picked for Copenhagen while in PVSUN3 it had to be taken for Lund. PVSUN3 seems to be the more conservative program, which is okay if it's known.

The final calculation done in HOMER is a sensitivity analysis. All the values calculated so far are done through average values. Average consumption, average wind speeds and average radiations. With HOMER sensitivity analysis the chosen system is subjected to e.g. different wind speeds to see if it can still handle the systems load. By specifying a range of values it is possible to determine how the variable is important and how the output changes depending on its value.

After the first simulation with one solar panel, as was found to be the cheapest option, is run through a sensitivity analysis it's clear that the system does not cope well with changes. The system was not able to function at all, meaning that more solar panels and batteries had to be installed. Sensitivity analysis also saw the first usage of the generator, as conditions were simulated where no power was available and batteries had been drained below 50 % (system condition for generator operation). The generator quickly recharges the batteries up to a nearly full SOC again.

The cheapest system, with one generator and one wind turbine, was found through sensitivity analysis to consist of 12 batteries and two solar panels. Total system cost for every component and supply of diesel for one year is 92 860 DKK. The batteries are still chosen over implementing more solar power as the solar power can contribute very little in the winter where the power is needed. Looking at Figure 14 one can see that the system has enough power from March to the beginning of November. Rather than sizing the system much larger the program recommends that the diesel generator helps to supply needed power. The generator can supply with as much as 3.4 kWh per liter of diesel, meaning that it can supply the battery with enough power to fully recharge in a few hours. From that stage the battery can again supply enough power with the help of the wind generator for at least a week.

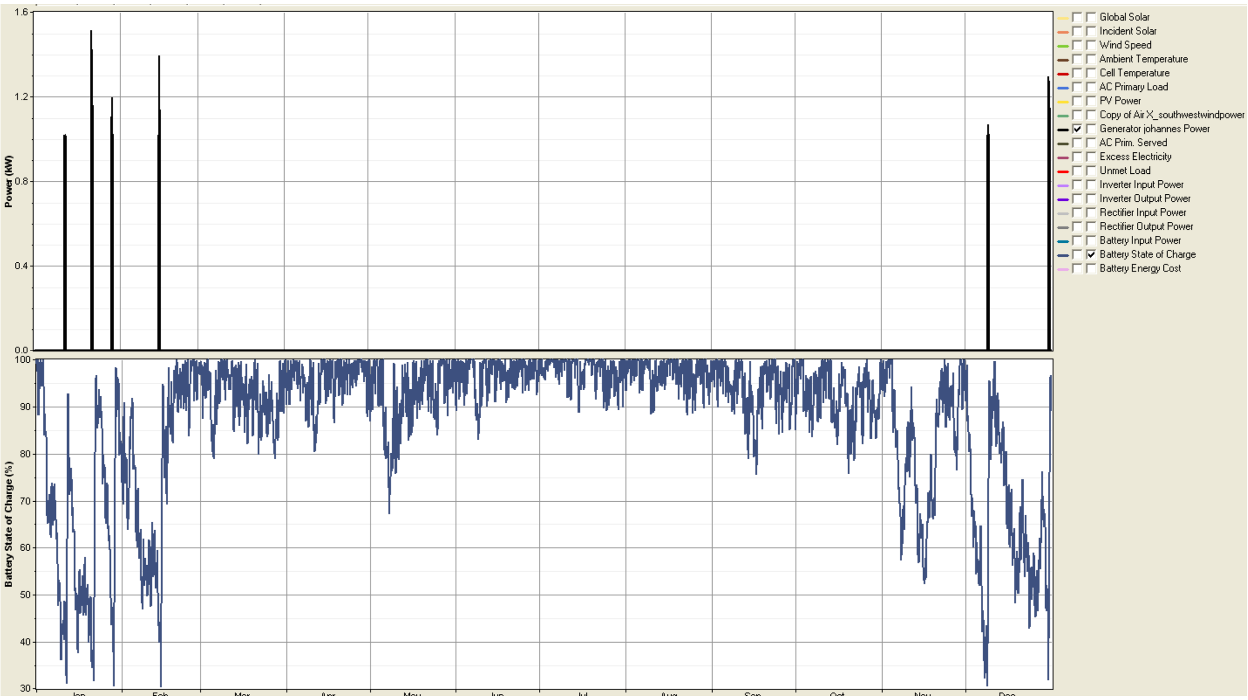


FIGURE 14: STATE OF CHARGE INCLUDING CHARGE FROM DIESEL GENERATOR

5. Conclusion

5.1 Simulations with PVSUN3

The simulations carried out in PVSUN3 show that it's very difficult to completely supply the energy requirement throughout the year when only using solar PV panels. There are several reasons for this. First of all is the fact that Denmark has very few daylight hours during winter and that they provide low radiation levels. The other factor is that during this same period, the solar PV panels are unable to supply the energy requirement of the building as the consumption of the dwelling increases. To add to it the batteries state of charge should not drop below 50 %, meaning that they need to be refilled frequently.

In order to meet the winter energy requirement it was found that 23 PV panels with a battery bank of 90 Trojan batteries equaling 120 kWh are needed. This then has the knock on effect of having an over loading of the batteries during the summer months. The panel area covers a span of approximately 23 m^2 which is too large for a small standalone system. This system is also very expensive on the initial investment, costing 248712 DKK.

Through the simulations from PVSUN3 it can be concluded that it's an unadvisable and non-economically feasible approach to try and completely cover the whole years electrical demand with only using PV panels in the Danish climate.

5.2 Comparison of the two simulation programs

Running the same simulation inputs in both simulation programs provides very different results. PVSUN3 indicated that 90 batteries and 23 PV panels are required while HOMER suggests that only 44 batteries and 15 PV panels are required. This difference is partly because Homer can only simulate for one year as opposed to two years. There are also far more inputs with higher accuracy in Homer then PVSUN3. An example of this is the weather data inputs. In PVSUN3 the selection from the database gives Lund as the best possible simulation location. With HOMER however specific data can be added for the specific GPS coordinates, taken from NASA in the project case.

In order to have more accurate simulations it's advised to use HOMER.

5.3 Simulations with HOMER

Allowing Homer to choose the best layout of the system gives a case of one wind turbine, converter, controller and eight batteries. Giving a total installation cost of 57 846 DKK. Due to the larger power output and lower cost of wind turbines it suggests installing no PV panels at all. Denmark is situated far to the north in Europe, giving low power production for PV's during the winter months where the power is needed. Wind turbine of 400 W is able to supply enough power all year. Even in the summer when the PV should have their greatest use it is not necessarily required and for the winter system benefits much more from installing another battery than installing PV.

If focusing on setting up only a PV system, with the aid of the simulations conducted it became apparent that it is a more feasible idea to construct a solar PV system for summer use only, for example in a summer house.

A sensitivity analysis was carried out with a system including one PV panel, one wind turbine and one generator. The analysis proved that optimizing the system for an average load with average weather data inputs is not enough. This is where the role of back-up power comes into play, to be able to supply enough power when deviations occur. The system is also suddenly more optimized by installing solar panels to secure energy supply, making the system less dependent on wind. The most cost effective choice was determined to consist of one generator, one wind turbine, 12 batteries and two solar panels. Total system costs were increased to 92 860 DKK, reasons being more components, diesel for the generator and increased depreciation of components at the end of the 25 year lifetime of collector.

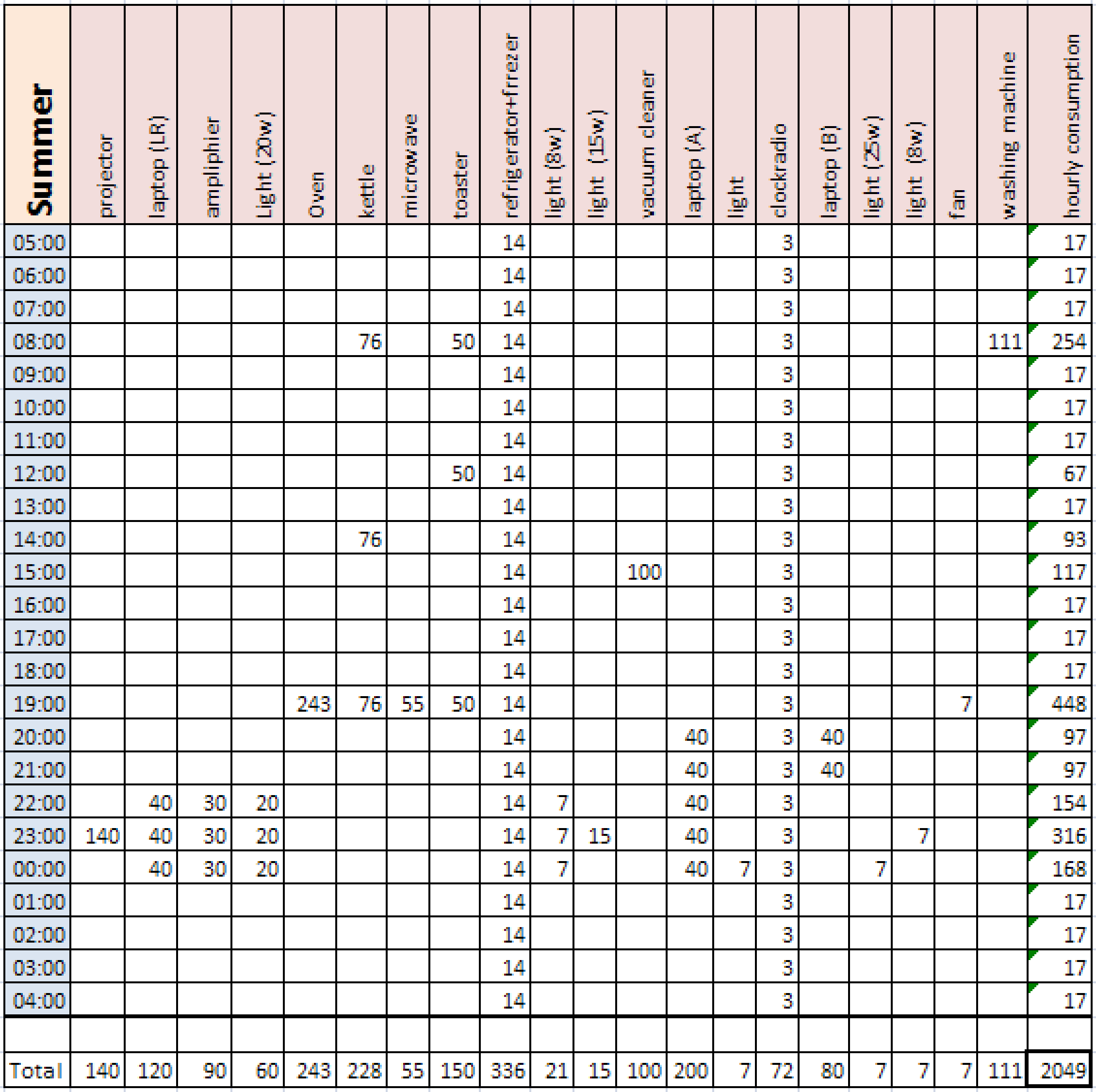
Through components investigation it was discovered that the system should have been designed for a 24 or 48 Volt system. Higher voltage gives the opportunity to install components that can have much larger power output and require a much smaller area.

Simulating the conditions helped to size a system much more accurate for the actual usage than any of the theoretical calculations could have done. This is especially true when considering the sensitivity analysis that was performed. The final system configuration is able to supply electricity for all weather conditions.

The final system is however quite expensive, initial investments are high. It’s a large investment for the general public and an off-grid system, while not a bad choice, is still unpractical when grid connection is available. It also require changes of components and manual refuelling of generator so there is more work involved than simple flipping a switch. With further decrease in components cost or higher electricity prices it might become a more appropriate consideration.

Appendix A: Load calculations

TABLE 12: SUMMER CONSUMPTION AND OPERATION TIME



Summer	projector	laptop (LR)	amplifier	Light (20w)	Oven	kettle	microwave	toaster	refrigerator+frrezer	light (8w)	light (15w)	vacuum cleaner	laptop (A)	light	clockradio	laptop (B)	light (25w)	light (8w)	fan	washing machine	hourly consumption
05:00									14						3						17
06:00									14						3						17
07:00									14						3						17
08:00						76		50	14						3					111	254
09:00									14						3						17
10:00									14						3						17
11:00									14						3						17
12:00								50	14						3						67
13:00									14						3						17
14:00						76			14						3						93
15:00									14			100			3						117
16:00									14						3						17
17:00									14						3						17
18:00									14						3						17
19:00					243	76	55	50	14						3				7		448
20:00									14				40		3	40					97
21:00									14				40		3	40					97
22:00		40	30	20					14	7			40		3						154
23:00	140	40	30	20					14	7	15		40		3			7			316
00:00		40	30	20					14	7			40	7	3		7				168
01:00									14						3						17
02:00									14						3						17
03:00									14						3						17
04:00									14						3						17
Total	140	120	90	60	243	228	55	150	336	21	15	100	200	7	72	80	7	7	7	111	2049

Experiment

In order to determine the real consumption of each device an electricity meter was used. It records the peak consumption of the device, the watts drawn each second and the total consumption in kWh.

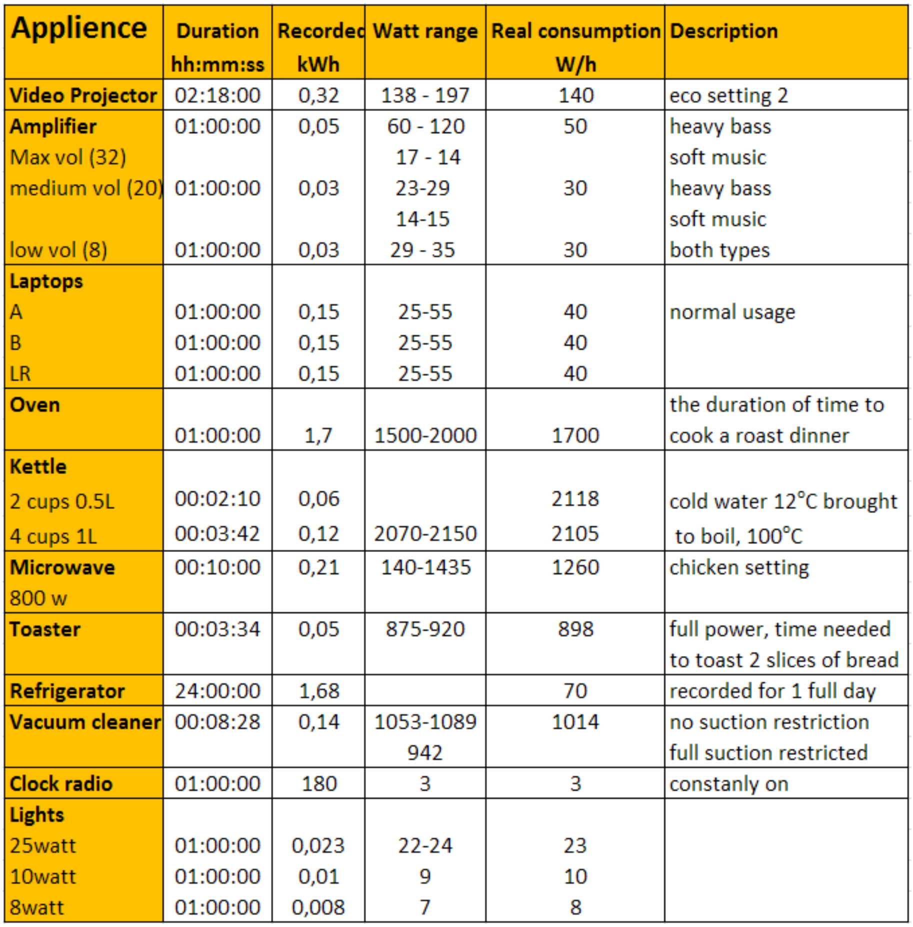
Appliances that are generally used over a long period of time, e.g. lights and amplifier, were measured over a one hour period. Then the electrical consumption was put in a table over the hourly time step to determine daily consumption of the building, see Table 13

For short usage appliances individual testing guidelines were selected:

- Kettle: Energy consumption needed to boil two and four cups of water, standard quantity of the household occupants.
- Microwave: A ten minute testing period is used to take into account the time needed to heat two plates of food.
- Oven: One hour is selected because this is the average time it takes to cook a roast.
- Toaster: The needed power to toast two slices of bread.
- Refrigerator: A 24 hour period was selected as the compressor is only turned on when the refrigerator needs to be cooled down. This was then divided by 24 hours to put it into the daily consumption table.
- Vacuum cleaner: The time it takes to vacuum the entire building.

Results are displayed in Table 13.

TABLE 13: EXPERIMENTATIONS

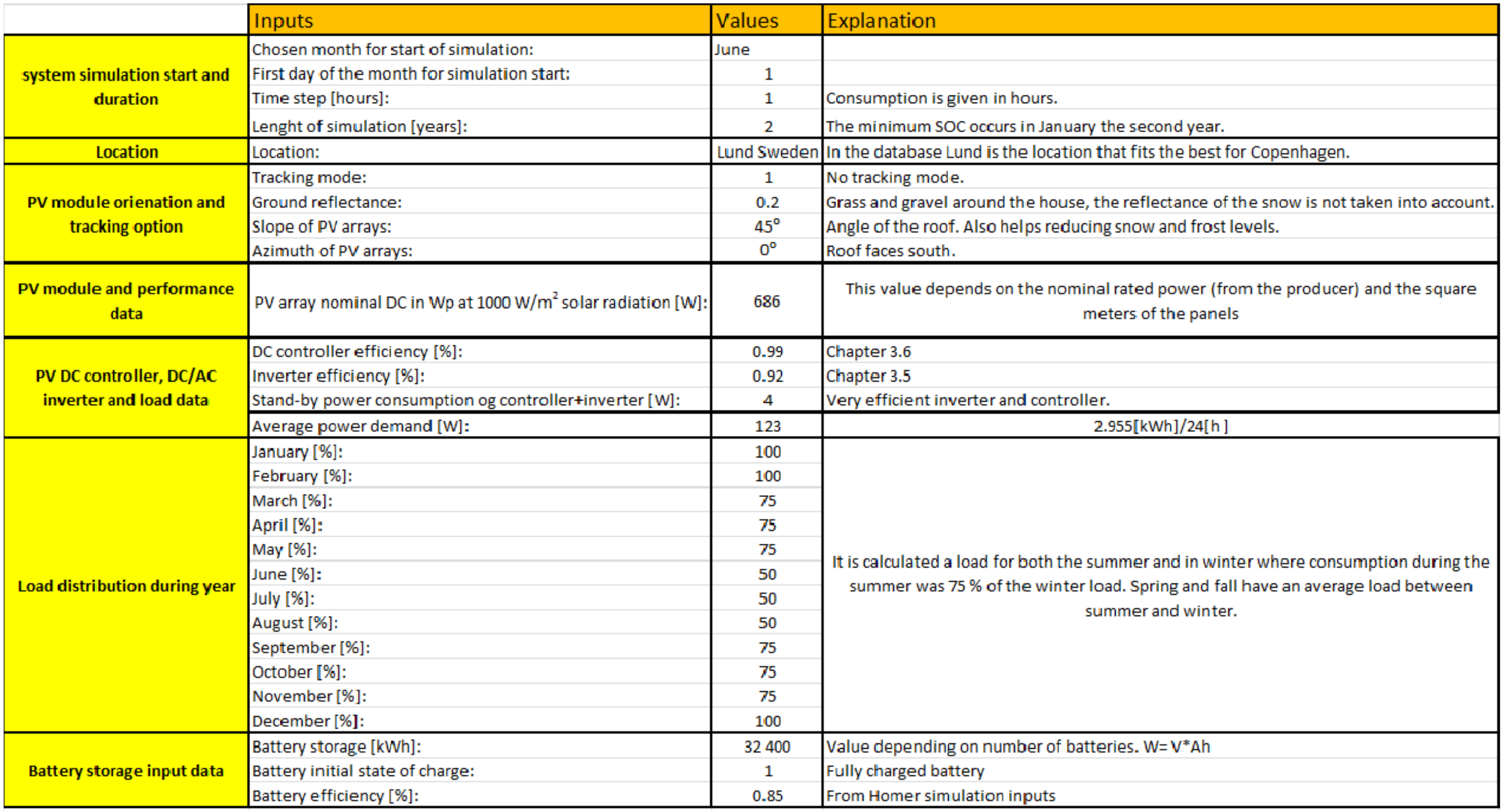


Applience	**Duration hh:mm:ss**	**Recordec kWh**	**Watt range**	**Real consumption W/h**	**Description**
Video Projector	02:18:00	0,32	138 - 197	140	eco setting 2
Amplifier	01:00:00	0,05	60 - 120	50	heavy bass
Max vol (32)			17 - 14		soft music
medium vol (20)	01:00:00	0,03	23-29	30	heavy bass
			14-15		soft music
low vol (8)	01:00:00	0,03	29 - 35	30	both types
Laptops					
A	01:00:00	0,15	25-55	40	normal usage
B	01:00:00	0,15	25-55	40	
LR	01:00:00	0,15	25-55	40	
Oven	01:00:00	1,7	1500-2000	1700	the duration of time to cook a roast dinner
Kettle					
2 cups 0.5L	00:02:10	0,06		2118	cold water 12°C brought
4 cups 1L	00:03:42	0,12	2070-2150	2105	to boil, 100°C
Microwave 800 w	00:10:00	0,21	140-1435	1260	chicken setting
Toaster	00:03:34	0,05	875-920	898	full power, time needed to toast 2 slices of bread
Refrigerator	24:00:00	1,68		70	recorded for 1 full day
Vacuum cleaner	00:08:28	0,14	1053-1089	1014	no suction restriction
			942		full suction restricted
Clock radio	01:00:00	180	3	3	constanly on
Lights					
25watt	01:00:00	0,023	22-24	23	
10watt	01:00:00	0,01	9	10	
8watt	01:00:00	0,008	7	8	

Appendix B: PVSUN3 simulation

PVSUN3 is a simple program where very little data is needed to simulate. The inputs that were used are displayed in Table 14.

TABLE 14: PVSUN3 INPUTS



	Inputs	Values	Explanation
system simulation start and duration	Chosen month for start of simulation:	June	
	First day of the month for simulation start:	1	
	Time step [hours]:	1	Consumption is given in hours.
	Lenght of simulation [years]:	2	The minimum SOC occurs in January the second year.
Location	Location:	Lund Sweden	In the database Lund is the location that fits the best for Copenhagen.
PV module orienation and tracking option	Tracking mode:	1	No tracking mode.
	Ground reflectance:	0.2	Grass and gravel around the house, the reflectance of the snow is not taken into account.
	Slope of PV arrays:	45°	Angle of the roof. Also helps reducing snow and frost levels.
	Azimuth of PV arrays:	0°	Roof faces south.
PV module and performance data	PV array nominal DC in Wp at 1000 W/m^2 solar radiation [W]:	686	This value depends on the nominal rated power (from the producer) and the square meters of the panels
PV DC controller, DC/AC inverter and load data	DC controller efficiency [%]:	0.99	Chapter 3.6
	Inverter efficiency [%]:	0.92	Chapter 3.5
	Stand-by power consumption og controller+inverter [W]:	4	Very efficient inverter and controller.
	Average power demand [W]:	123	2.955[kWh]/24[h]
Load distribution during year	January [%]:	100	It is calculated a load for both the summer and in winter where consumption during the summer was 75 % of the winter load. Spring and fall have an average load between summer and winter.
	February [%]:	100	
	March [%]:	75	
	April [%]:	75	
	May [%]:	75	
	June [%]:	50	
	July [%]:	50	
	August [%]:	50	
	September [%]:	75	
	October [%]:	75	
	November [%]:	75	
	December [%]:	100	
Battery storage input data	Battery storage [kWh]:	32 400	Value depending on number of batteries. W= V*Ah
	Battery initial state of charge:	1	Fully charged battery
	Battery efficiency [%]:	0.85	From Homer simulation inputs

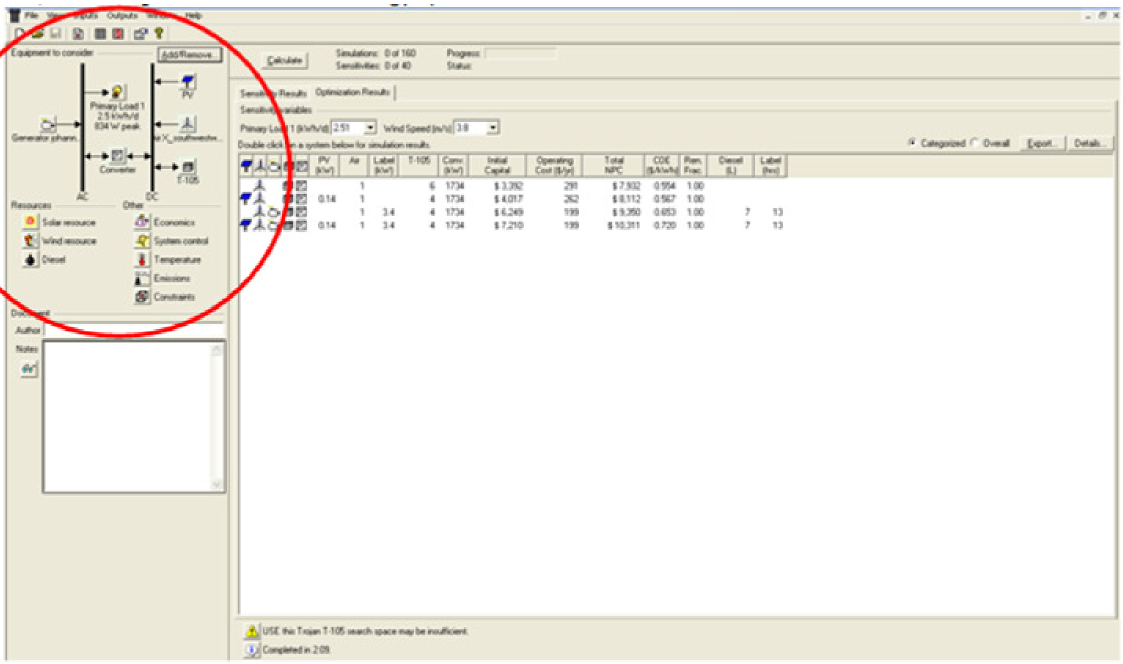
Final calculations for PVSUN3 simulations are displayed in Figure 15.

Number of simulations	Number of solar panels	Cost of solar panels	Area of solar panels [m^2]	Rated power [W/m^2]	PV power (W)	Number of batteries	Power for each battery [W]	Battery-bank capacity [W]	Cost of one battery [DKK]	Battery bank cost [DKK]	Total System costwith invertre& generator [DKK]
1	2	10464	0,98	140	274,4	24	1350	32400	901	21624	38964
2	5	26160	0,98	140	686	24	1350	32400	901	21624	65436
3	5	26160	0,98	140	686	40	1350	54000	901	36040	87036
4	5	26160	0,98	140	686	60	1350	81000	901	54060	114036
5	5	26160	0,98	140	686	75	1350	101250	901	67575	134286
6	5	26160	0,98	140	686	90	1350	121500	901	81090	154536
7	10	52320	0,98	140	1372	90	1350	121500	901	81090	180696
8	15	78480	0,98	140	2058	90	1350	121500	901	81090	206856
9	25	130800	0,98	140	3430	90	1350	121500	901	81090	259176
10	20	104640	0,98	140	2744	90	1350	121500	901	81090	233016
11	23	120336	0,98	140	3155,6	90	1350	121500	901	81090	248712
12	22	115104	0,98	140	3018,4	90	1350	121500	901	81090	243480

FIGURE 15: PVSUN3 CALCULATIONS

Appendix C: Homer simulation

Using HOMER requires a range of inputs to the model describing load, components used, economics, system control and metrological data. The program then uses the inputs to simulate different system configurations or combinations of components. The results can then be viewed as a list of feasible configurations sorted by net present cost.



Simulations: 0 of 160
Sensitivities: 0 of 40

Primary Load 1 (kWh/d) 2.51 Wind Speed (m/s) 3.8

Double click on a system below for simulation results.

PV (kW)	Air	Label (kW)	T-105	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Label (hrs)
	1		6	1734	$ 3,392	291	$ 7,932	0.554	1.00		
0.14	1		4	1734	$ 4,017	262	$ 8,112	0.567	1.00		
	1	3.4	4	1734	$ 6,249	199	$ 9,350	0.653	1.00	7	13
0.14	1	3.4	4	1734	$ 7,210	199	$ 10,311	0.720	1.00	7	13

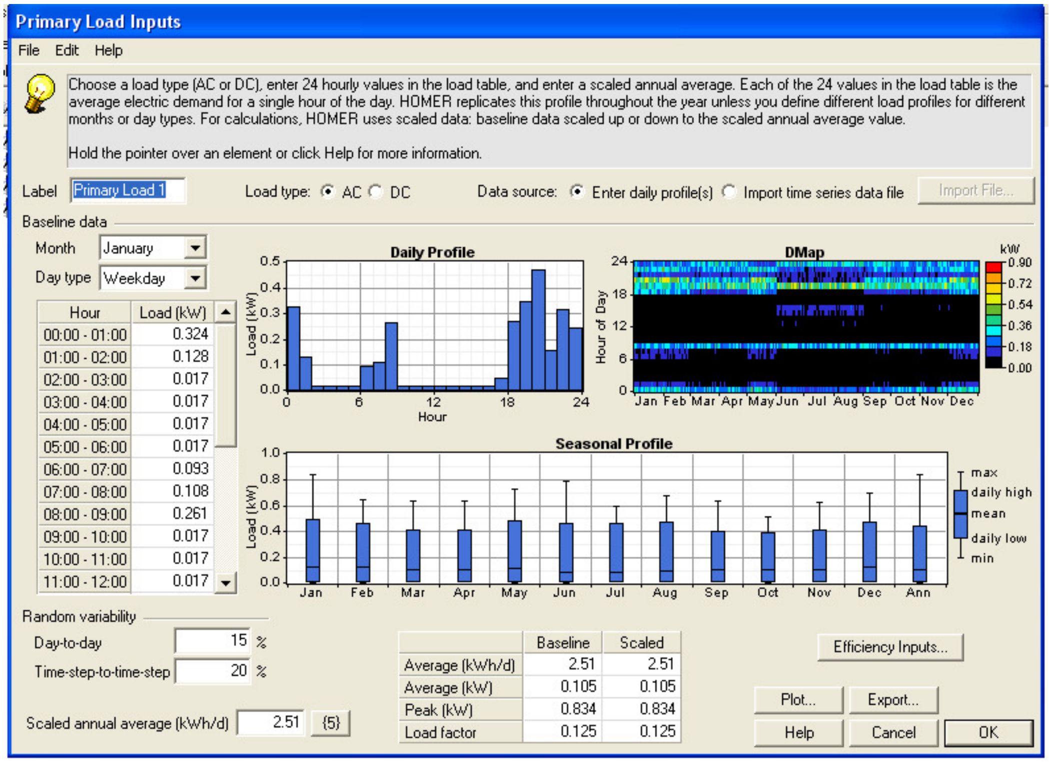
USE this Trojan T-105 search space may be insufficient.

Completed in 2.09.

FIGURE 16: THE SYSTEM

Load

The load data is the electrical demand the system must serve. It's inserted in a 24-row table which gives the average electrical demand for every hour of a day. It's possible to enter different load profiles for different months or days. In the project case an average day profile was chosen and three different monthly profiles representing winter, summer and spring/fall.



Choose a load type (AC or DC), enter 24 hourly values in the load table, and enter a scaled annual average. Each of the 24 values in the load table is the average electric demand for a single hour of the day. HOMER replicates this profile throughout the year unless you define different load profiles for different months or day types. For calculations, HOMER uses scaled data: baseline data scaled up or down to the scaled annual average value.

Hold the pointer over an element or click Help for more information.

Label: Primary Load 1

Load type: ● AC ○ DC

Data source: ● Enter daily profile(s) ○ Import time series data file

Baseline data

Month: January

Day type: Weekday

Hour	Load (kW)
00:00 - 01:00	0.324
01:00 - 02:00	0.128
02:00 - 03:00	0.017
03:00 - 04:00	0.017
04:00 - 05:00	0.017
05:00 - 06:00	0.017
06:00 - 07:00	0.093
07:00 - 08:00	0.108
08:00 - 09:00	0.261
09:00 - 10:00	0.017
10:00 - 11:00	0.017
11:00 - 12:00	0.017

Random variability

Day-to-day: 15 %

Time-step-to-time-step: 20 %

Scaled annual average (kWh/d): 2.51 {5}

	Baseline	Scaled
Average (kWh/d)	2.51	2.51
Average (kW)	0.105	0.105
Peak (kW)	0.834	0.834
Load factor	0.125	0.125

FIGURE 17: PRIMARY LOAD INPUTS

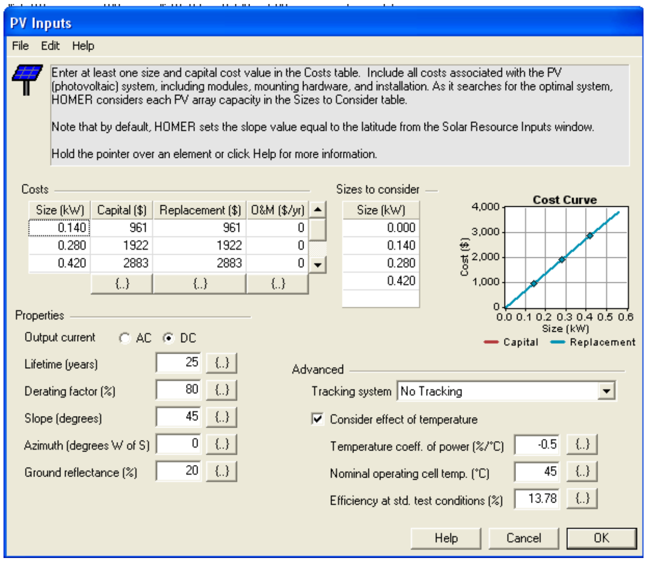
Components

For every chosen component a list of general data needs to be given, cost, power size, lifetime. Some components might also require more specific properties, these will be explained here.

PV

In addition to the rated power it's important to define:

- Collector slope: 45^o for system case
- Azimuth angle: 0^o for panels facing south
- Ground reflectance: 0.2 for a house with surrounding grass. Reflectance of snow is not considered even though it gives a positive effect, it's difficult to estimate.
- Collector efficiency: 13.1 %
- Nominal operating cell temperature: 45^oC
- De-rating factors: This is a reduction factor to account for real world simulations as the PV array power was rated at ideal conditions in a factory. If a user is simulating a PV battery system or grid-connected PV system the best place to include the charge controller costs and efficiency is in the PV inputs. So the cost of the controller is added together with PV and efficiency is multiplied with the de-rating factor. In the project a factor of 80 % was assumed to simulate losses and the controller has an efficiency of 99 %, 80*99= 79.2 %.



Enter at least one size and capital cost value in the Costs table. Include all costs associated with the PV (photovoltaic) system, including modules, mounting hardware, and installation. As it searches for the optimal system, HOMER considers each PV array capacity in the Sizes to Consider table.

Note that by default, HOMER sets the slope value equal to the latitude from the Solar Resource Inputs window.

Hold the pointer over an element or click Help for more information.

Costs

Size (kW)	Capital ($)	Replacement ($)	O&M ($/yr)
0.140	961	961	0
0.280	1922	1922	0
0.420	2883	2883	0
	{..}	{..}	{..}

Sizes to consider

Size (kW)
0.000
0.140
0.280
0.420

Properties

Output current ○ AC ● DC

Lifetime (years)	25	{..}
Derating factor (%)	80	{..}
Slope (degrees)	45	{..}
Azimuth (degrees W of S)	0	{..}
Ground reflectance (%)	20	{..}

Advanced

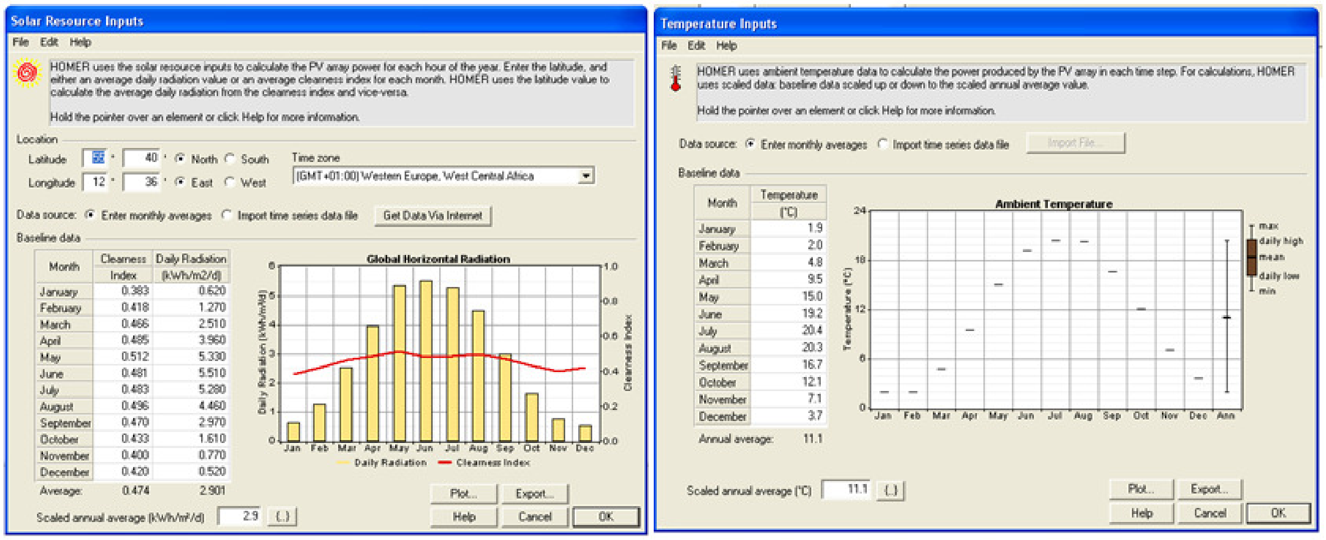
Tracking system: No Tracking

☑ Consider effect of temperature

Temperature coeff. of power (%/°C)	-0.5	{..}
Nominal operating cell temp. (°C)	45	{..}
Efficiency at std. test conditions (%)	13.78	{..}

FIGURE 18: PV INPUTS

The PV also requires the solar resources and temperatures in the project area. For solar resource the latitude, longitude, clearness index and solar radiation (NASA, 2010) are required. Monthly average ambient temperature data is also necessary (Danmarks Meteorologiske Institut, 2010).



HOMER uses the solar resource inputs to calculate the PV array power for each hour of the year. Enter the latitude, and either an average daily radiation value or an average clearness index for each month. HOMER uses the latitude value to calculate the average daily radiation from the clearness index and vice-versa.

Hold the pointer over an element or click Help for more information.

Location

Latitude 55 ° 40 ' ● North ○ South

Longitude 12 ° 36 ' ● East ○ West

Time zone: (GMT+01:00) Western Europe, West Central Africa

Data source: ● Enter monthly averages ○ Import time series data file

Baseline data

Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	0.383	0.620
February	0.418	1.270
March	0.466	2.510
April	0.485	3.960
May	0.512	5.330
June	0.481	5.510
July	0.483	5.280
August	0.496	4.460
September	0.470	2.970
October	0.433	1.610
November	0.400	0.770
December	0.420	0.520
Average:	0.474	2.901

Scaled annual average (kWh/m²/d): 2.9 {..}

HOMER uses ambient temperature data to calculate the power produced by the PV array in each time step. For calculations, HOMER uses scaled data: baseline data scaled up or down to the scaled annual average value.

Hold the pointer over an element or click Help for more information.

Data source: ● Enter monthly averages ○ Import time series data file

Baseline data

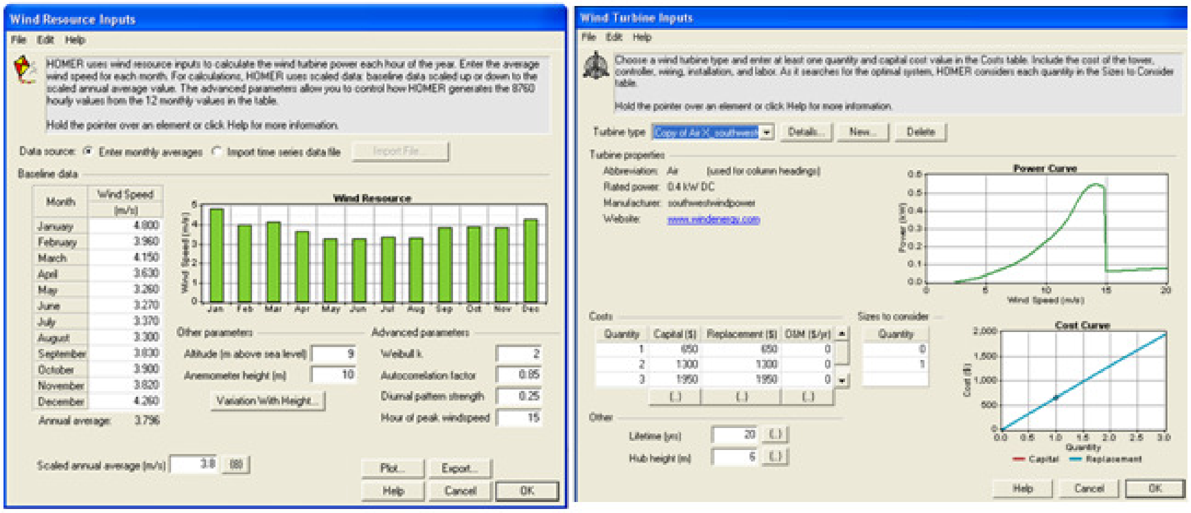
Month	Temperature (°C)
January	1.9
February	2.0
March	4.8
April	9.5
May	15.0
June	19.2
July	20.4
August	20.3
September	16.7
October	12.1
November	7.1
December	3.7
Annual average:	11.1

Scaled annual average (°C): 11.1 {..}

FIGURE 19: SOLAR RESOURCE AND TEMPERATURE

Wind Turbine

When choosing a wind turbine for HOMER three factors are necessary. A power curve (power output as a function of wind speed), the elevation from the ground (6 m in project) and the average wind speed per month (NASA, 2010).



HOMER uses wind resource inputs to calculate the wind turbine power each hour of the year. Enter the average wind speed for each month. For calculations, HOMER uses scaled data: baseline data scaled up or down to the scaled annual average value. The advanced parameters allow you to control how HOMER generates the 8760 hourly values from the 12 monthly values in the table.

Hold the pointer over an element or click Help for more information.

Data source: ● Enter monthly averages ○ Import time series data file

Baseline data

Month	Wind Speed (m/s)
January	4.800
February	3.960
March	4.150
April	3.630
May	3.260
June	3.270
July	3.370
August	3.300
September	3.830
October	3.900
November	3.820
December	4.260

Annual average: 3.796

Other parameters

Altitude (m above sea level) 9

Anemometer height (m) 10

Advanced parameters

Weibull k 2

Autocorrelation factor 0.85

Diurnal pattern strength 0.25

Hour of peak windspeed 15

Scaled annual average (m/s) 3.8

Choose a wind turbine type and enter at least one quantity and capital cost value in the Costs table. Include the cost of the tower, controller, wiring, installation, and labor. As it searches for the optimal system, HOMER considers each quantity in the Sizes to Consider table.

Hold the pointer over an element or click Help for more information.

Turbine type: Copy of Air X_southwest

Turbine properties

Abbreviation: Air (used for column headings)

Rated power: 0.4 kW DC

Manufacturer: southwestwindpower

Website: www.windenergy.com

Costs

Quantity	Capital ($)	Replacement ($)	O&M ($/yr)
1	650	650	0
2	1300	1300	0
3	1950	1950	0

Sizes to consider

Quantity
0
1

Other

Lifetime (yrs) 20

Hub height (m) 6

FIGURE 20: WIND RESOURCE AND TURBINE INPUTS

Generator

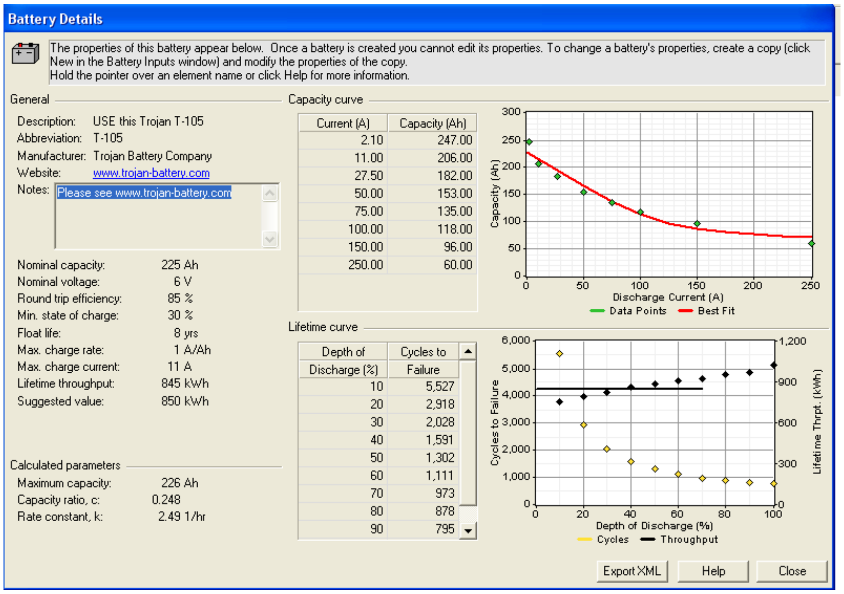
For the generator the type and the maximum efficiency are the only relevant inputs for our project. They were chosen as a diesel generator with a maximum efficiency of 30 %. Two more inputs could be important for other studies:

- Schedule: Specify certain intervals where the generator is allowed to be used, or has to be used.
- Emissions.

Battery

In order to reach the required voltage of the system it's important to define the number batteries per string. The batteries are mainly defined by two curves:

- Capacity curve: The capacity of a battery is defined as the amount of energy that can be withdrawn from a fully charged battery. The capacity depends on the rate at which the electricity is withdrawn; higher discharge current gives a lower capacity.
- Lifetime curve: In a lifetime test the battery is subjected to regular repeating charge and discharge cycles. For every cycle the battery is discharged down to a certain depth before it's fully recharged again. The test determines how many such cycles the battery can withstand before it needs replacing. This is highly dependent on the battery, but a default curve could be created with 200 cycles at 80 % discharge, 1000 cycles at 50 % and 2000 at 25 %.



The properties of this battery appear below. Once a battery is created you cannot edit its properties. To change a battery's properties, create a copy (click New in the Battery Inputs window) and modify the properties of the copy.
Hold the pointer over an element name or click Help for more information.

General

Description: USE this Trojan T-105
Abbreviation: T-105
Manufacturer: Trojan Battery Company
Website: www.trojan-battery.com
Notes: Please see www.trojan-battery.com

Nominal capacity: 225 Ah
Nominal voltage: 6 V
Round trip efficiency: 85 %
Min. state of charge: 30 %
Float life: 8 yrs
Max. charge rate: 1 A/Ah
Max. charge current: 11 A
Lifetime throughput: 845 kWh
Suggested value: 850 kWh

Calculated parameters

Maximum capacity: 226 Ah
Capacity ratio, c: 0.248
Rate constant, k: 2.49 1/hr

Capacity curve

Current (A)	Capacity (Ah)
2.10	247.00
11.00	206.00
27.50	182.00
50.00	153.00
75.00	135.00
100.00	118.00
150.00	96.00
250.00	60.00

Lifetime curve

Depth of Discharge (%)	Cycles to Failure
10	5,527
20	2,918
30	2,028
40	1,591
50	1,302
60	1,111
70	973
80	878
90	795

FIGURE 20: BATTERY DETAILS

Finally the efficiency of the battery should be considered.

Inverter

Input values are energy size, cost, lifetime and efficiency.

Economics

Certain values are needed for the program to calculate economics.

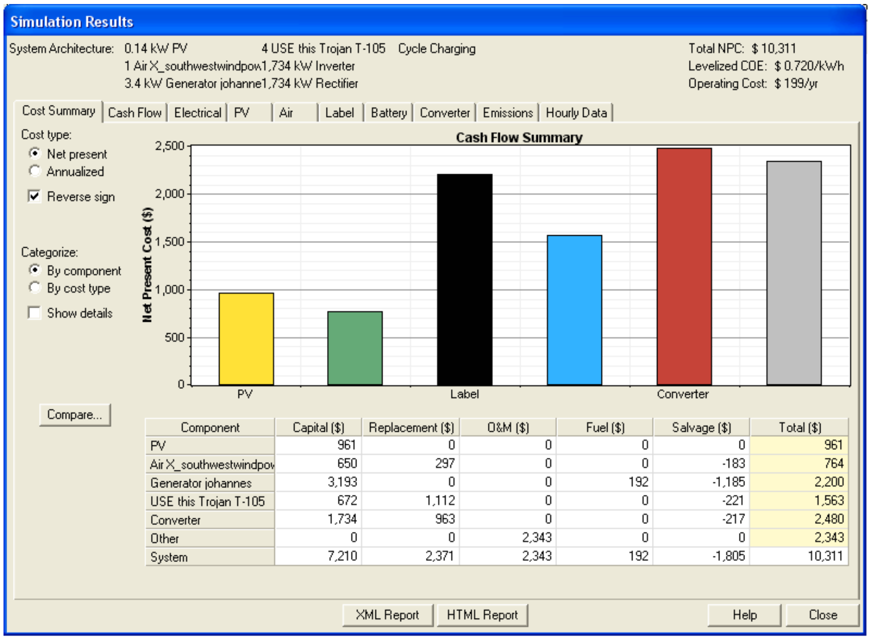
- Annual interest rate: Discount rate used to convert between one-time costs and annualized costs (4 % in the project).
- Project lifetime: The number of years over which the net present cost should be calculated (25 years in the project).
- Fixed capital costs: costs that occur regardless of system operation (0 $ in the project).
- Fixed Operation and Maintenance costs: (150 $/year in the project).
- Capacity shortage penalties: Penalties applied to the system if there are any capacity shortages (0 $ in the project).

System control

This section provides models of operation for the battery bank and the generator. Inputs are simulation time steps and adding a set point of charge.

Output

HOMER show's simulation results with the top ranked system configurations according to the net present cost. Inside each system there is a wide variety of tables and graphs that help to compare configurations and evaluate them on their economic and technical merits.



System Architecture: 0.14 kW PV
1 Air X_southwestwindpow
3.4 kW Generator johanne
4 USE this Trojan T-105
1,734 kW Inverter
1,734 kW Rectifier
Cycle Charging

Total NPC: $ 10,311
Levelized COE: $ 0.720/kWh
Operating Cost: $ 199/yr

Cost type:
● Net present
○ Annualized
☑ Reverse sign

Categorize:
● By component
○ By cost type
☐ Show details

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	961	0	0	0	0	961
Air X_southwestwindpov	650	297	0	0	-183	764
Generator johannes	3,193	0	0	192	-1,185	2,200
USE this Trojan T-105	672	1,112	0	0	-221	1,563
Converter	1,734	963	0	0	-217	2,480
Other	0	0	2,343	0	0	2,343
System	7,210	2,371	2,343	192	-1,805	10,311

FIGURE 21: SIMULATIONS RESULTS

The results can also be viewed categorized, giving the cheapest components in the system in ranked order.

It’s also possible to do a sensitivity analysis which allows the user to explore how variations in the average annual variables affect the optimal design of the system. A sensitivity analysis can however result in a huge amount of output data. HOMER will typically give results in several dozen summary outputs, e.g. annual fuel consumption, plus a dozen arrays of hourly data, e.g. output from wind turbine. HOMER will perform hundreds or thousands of these simulations per sensitivity case and a sensitivity analysis can easily involve hundreds of such cases.

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