Sizing and assessment of an off-grid PV system using a Lithium battery bank

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Resumo

Este trabalho foca-se no dimensionamento de consumo e demanda de carga de um sistema eléctrico doméstico em que a sua validação é obtida através de uma folha interactiva e correlacionada com os resultados do uso das ferramentas do programa PVsyst

O objetivo principal a ser a construção e teste de um sistema independente da rede. O sistema será composto de um qualquer número de painéis solares fotovoltaicos e baterias de lítio.

Após validar a demanda de carga de um sistema doméstico comum, três simulações foram feitas com recurso ao programa PVsyst, uma para simulação de consumo excessivo, optimizado e finalmente para uma aproximação mensal, sendo esta uma mistura das duas anteriores.

Os relatórios para cada simulação são analisados e discutidos com detalhe e ênfase em parâmetros como perdas, geração, consumo e performance do sistema. Por fim um caso práctico é apresentado que é o caso do veleiro SV Delos, cujo sistema é composto por maioritariamente geração solar e um banco de baterias de Lítio. O veleiro SV Delos é capaz de transportar uma tripulação de 6 pessoas e fornecer as suas necessidades energéticas básicas com facilidade enquanto está independente da rede.

Palavras-chave: Solar Fotovoltaico, Independente da rede, Baterias de Lítio, Sistema móvel PV, Energias Renováveis

Abstract

In this work a validation of household consumption and load demand (size) is made via a created interactive spreadsheet further correlated with the system design tools of software PVsyst. The main objective being appropriate off-grid system design and assessment. The system is to be comprised of any number of Solar Photovoltaic panels and Lithium battery units. After validating the load demand of a common household, 3 simulations are made with software PVsyst, one for a daily excessive consumption, another for an optimized daily consumption and finally one for a monthly approximation consumption made by mixing the load demands for the first two simulations.

The reports for each simulation are analyzed and discussed with detail, with emphasis in parameters of losses, generation, consumption and system performance. Finally a proof-of-concept case is presented that is the system present in a sailing vessel SV Delos. Its system is comprised of (mainly) Solar generation and a large lithium battery bank. SV Delos can house a crew of 6 and supply their energy needs with easy whilst being completely off-grid.

Keywords: Solar PV, Off-grid, Lithium Battery , Mobile PV system, Renewable Energy

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Nomenclature

Greek symbols

μC Thermal Loss factor.

μVOC Temperature Coefficient of the open circuit voltage.

Ω Ohms.

ρ Resistivity.

Roman symbols

A_{cs} Cross sectional Area.

I_{MP} Current at Maximum Power.

N_s Number of cells.

P_{Nom} Nominal Power.

V_{Drop} Voltage Drop.

V_{MP} Voltage at Maximum Power.

V_{OC} Open Circuit voltage.

AC Alternating Current.

$BIPV$ Building Integrated Photovoltaics.

C Celsius.

DC Direct Current.

h Hours.

I Current.

Lc Collection losses.

LFP Lithium Iron Phosphate Battery [LiFePO4].

LOL Loss of Load probability.

Ls System losses.

Lu Unused Energy.

m Meters.

$MPPT$ Maximum Power Point Tracker.

PR Performance Ratio.

PV Solar Photovoltaic.

SF Solar Fraction.

SOC State of Charge.

STC Standard Test Conditions.

V Volt.

W Watt.

Ya Array yield.

Yf System yield.

Yr Reference system yield.

A Amp.

$A.M.$ Ante meridiem.

Chapter 1

Introduction

The motivation behind this work comes from an urgent necessity in finding alternative domestic energy supply systems that are compatible with an overarching sustainable development strategy. Whether rural or urban, stand-alone systems have their advantages and disadvantages, one could argue that both have their respective time and place for implementation. However, there are situations where a grid connection is just not feasible or even economically viable. Isolated rural spots suffer the most from lack of access to an energy supply that can satisfy the basic needs of the 21st century. Furthermore, with an increasing unpredictability of weather events/political instability that displace large populations, an increasing demand for fast deploy systems that can supply energy to medical providers and dislodged families has presented itself with urgent necessity.

That may not be the case in an urban setting, where there is vast access to the energy grid. Nonetheless the housing crisis that plagues younger generations like my own opens a clear pathway for smaller – yet powerful - scale systems. From a small house, up to a communal neighborhood generating its own energy grid to even mobile systems like Van conversion or sailing boats, the technology nowadays is capable to respond to the needs those systems imply, presenting an alternative that as of yet is a small niche but in the future has a large cap on its potential to offer alternate and independent solutions to their users. Said systems are the core of this work, where two Solar Photovoltaic (PV) + Lithium battery systems are put to the test on whether they are feasible and robust in order to serve a specific purpose that is supply energy to a household without grid support and an autonomy of five days or as in the proof-of-concept a sailing vessel. With the current technology of lithium battery cells, PV panels and an MPPT this work will try to validate that a domestic system can be implemented and support the daily loads of a domestic household at a long term.

1.1 Objectives and Deliverables

Considering the context explored throughout this work, the objective is validation of feasibility of a regular domestic sized system through the use of a combination of Solar PV panels and Lithium (LFP) batteries. The system is to be configured by default on a DC mode without the use of an inverter although naturally the inclusion and small changes for different implementations needs to be a choice and not an hindrance that makes the system implementation impossible. To do that a calculation spreadsheet was made with software Microsft Excel that is capable of sizing the power loads of any domestic system and offer information about tension drops throughout different circuits of the system if the desired circuit length is introduced beforehand. The data from this spreadsheet is then further validated by the use of the software PVsyst, where three simulations are made and its results confirming the validation of the system structure are discussed. Finally the work concludes with a proof-of-concept case, that due to the nature of its implementation and available data supplied proves to be a valuable addition in understanding the range off-grid systems have.

1.2 Thesis Outline

In Chapter Two, a brief literature review is made, focusing mainly on needs of stand-alone off-grid systems - whether in emergency situations, or as a life choice -, and the current state of PV technologies and Lithium battery technology. The Methodology Chapter goes into detail of how the Excel calculation spreadsheet was devised and how to work with it in order to extrapolate the desired information. Then the chapter explains how that information is validated with the use of the PVsyst software and how the Simulation data was worked with emphasis on choosing parameters to produce a more robust simulation with accurate results. Accordingly the next chapter (Chapter Four - Results), focuses on discussing the results of the three simulations made (one for a daily excessive consumption, another for an optimized daily consumption and finally one for a monthly approximation consumption made by mixing the load demands for the first two simulation). Finally in the Discussion Chapter (Chapter Five) the potential for this work is addressed and the chosen Proof-of-Concept case is described with recourse to supplied data from the owner of the system.

Chapter 2

Literature review

One of the applications for systems as the one proposed on this work is the supply of energy in emergency situations where grid access is not possible or even nonexistent at all. Literature suggests the clear connection between the effect of world policy (MacPherson et al. (2007)) and climate change and its reflection on natural/weather disasters as crucial factors in population displacement (Oliver-Smith (2012)).

Situations of disaster, policy change and lack of access to basic necessities (such as electricity) often force the population to abandon their region in search for better conditions as can be verified by the current trend in these last few years (McAuliffe et al. (2018)). Until the displaced population can return to their home, find a new one through immigration processes, or gain the access to those basic necessities the people who were displaced are placed into emergency shelters (Uddin et al. (2018)).

Adding to those situations, there are multiple regions of the world where default grid access was never developed. That situation is common on less developed regions of the world, for example in sub-Saharan Africa where over half a billion people still do not have access to electricity, however that number is steadily decreasing in recent years. To that effect literature can be found on several studies regarding rural electrification of those areas – which is undoubtedly a factor contributing to the decrease in the number of people with lack of access to electricity – and studies focusing on the supply of energy to health facilities which correlates to the aforementioned situations of emergency deployment.

In (Salihu et al. (2020)) and (Longe et al. (2014)) two renewable energy (Solar PV) microgrids are studied with emphasis on viability and improvement on quality of life for the people living in the area of their implementation. The quality-of-life improvements for the villagers in those regions are apparent. Productive capabilities increase mainly connected with irrigation which also helps to achieve a larger harvest time per year.

To move along with the topic of supplying basic necessities, an assortment of papers focuses on using these off-grid systems to power healthcare facilities. (Ayodele et al. (2021)) presents a microgrid design for a ten bed clinic as is common on a South-African village, where the sources of energy are PV and Wind and the storage is Hydrogen. This paper focuses on the cost vs cost of a grid extension and found that the renewable grid to be advantageous compared to the grid extension option.

On a larger comparison and study, (Opoku et al. (2020)) highlights several socioeconomic benefits derived from the implementation of the discussed PV systems. From time saving improvements (15-43 hours mostly for women and children) and their reflection in the ability for people to develop more productive work and the excess electricity generation - that in this study ranges from 148 kWh to 304 kWh used for a wide range of applications from charging phones to cold storage which generates revenue for the healthcare facility - the benefit these installations gain from coupling with PV systems is undeniable.

To conclude this part in (Al-Akori (2014)) there is a larger focus on lessons learnt from international development organizations in the best way to deploy PV off grid systems and ensure their sustainability.

There are other reasons for the implementation of off-grid systems, and without getting far beyond the scope of this work, CO2 emissions mitigations, independence and sustainable development are among those reasons. In (De Carli et al. (2012)) a study is conducted on the development of a region located on the Italian Dolomites mountain territory, in an effort to modernize the region. Energy production is analyzed in order to evaluate potential margin for improvement with an emphasis on renewable energy, mainly Solar PV.

After the stage of finding necessity for these systems there comes undoubtedly a stage of viability and assessment of implementation. Those studies usually focus on economic impacts of implementation, some on social factors and some - as this work - on validation. Economic and environmental factors are usually the first to be addressed as can be seen on (Ortega-Arriaga et al. (2021)) where the impacts of grid-extension vs off-grid system are compared (centralized conventional fossil-fuel grid-extension and off-grid PV systems). This paper focuses on the many grid-extension costs that are affected due to geographic, social and energy factors and how those do not directly translate themselves to off-grid solutions thus rendering them to be the most cost-effective option. These systems can be designed to work on a DC mode or with an inverter to supply AC, although the trend seems to be cementing itself on DC – the same as the one proposed in this work. In (Castillo-Calzadilla et al. (2018)), a research paper where a DC photovoltaic microgrid is proposed, some advantages are enumerated such as Higher efficiency, larger reliability, and a higher degree of safety for consumers. The methodology fulfills the necessary criteria when analyzing the development of a Solar microgrid by computing real data of temperature, irradiance and most importantly consumption data in a similar fashion to that of the one done in this present work.

One key aspect of literature for PV off-grid systems is the one regarding its most important components, that is the Batteries and their chosen technology which will comprise the capacity and energy delivery part of the system in the form of a battery bank and the solar photovoltaic panels that represent the generation component of the system.

In what concerns the batteries (Zubi et al. (2020)) concisely demonstrates why Lithium – more precisely LFP type – is the technology better suited to pair with Solar generation. LFP batteries have several advantages to the incumbent technology that is Lead-Acid, they have a lighter design, performance – with astounding difference in usable SOC – advantages and a greater cycle life. And this paper illustrates the case clearly for LFP by giving an overview of the technical aspects of this technology. The conclusion being that although LFP has a high initial capital cost, they are an energy storage wise cost competitive technology and the most accepted common choice in the present and near future for Solar PV off-grid systems. The paper closes its argument with the fact that with incentives and favorable conditions the implementation price barriers of the past will be reduced.

By being the standard for battery technology, current literature in possible improvements is also readily available and being produced. (Yin-Quan (2011)) focuses on a new charging method for LFP by manipulating the battery charge rate. The advantages being the full charge to 100% SOC whilst avoiding over voltages and over charging, factors that will further extend battery cycle life. Adding to the support of LFP (Ahsan et al. (2020)) focuses on improvement on the cathode material with techniques such as surface modification, particle size and lattice substitution, thereby gathering the most effective strategies for capacity enhancement for LFP battery technology.

To conclude the battery section it is worth noting one of the most overlooked factors with these types of system pairings of solar panels and batteries, which is the physical distance between these components and why they do not go next to each other (for example in situations where space is a limited resource). (Vega-Garita et al. (2019)) discusses this situation and makes the case for LFP being the appropriate technology to use in PBIMs, PV-battery Integrated Modules.

Solar Photovoltaic literature is showing a shift in volume to newer and experimental technologies. Currently up to the second generation of Solar PV technologies has its dissemination through the market well established therefore the industry is pushing for new developments (Figure 2.1). In the IRENA 2019 Future of solar report (IRE (2019)) a larger report on the current state of Solar PV, it establishes the future trends for present and upcoming technologies.

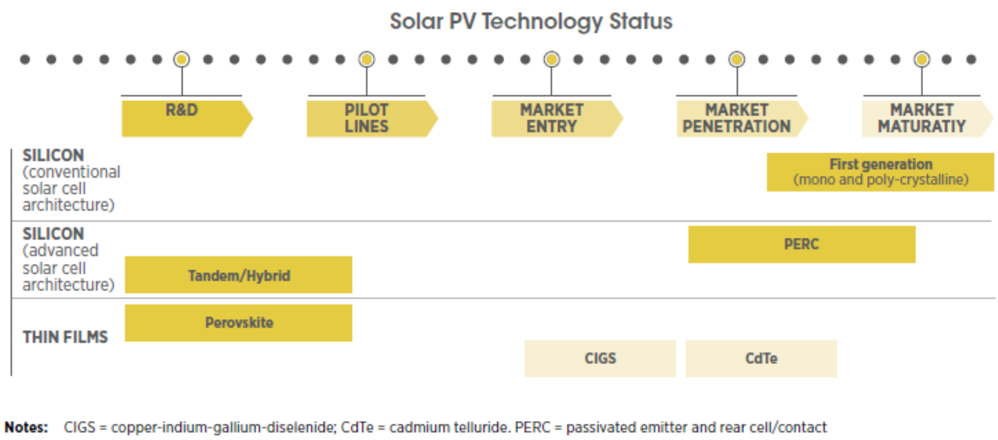

Figure 2.1: Solar PV Technology status as seen in [IRE (2019)].

For Silicon based technologies - whether with conventional or advanced architecture – it it shown that the stage that these technologies are at is of mostly market maturity with wide dissemination. Those include Polly and Mono as well PERC (Tandem and Hybrid technologies are still on R&D phase as shown). The first two make up the largest share of implemented solar technologies and in (Garcia et al. (2020)) a comparative study in optimal and equal operating conditions shows that the difference overall is at around 2W greater for the Mono technology. The study was conducted over the course of 3 months where variables such as temperature, humidity, solar irradiance, power and I-V operation were computed to extrapolate each respective technology's conversion efficiency. An important takeaway from this study was the effect of relative humidity due to reflective and refractive factors that affected irradiance levels. To conclude the available technologies for Solar PV, 2nd generation Solar PV cells focus on Thin film which is the direction research is being conducted whether it being applied in tiles (as mentioned later on in this work) or even paint as in (Khan and Rahman (2019)) where the potential for this technology to overtake the previous one is studied. Tunable size characteristics, flexibility and cost-effective manufacture all endorse this large potential, previously validated by the inception of thin film technology. The research paper closes with the argument for Quantum dots and Pervoskite based thin film photovoltaic paints providing viability to enhance the efficiency of this technology.

On concluding this state-of-the-art and to what possibly is its research gap, Solar powered mobile homes whether maritime or terrestrial have the enormous advantage of mobility and off-grid independence. To the best of the knowledge of the author, this type of study has not been explored in the literature - at least with the methodology followed on this work's Proof-of-Concept – and it would be where future work could follow. Of course when researching there are already numerable practical cases as the one presented on the Proof-of-Concept however few (apparently none) show viable studies from their performance on a considerable time basis which would be extremely beneficial to these types of systems and would light possible areas for improvement and management/control.

Chapter 3

Methodology

The methodology behind this work was divided in two fronts, one for validating household consumption (appliance load management) through data collection and calculation for two separate days (excel interactive spreadsheet), and the other to compliment the robustness of household consumption through the sizing of the system with the aid of the PVsyst software (Designed by Webgenève).

3.1 Microsoft Excel® Spreadsheet

The Excel spreadsheet was elaborated with a clear purpose of being developed into a sizing tool later on. As obvious as it is that no two systems are alike and that a strong planning phase is crucial to the development of any PV off-grid system, the need for a tool that can be adaptable to multiple parameter changes presented itself.

As the Excel spreadsheet deals mostly with loads, the parameter of Voltage Drop [V_{Drop}] and its effect on the system was dealt with there. A small calculation toolbox (Figure 3.1) was devised where the user can input three sets of parameters in order to calculate the resistance throughout the cables/harness of the system, those are Length (m) of the cables, the cross sectional area of the cables (m^2) and finally the Resistivity of the materials of which the cables are made of (Ω.m). When combined, and these values are inserted in Equation 3.3 for the Calculation of Resistance, the output represents the resistance (Ω) the cables exert on any given circuit that is being calculated. With that value of resistance, the Excel spreadsheet can calculate the voltage drop. Firstly, given the power of the load and the voltage of the system, we can extrapolate the current the appliance draws from it.

$$P = U * I \tag{3.1}$$

Then with the value for the resistance of the circuit previously calculated, and the current that is being drawn from it we can achieve a somewhat accurate value for V_{Drop}. Bearing in mind that the greater the resistance value of our cable harness the stronger the effect of V_{Drop} will be.

$$V_{Drop} = R * I \tag{3.2}$$

Battery Capacity [Ah]			
2520			
System Voltage (V)			
48			
Resistivity Copper (Ω.m)			
0.000000017			

	L(m)	A(mm^2)	Resistance(Ω)
WC	15	25	0.102
SALA	25	25	0.17
QUARTO	15	25	0.102
LAVAGENS	20	5	0.068
Cozinha	15	5	0.051

Figure 3.1: Excel Spreadsheet - Resistance calculation toolbox.

It is imperative that a calculation for V_{Drop} is present on the spreadsheet because it is a factor that gets exacerbated the more power a load draws from each respective circuit. The spreadsheet calculates the value for V_{Drop} automatically for each active load present in the circuit for any given time-slot, which the minimum by default is 15 minutes (ninety-six entries for a full 24 hour day cycle). Considering Equation 3.1, the bigger the power for each appliance is, the more current it will draw in a proportional fashion, and – as is the case in many 15 segment slots of any each hour – if more than one load is present at the same time in a circuit, the value for V_{Drop} is cumulative between each active load for the circuit in question. Consequently, the effect of V_{Drop} will increase the more loads there are being active in a circuit.

The Spreadsheet indicates with a red colored code on the cell in which the calculated value for V_{Drop} exceeds the defined threshold of 10% of the system voltage, so in the system the work proposes, the limit value any given load or multiple loads can achieve is 10% of 48V which is 4.8V (Figure 3.2).

LAVAGENS			
2000	Máquina de Lavar	2000	2000
2000	Máquina de Secar	2000	2000
1100	Ferro de engomar		
	Total [W]	4000	4000
	TOTAL Vdrop [V]	5.666666667	5.666667

Figure 3.2: Excel Spreadsheet - V_{Drop} calculation example.

That is the case in the “washing room” circuit where, in the Worst Case Consumption day, two 2000W appliances are working in the same time segment, for a total of 4000W. Considering the Length for the cables being 20m and a building code compliant cross sectional area of those cables to be 5mm^2 (due to amperage limitations on smaller section cables) that computes for a Resistance value of 0.068Ω, which then when computed on Equation 3.2 outputs a value of 5.66V for V_{Drop}. A value that exceeds the defined threshold of 4.8V. In this case the recommended action would be to not run the two appliances at the same time, to not risk damaging them due to insufficient voltage supplied.

This tool that allows the user to have a clear understating where there might occur problems regarding V_{Drop}, presents a clear benefit regarding the schedule organization for load management with an easy to use visual and quantitative interface that clearly indicates which two or more overlapping loads (or one if bigger than xW) exceed the System Limit. Retroactively and if planned beforehand, the user might use the information supplied by the spreadsheet to make alterations to the planned designed by altering the length, cross sectional area of the cable circuits, even the material in order to minimize the resistance of the cable circuit. All this whilst still maintaining code friendly values for the cross sectional area of cable. This further reinforces the benefits of a thorough planning regarding the loads the user plans on running at any given hour.

As previously mentioned in the spreadsheet, problems of V_{Drop} occur only in the early hours of the day if the user runs the two washing and drying machine loads simultaneously, which reflects on a value for V_{Drop} higher than the threshold. For a given circuit a maximum power value that does not incur in creating V_{Drop} problems can be calculated. As is, and still analyzing the washing machine circuit, the maximum wattage possible at any given moment in that system is approximately 3400W. That calculation can be done for any system the user plans on designing, if the case for a bigger margin in Wattage is needed and known beforehand. The user can define a separate circuit that meets their needs and adjust all the aforementioned parameters in order to give the circuit a wider margin for greater power loads such as heavy machinery or power tools. In what concerns the other time segments of the day – and still analyzing the worst case consumption – there are not any other V_{Drop} problems deriving from excessive power loads. The other two notable power draws occur in the kitchen circuit at 7:30 A.M. when the user runs the microwave and toaster appliances simultaneously (and the constant load that is the fridge running 24/7), which generates a 2600W power draw, resulting in a 2.7625V of V_{Drop}. That value is 57% of the 4.8V threshold for the system. And finally, at later hours of the day, in the Living Room circuit, where the television, media box, Lamp and Console generate a 531.1W power draw resulting in a value of V_{Drop} of 1.88098V, 39% of the threshold limit. All the other values for V_{Drop} present throughout the 24hour day cycle are smaller than these therefore manageable and a natural and expected component of any given electrical circuit (Mouheb et al. (2012)).

The Excel spreadsheet was devised with some core principles in mind, firstly it should be versatile and adjustable. No two systems are going to be alike, and alterations are expected since the beginning phase until when the system is deployed and running. Our daily behavior regarding energy consumption is not in a fixed state, as new technologies and habits are developed over time, therefore the spreadsheet must be ready to deal with those alterations in order to satisfy the user's needs. It is capable of having new loads added to whichever circuit the user plans on changing and at any given time, this allows the user a greater margin in the planning phase if the user intends to add more loads at a later point in life further on than the implementation date of the system, as long as they are planned and their Wattage known. In this case, the user would plan a system with a larger margin regarding capacity. Furthermore the spreadsheet must have a clear distinction between circuits and encourage building code compliant rules in what regards maximum number of outlets, separation between lighting circuits and dimensions of cable length. In what concerns the time segmentation of the spreadsheet, 15 minute intervals were selected as the more appropriate timing for adjusting to the user's natural household appliance usage.

It is detailed enough to capture the usage for appliances that run for 24 hours to smaller more punctual usages such as a dryer and a microwave. Obviously in the case of those latter appliances, the 15 minute usage time erss on the side of caution, but that only adds to the robustness of the system by giving a larger margin for capacity consumption. And for purposes of wattage and V_{Drop} calculation as the effect is immediate, it does not matter in which of the 15 minutes it manifests itself as long as the loads that are creating are active in one of those minutes (instants).

The spreadsheet presents the user with three tables to interact, two auxiliary ones for calculations, and the main table where loads are scrutinized and allotted to their respective time-slot of use. In the top left one, the user has three parameters for input, those are Battery Capacity (Ah), System Voltage (V) and finally Resistivity ($\Omega.m$) of the material out of which the electrical conduits of the circuit are made as can be seen on Figure 3.1. The first two deal with the scaling of the system, ideally these values after the user scrutinizes the loads, should be the same as those suggested by the software PVsyst, a topic that will be later on developed in this work. They also play a part in the last column of the main table and allow the user to have a ratio of consumed energy per capacity of the battery. These values when analyzed per circuit correspond to the percentage any given circuit is consuming out of the overall capacity of the battery. And when added together for every circuit of the system, they output a value that represents the overall consumption % of the total system capacity. This value should not exceed 25/30% of the total capacity, due to the fact that the spreadsheet does not deal with one rather crucial aspect of any off-grid system, which is its autonomy. Therefore, the maximum value of 25% of overall capacity is achieved in order to have 3 to 5 days of system autonomy. As of now the day with the worst-case consumption sits at 19% where the optimized consumption one rests at 9%. Given the fact that the more prominent loads that differ between those days are the loads in the Washing Room circuit, washing and drying machines respectively, there is a considerable margin in what regards to system autonomy, as the case in most households is that there are not more than 3 days where those appliances are active per week. This assumption is further reinforced by the PVsyst software where a value for 5 days of autonomy was selected. The second interactive box allows the user to input their desired electrical conduit length, the selected cross sectional area, and when computed with the value of Resistivity of the material which the cables are made, outputs the value of Resistance for the respective circuit the user is designing by means of Equation 3.3.

$$R = \frac{\rho \times \mathrm{L}}{A_{cs}} \tag{3.3}$$

This box is where the user is encouraged to carefully plan the dimensions of their circuit, the more accurate the values for Length, the more precise the values for Resistance will be. As was previously mentioned the value for Resistance is paramount in order to calculate an accurate value for V_{Drop}, that is the case in the construction of this spreadsheet. When the user makes changes to the aforementioned second table, the values of V_{Drop} are changed in the main one.

Finally there is the core of the spreadsheet, which is a massive table where all the different circuits the user is planning on creating for their system are laid out, inside of which all the loads are specified with

Cargas [W	Cargas [descrição]	0:00	0:15	0:30	0:45	1:00	1:15	22:45	23:00	23:15	23:30	23:45	TOTAL [h]	Total Energy [KWh]	Racio de energia consumo/bat [%]
VC															
1500	Secador												0.25	0.375	0.003100198
6	Carregador Escova/máq. Barbea	6	6	6	6	6	6						4.25	0.0255	0.000210813
													0	0	0
													0	0	0
	Total [W]	6	6	6	6	6	6	0	0	0	0	0		0	
	TOTAL V_{drop} [V]	0.01275	0.01275	0.0128	0.0128	0.0128	0.0128	0	0	0	0	0		0	
SALA															0
140	TV							140	140	140	140	140	7	0.98	0.008101852
17.1	Box							17.1	17.1	17.1	17.1	17.1	7	0.1197	0.000989583
0	TV standby	0	0	0	0	0	0						17	0	0
0	Box standby	0	0	0	0	0	0						17	0	0
350	Consola							350	350	350	350	350	2	0.7	0.005787037
24	Candeeiro							24	24	24	24	24	9	0.216	0.001785714
	Total [W]	0	0	0	0	0	0	531.1	531.1	531.1	531.1	531.1			
	TOTAL V_{drop} [V]	0	0	0	0	0	0	1.881	1.881	1.881	1.881	1.881			
QUARTO															
14	Candeeiro							14	14	14	14	14	5	0.07	0.000578704
20	Carregador Tlm	20	20	20	20	20	20						7	0.14	0.001157407
0.1	Despertador/Rádio	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	24	0.0024	1.98413E-05
													0	0	0
													0	0	0
													0	0	0
	Total [W]	20.1	20.1	20.1	20.1	20.1	20.1	14.1	14.1	14.1	14.1	14.1			
	TOTAL V_{drop} [V]	0.0427125	0.04271	0.0427	0.0427	0.0427	0.0427	0.03	0.03	0.03	0.03	0.03			
LAVAGENS															
0	Máquina de Lavar												0	0	0
0	Máquina de Secar												0	0	0
1100	Ferro de engomar												0.75	0.825	0.006820437
													0	0	0
	Total [W]	0	0	0	0	0	0	0	0	0	0	0			
	TOTAL V_{drop} [V]	0	0	0	0	0	0	0	0	0	0	0			
COZINHA													0		
1200	Microwave												0.75	0.9	0.007440476
1200	Torradeira												0.5	0.6	0.004960317
1200	Máquina de Lavar							1200	1200				1.5	1.8	0.014880952
250	Varinha Mágica												0.25	0.0625	0.0005167
200	Fridge	200	200	200	200	200	200	200	200	200	200	200	24	4.8	0.03968254
													0	0	0
													0	0	0
	Total [W]	200	200	200	200	200	200	1400	1400	200	200	200			
	TOTAL V_{drop} [V]	0.2125	0.2125	0.2125	0.2125	0.2125	0.2125	1.4875	1.4875	0.2125	0.2125	0.2125			
														11.9311	**0.098636739**
ILUMINAÇ	**TOTAL/hora**	226.1	226.1	226.1	226.1	226.1	226.1	1980.2	1980.2	780.2	780.2	780.2			
35	Lâmpadas LED							35	35	35	35	35	9	0.315	0.002604167

Figure 3.3: Excel Spreadsheet - Main loads table.

their respective average power consumption, description and through the aid of a visual colored coded system, their allotted usage time is laid out throughout the 24 hours of a day in 15 minute segments, (Figure 3.3). That results in ninety-six 15 minute entries, for all the loads allowing the user to specify in which hour of the day they are planning on using them. A light green colored cell with the power consumption value for the respective appliance means that the load is active for that respective time-slot, contrarily a grayed out cell without any value means that the load is not active for that respective time-slot. For that, the user adds the value previously specified for each load to the cells corresponding to the desired time-slots, and then the spreadsheet can work those values in order to output different kinds of data. Firstly those values of power are added in the line “Total[W] “ for each time-slot, this is fundamental for calculating V_{Drop} at any given time and to have the overall consumption of power in a single time-slot. Later on those values are also added for the entirety of the ninety-six time-slots, and they represent the total power a circuit consumes on that day, and when combined with the automatic calculation for hours that a load is active “TOTAL [h]” the user is presented with the column for energy consumption “Total energy [kWh]”.

The “Total energy [kWh]” by itself is a good indicator for what size a PV off-grid system should be, further on these values - the sum of them more precisely - need to be similar and within a small margin of error of those that are provided by the PVsyst software, where there will be also a component to scrutinize the loads by time usage. However, the software tool for that task is not as detailed as the spreadsheet, so some fluctuation regarding the values is to be expected, but still under 5-10%. The closer the value, the stronger the confidence in the sizing suggested by the software will be. In the main table, the user will also have the chance to specify passive or “stand-by” loads. For that the user should add to the “Loads (description)” column which loads they normally would leave on stand-by. In an off-grid system where capacity is limited, all consumption counts, and for that the user is advised to indicate which loads they normally leave on stand-by. In the spreadsheet those loads will be color coded Pink and only be active when the appliance is not being used. For instance in the “living room” circuit that is the case with both the television and the media box appliances, which are loads that have a consumption when they are not being used, 5 and 16.6 Watts respectively. And those loads are only active in the time-slots where the appliance is not, therefore there must be a total match inversely between the appliance in the “Loads (description)” column and their stand-by counterpart in that same column. What that does is present the user with accurate values for stand-by consumption and encourage behaviour adjustment regarding those loads (Huber et al. (2018)), (Kaboli et al. (2016)).

That is why an ”Optimized consumption” spreadsheet exists. The idea behind is that small however many passive loads like that can have a large impact on the sizing of the system. The discrepancy between those two spreadsheets is what is expected to encourage behavioural change in the user. Bearing in mind that the changes between the two is the exception of the heavy loads from the “Washing Room“ circuit and the stand by consumption on the “living room” circuit the change in energy consumption is 11.36 kWh, which is almost what the whole system consumes on an “optimized consumption day”, that is 11.9311 kWh. That difference is highlighted by a simple mechanism on the spreadsheet that allows the user to nullify a load by defining its value to be 0 (color coded red) on the “Cargas [W]” column. Therefore the user is also presented with a chance to individually see the impact of each respective load in the overall system (notably on the total for the “Total Energy [kWh]” column), after that load is specified in the spreadsheet, which is an helpful feature.

Visually that difference can be analyzed with the help of of the graph in Figure 3.4, present on the ”Optimized consumption” spreadsheet, where both the consumption per hour for the Worst Case and the optimized consumption are compared.

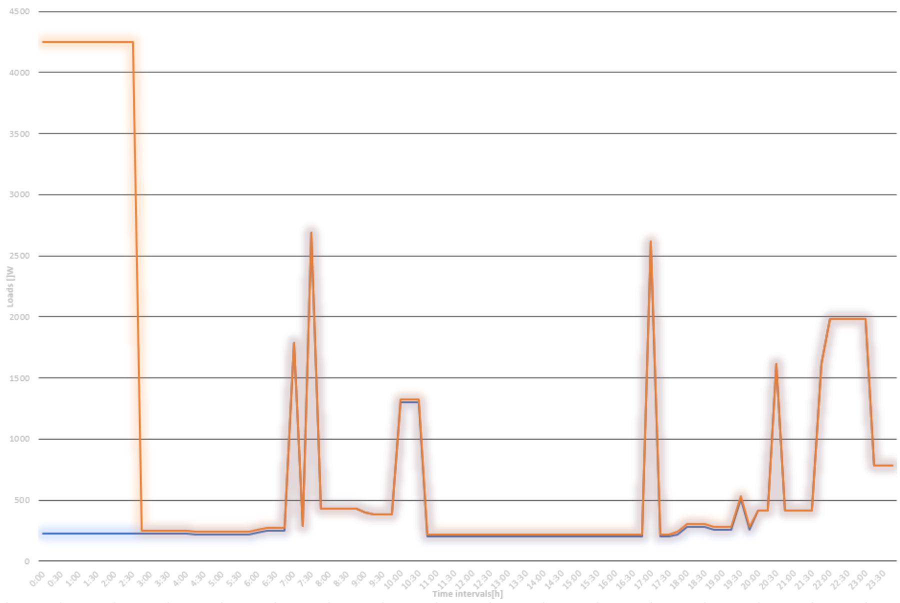

Figure 3.4: Excel Spreadsheet - Hourly profile distribution of ”optimized consumption” vs ”worst-case consumption”.

3.2 PVsyst® software

The second part of the methodology for this work was made with recourse to the system designer software PVsyst® designed by webgenève. This software was chosen due to its ability to design an off-grid PV system that allows its user to input significant parameters deemed important for the validity of this work. The software in and of itself is a rather complex tool that works significant amounts of different data in order to design/propose a viable system that fits the user's needs. To do that, a linear construction and assembly of parameters needs to be done, each step providing more information to the software.

3.2.1 System design

The first step in designing a system that works with the Sun being its primary source of energy is the system's location. The site location of a proposed off-grid system contains two parameters crucial to calculate the Sun's position throughout the year, those are Latitude and Longitude, which are crucial to positioning equations. These equations compute different factors such as Incidence-angle and Irradiance. With the system location the software can then fetch a Meteo file from different databases (and can also convert other meterological databases to a format compatible with the software). This is important as it provides two crucial parameters which are : Horizontal Global Irradiance and Ambient temperature. The meteofile can also provide two additional parameters Horizontal Diffuse Irradiance and Wind Velocity, both optional for the system design. The first can be calculated through a model and the latter is used for modelling temperature calculations. These 4 parameters come as an hourly database.

Continuing forth with the design, the user is required to specify some extra values on the Project Settings phase such as Albedo that has a common value of 0.2 but can be changed depending on site characteristics and the software offers a table representing those changes, array maximum voltage which for the project in this work was set at 1000V, μVOC derived from the one diode model, and finally some operating thresholds regarding Temperature as seen in Figure 3.5.

Note that a solar panels's efficiency is inversely dependent on temperature, so as temperature rises, the panel's efficiency decreases (Chandrasiri (2017)). The next step is defining the plane orientation for the panel array. The software is capable of multiple orientations, tracking (both horizontal and vertical) as well as a fixed position and one where there occurs a seasonal tilt adjustment, which for ease of use in most cases was the one defined for this work.

Given that a core principle for this work is proving accessibility and viability of this systems for common households, creating a system that would have a tracking mount would increase the initial investment on top of not being able to be implemented in every domestic scenario with the same ease as a simple mount would in what concerns the placement of the solar panels. The vast majority of common household roofs is not prepared to receive such a heavy load of a tracking device that sometimes can weigh up to 2000 kilograms. Furthermore, when accessing available area for ground deployment of a tracking system as is the norm, not all households have the available area on their property to do so.

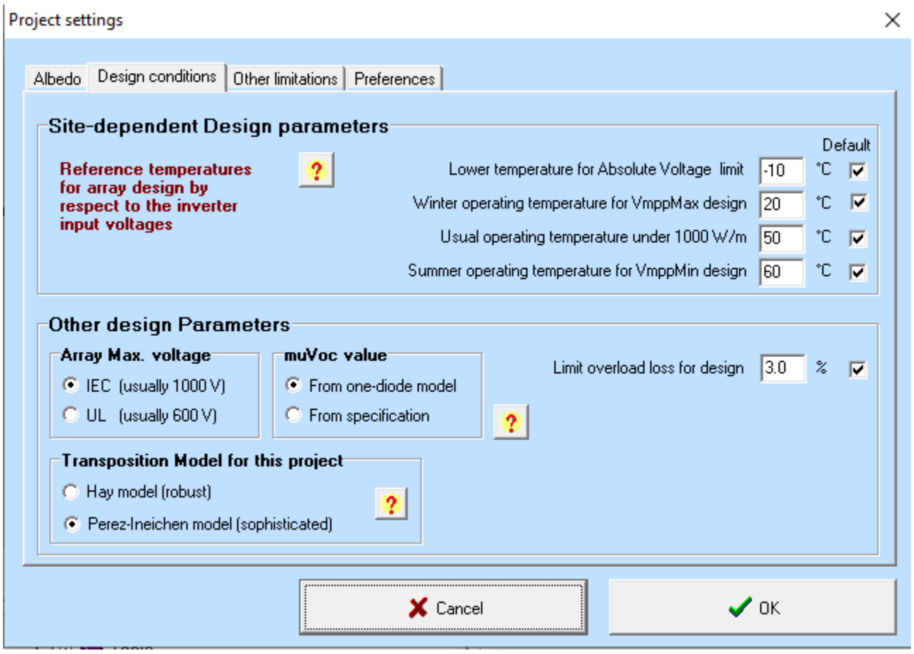

Figure 3.5: PVsyst software - Project settings, Design conditions.

However if that is the case, it is advised if the investment cost does not affect the viability of purchasing the system. The use of a seasonal adjustment provides benefits due to fact that adjusting the incident radiation on a panel provides an increase in efficiency (Michalakopoulos and Perraki (2014)).

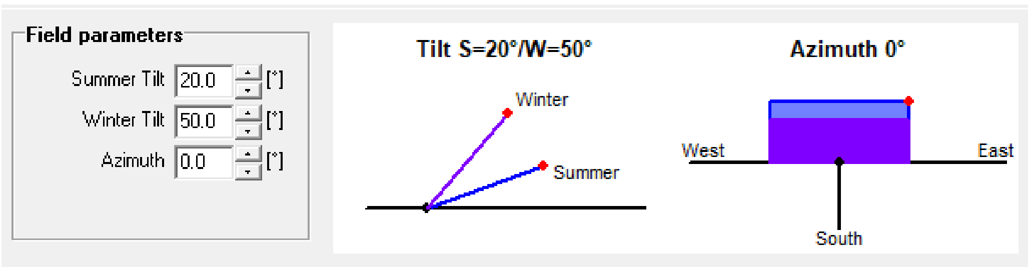

Figure 3.6: PVsyst software - Project design, Field parameters.

The PVsyst software can also implement within its simulation the use of concentrating systems, however that is beyond the scope of this work.

Moving forward to the next mandatory input parameter, the software presents the user with a toolbox where they will define the number of loads (appliances) to be active during the day, their power rating [Watt] and finally the number of hours that the user is planning on having them active. This is the part of the software that is replicated and more scrutinized in the Excel spreadsheet. It is paramount that the information is the most similar it can be between the software PVsyst and the Excel spreadsheet in order to have a good and corroborated match in the results of the simulation. For that the user can specify which hours of the day the loads they defined will be active through the use of a visual tool similar to a clock as can be seen in Figure 3.7.

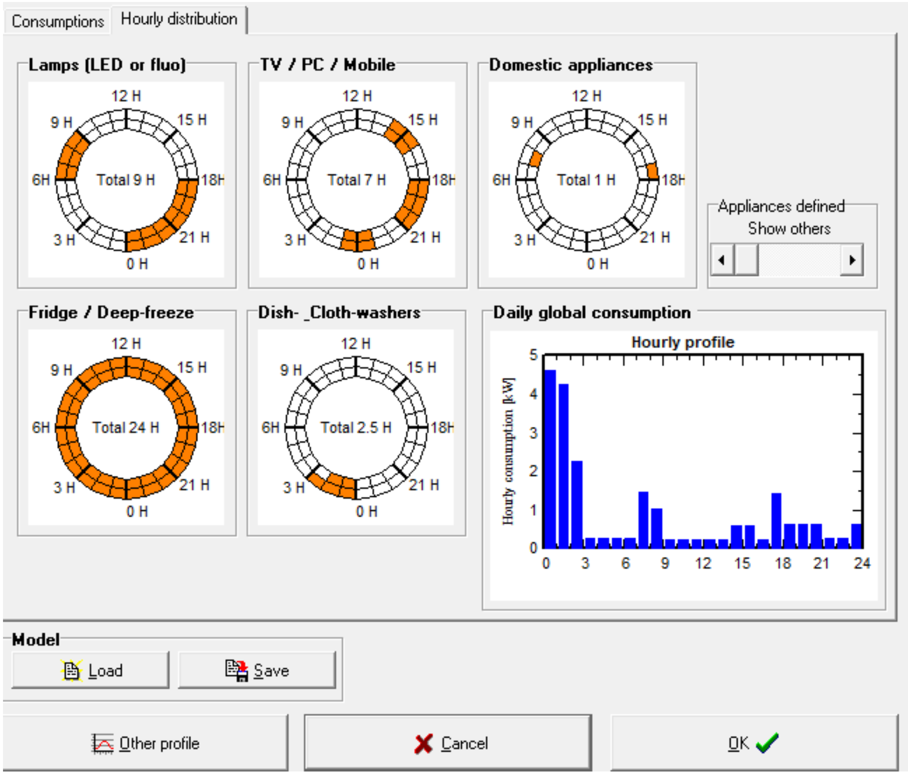

Figure 3.7: PVsyst software - Hourly profile distribution.

3.2.2 Sizing

Comparing the Daily global consumption graphic with the one from the Excel spreadsheet, there is an near identical match, which should not be hard to achieve if the user is careful with the information supplied to the software. Finally, after the user defines all the required parameters for this stage, the software supplies the values for Total daily Energy 21462 Wh/day and Monthly Energy 643.9kWh/ month as can be seen on Table 4.3.

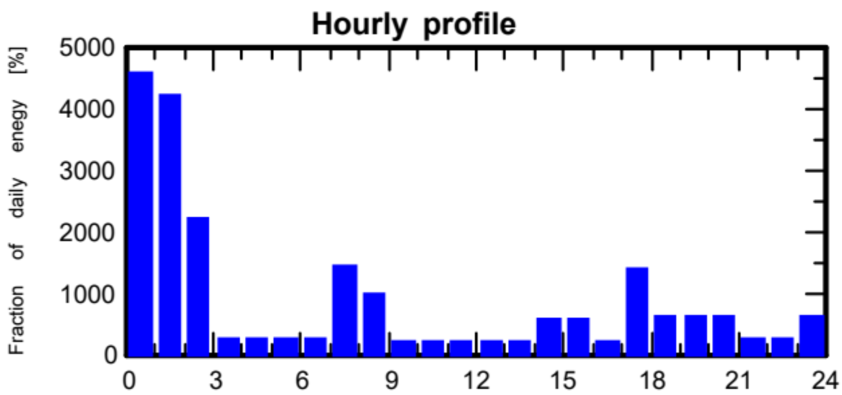

Figure 3.8: PVsyst software - User's needs and Hourly profile.

As previously mentioned, there was a 4.8% deviation between the two Final consumptions due to the fact that loads within the Excel environment were easier to specify than on the PVsyst software. That margin was taken into consideration and found to be within an acceptable margin of error, and that the deviation in consumption would not affect the final results the simulation would yield. Note that the PVsyst software is also able to work with different pre-made templates of household consumption to more easily access the effect of different load profiles according to the possible needs of the user. A template such as a fixed constant Load, or even a more detailed daily profile can be uploaded/constructed to the software. Worth mentioning that the toolbox for the definition of household consumption has a parameter dedicated to stand-by consumption by non-active loads, one that also should match the values that were defined on the Excel spreadsheet.

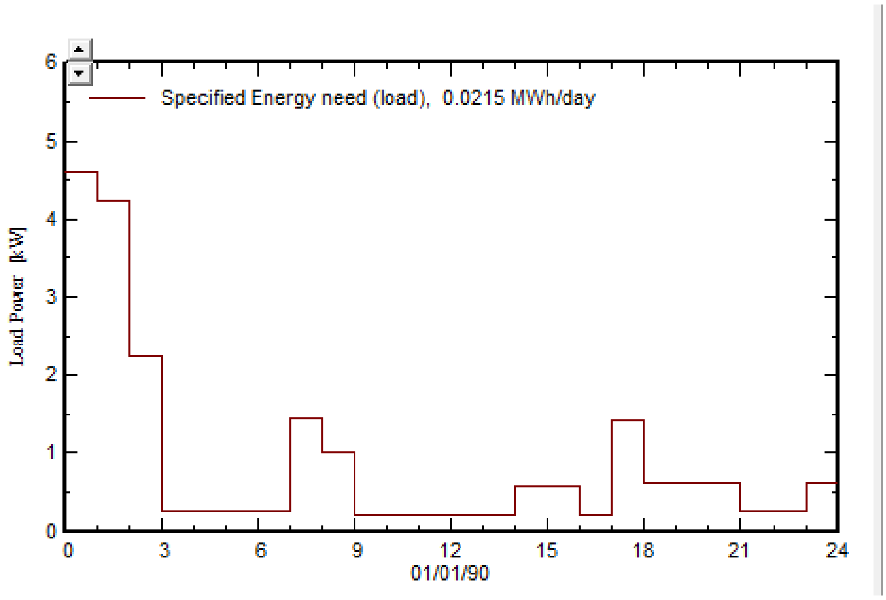

Figure 3.9: PVsyst software - Specified Energy needs graph.

For the system itself, the PVsyst software has a highly detailed toolbox that allows the user to fine-tune most of the aspects of an off-grid PV system. First and foremost a Pre-sizing suggestion work space shows three major parameters: accepted LOL%, autonomy days and battery voltage. The LOL probability or Loss of Load is the probabilistic value that the user's needs that were defined in a previous step cannot be met. It is calculated as a fraction of time when the battery pack's charge [SOC] is below the threshold of minimum charge that system will define. For a Lithium battery pack the value was defined to be between 20 and 25% (Zhang et al. (2018)).

The autonomy was defined to be 5 days, this value represents the number of days the system can function and supply the user's needs whilst not receiving charge from the solar panels. Keeping in mind that the values for the "Worst case simulation" have the greatest load demand out of all the simulations made, this corresponds to the Excel spreadsheet for the worst-case consumption day, the one that has both washing machines running. Therefore, it is predictable that the sizing for this system to be larger to accommodate that heavy power demand.

Finally the user is prompted to define the battery voltage. Although the software in its manual suggests 12 to 24V for house appliances and domestic use, in this work it was chosen a value of 48V due to several reasons, the first being that one of the objectives of this work is to prove an alternative to energy supply for common households, which have common appliances i.e. ones with greater power demand than 1000W such as normal washing machines microwaves and the like, and the greater the power demand is the greater the potential for V_{Drop} to occur beyond safe values for the system, hindering it by default due to poor planning. A design flaw that is easily fixed by raising the tension at which the battery pack operates. Secondly, the system having a battery bank with greater Voltage level allows the system to have a greater cable length, also preventing V_{Drop} problems due to small electrical conduit length, which increases resistance and therefore potentiates the creation of a drop of tension between battery pack and user end appliances. To conclude the pre-sizing suggestions, the software, based on the defined aforementioned parameters suggests a value for overall capacity of 2466[Ah] and PV power 5.26 [kWp].

The next step was selecting the models of lithium batteries that would be used for the system. The software allows to choose batteries with different technologies, from Lead-Acid to Lithium-ion. In this work we choose the Lithium-ion given their advantage in usability regarding state of charge, life cycles, and overall benefits of being paired to a solar generator to fulfill the storage part of a system. The selected model was: LFP-CB 25.6V / 180Ah which has the following characteristics seen in Figure 3.10.

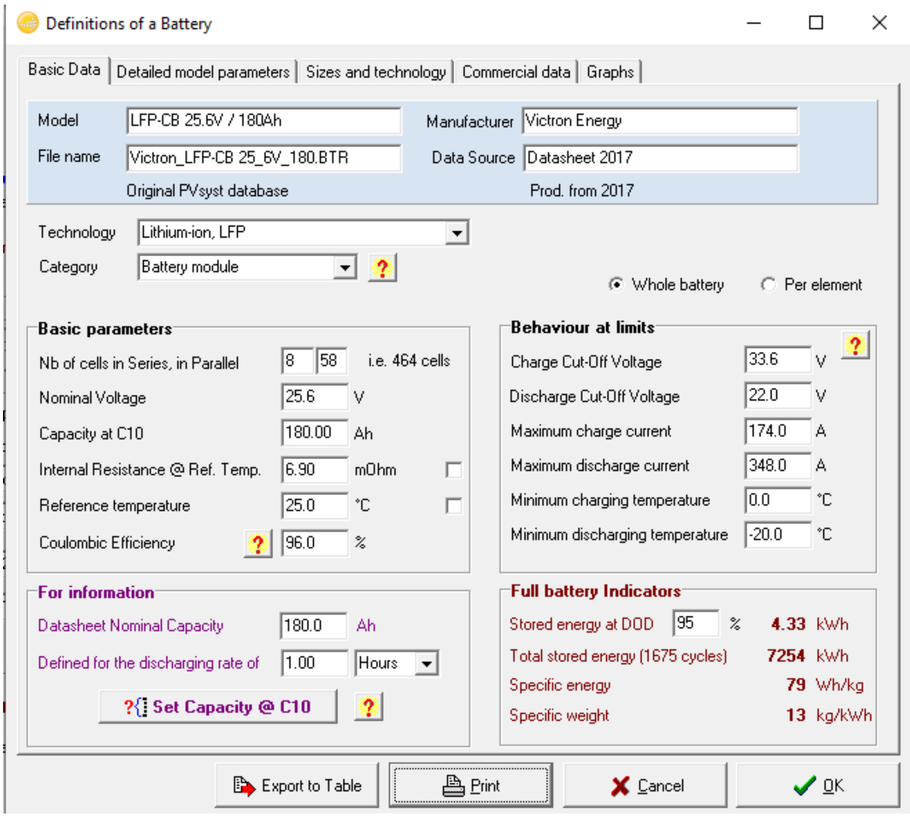

Figure 3.10: PVsyst software - Storage definitions.

The model was selected given its high capacity of 180Ah and operating voltage of 25.6V. A base operating voltage of that value means that to achieve the desired 48V of system operating voltage the user would only need to put two modules in series and the remaining ones in parallel, thus maximizing capacity. The final number of modules was 16.

For the PV modules, a generic 250 Wp 25V (60 cells) model was selected. Since the software was operating under the assumption that the worst case load would be the norm, instead of following the suggestion for planned power of 5.2 kWp, in this step a limitation in occupied area was the chosen approach. Keeping in line with what was previously mentioned regarding the goals and applicability of this work, a limit of 26m^2 was determined, it is well within the limit of surface area for normal south facing roofs. Note that with current and in development technology, the roof is not the only alternative for panel placement, solutions with vertical adjustable panels already exist and maximize the vertical facade of a building (Orhon (2016)), as well as PV tiles. With the area constraint, the software suggests 4 modules in series with a total of 4 strings, a total of 16 panels with an occupational area of 26m^2 culminating on an array with 4.0kWp nominal power @STC. The panel's characteristics can be analyzed below on Figure 3.11.

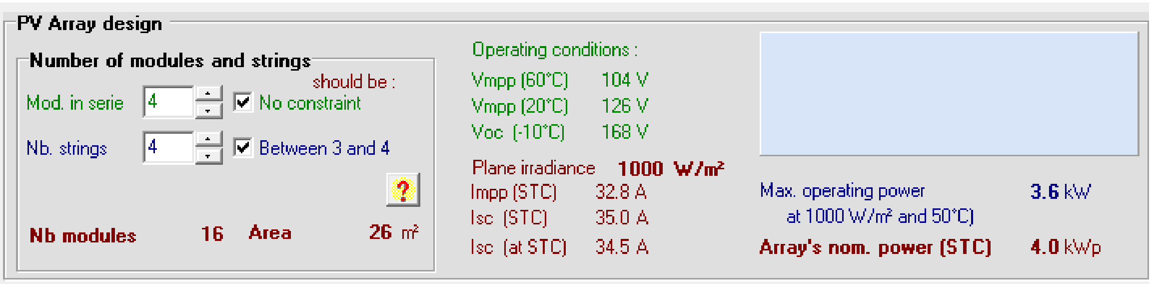

Figure 3.11: PVsyst software - PV Array design.

The final mandatory input parameters are the detailed losses. As is the case with any electrical system or component, electrical losses are prone to happen, the best that can be done, is minimizing them and planning with those losses taken into account. The results of the software's calculation regarding losses will be discussed in the next chapter. Here the losses defined were Thermal, Ohmic and the ones pertaining to the quality and orientation of the panel itself.

Chapter 4

Results

In the results section of this work, three simulations performed on the software PVsyst will be scrutinized and discussed. These simulations have the same parameters that were explained in the previous chapter Methodology and have the same input data regarding loads that was present in the excel spreadsheet. The three simulations are the ones for the “worst case consumption”, the “optimized consumption” and finally a third one for a “monthly approximation” of load demand. The latter was made due to the fact that the software can’t accurately process a 7-day week cycle where the loads vary from day to day, namely due to the difference caused by the usage of the appliances in the “Washing Room “circuit. The approximation made was that for any given 7 day week cycle, the appliances would operate no more and no less than 3 days per week, and this approximation was made as an average approach based on personal experience.

4.1 Simulations overview

The first simulation to be analyzed is the one for the worst case consumption. As is expected the strain the heavier load demand exerts on the system is higher due to the simulation interpreting the day in which all the heavy loads from the “Washing Room” circuit to be the norm. This causes the simulation to suggest and create a system in which additional power supply and capacity is needed. All simulations are going to be analyzed in the same way in order to facilitate comparison between the three. The report the software provides the user is organized by sections, the first one logically being the geographical and meteorological characteristics of the system itself.

Moving along with the report’s structure, the system type is Stand-alone system as is the goal of this work, however note that the possibility of installing a back-up generator is supported as can be seen on the system schematic on Figure 4.1.

The transposition model used by the software for its simulation is the Perez model for radiation on slopped/tilted surfaces and not for example the Hay, HDKR or Liu Jordan (Perez et al. (1992)). It is called transposition model because it is the calculation of incident irradiance based off of horizontal irradiance data. This model proves to more useful as it takes hourly data sequences into account, however this

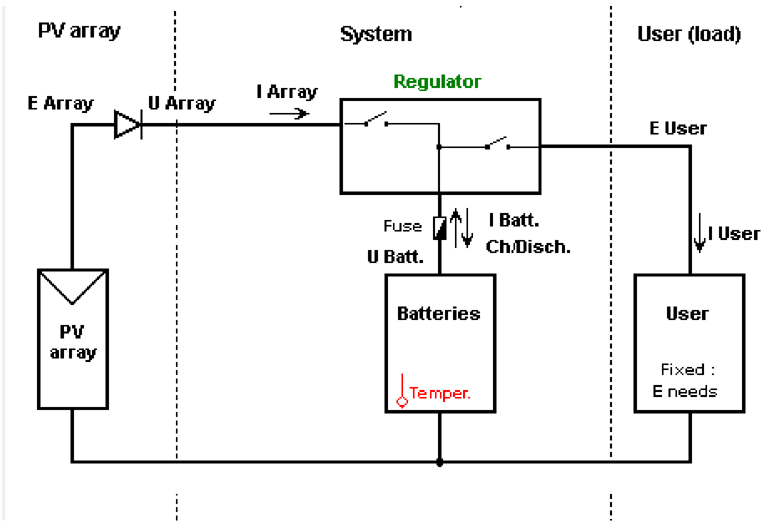

Figure 4.1: PVsyst software - System schematic.

model requires well measured horizontal data (Perez et al. (1990)). The diffuse component is obtained via Meteonorm and it is paramount for the accuracy of the transposition, therefore using measured values for the diffuse component such as the ones from Meteonorm improves accuracy. Furthermore, the Perez-Ineichen model subdivides the diffuse component of irradiance in three separate components, isotropic, circumsolar and "horizon band", the latter being the differentiating factor between this model's diffuse component and Hay's model. While comparing Hay and Perez-Ineichen models, the latter is more accurate in a range from 1.8-2.2% regarding mean errors, however their RMSE are similar. One side note of this model is that, depending on plane orientation, its values for yearly averages of irradiance are slightly higher than the one's from the Hay model, but not greater than 2% (PVsyst webgeneve).

Moving onward to the characteristics of the chosen panels, the simulation was done using a generic sample Poly 250Wp with N_s=60 cells. The number of suggested panels for the "worst case" system was 20, with the following disposition of 4 strings in parallel with 5 modules in series. The unit nominal power of each panel is 250 Wp and for the total array described the global power is 5000Wp (4474 Wp at operating conditions – 50ºC).

The array's operating characteristics (at 50ºC) are U_{MP} 136V, I_{MP} 33A. Note that for a larger system like this a common solar MPPT charger with 100V 50A limits is not advisable given that the output voltage is greater than the threshold, that however is not the case for the other simulations where a common solar MPPT charger (100v – 50A) more than capable of handling the respective arrays.

Regarding the PV array loss factors, they are all expected to be similar if not the same. Starting with the Thermal Loss factor μC that is a constant characteristic thus the same across all simulations, it takes a value of 20.0 W/m^{2}K, and the same situation occurs for a Thermal loss factor due to wind, which is negligible and defined to be zero. Where there is an expected change between simulations is the global resistance of the array itself. The simulation corroborates that, and it is only logical given that the extra cable length and added panels increase global resistance due to the addition of extra cable length and components. For the worst-case simulation (where there are more panels in the array) the value is slightly higher, sitting at 70mΩ (the same for the "monthly approximation simulation") versus the value for the other simulation where it is 46mΩ. This is such a small difference that when comparing V_{Drop} across all three simulations, the value remains the same, 0.7V. Given this we start to see the similarities between simulations, and what changes from one to another, as the simulation for the worst case assumes a heavier daily demand than what is in fact actually needed, the software counteracts that by injecting more power in the form of eight extra panels to the array. The supplied current is the same, only the operating voltage is higher in this simulation and the “monthly approximation simulation” than the ”optimized consumption simulation”, 136V to the other 82V in the latter one. The fact is that the system interprets the heavier power need in these simulations as a necessity of higher voltage and supplied power. An MPPT charging the batteries at a lower operating voltage might struggle to even reach float mode for charging the batteries in the hours where the heavier power demand takes place, if the SOC of the battery pack was not above a certain threshold, thus the higher operating voltage and number of panels are employed as a way to circumvent that scenario. Finally, to conclude the loss factors, the Wiring Ohmic losses represent a fraction of 1.5% at STC, the Serie Diode Loss 0.6% loss at STC, an arbitrary Module Quality Loss represents -0.8%, and to finalize the module and strings miss-match losses 2.5% (fixed voltage) and 0.10% respectively.

One direct consequence of having more panels suggested for the “worst-case simulation” and the “monthly approximation simulation” was the increase in panel area. For this factor the software allows to hard-cap the value, and the limits used were 30m^2 and 20m^2 for the worst case/ monthly approximation simulations and optimized consumption respectively. The module area was 32.5m^2 and 19.5m^2 and the effective cell area for the 20 and 12 panels was 29.2m^2 and 17.5m^2. These were the values for the simulation to compute efficiency as per equation 4.1.

$$\eta = \frac{\mathrm{P}_{max}}{A \times G} \tag{4.1}$$

The next part in the analysis of the simulation is the Battery Pack Characteristics. Here there is also a difference between the “worst-case” simulation and the optimized consumption/monthly approximation simulations. However instead of being caused by lack of supplied power it is caused by lack of capacity as the system requires a bulkier battery pack in order to accommodate the heavier consumption of the “worst-case” simulation. If the system was undersized or sized in the same manner as the other two simulations, an autonomy of 5 days would not be achievable. Since that parameter takes precedence, the software increases the battery pack size.

The model selected was Victron Energy’s LiFePO4 battery 25.6V 180Ah battery module. The technology of Lithium Iron Phosphate was selected due to various reasons, namely: high energy, power density, low discharge rate and overall usage of available capacity. These LiFePo4 batteries are able to be charged at a more efficient rate than their competitors and the tendency is to increase that efficiency as new methods are developed regarding charging of these types of batteries (Yin-Quan (2011)). When comparing this battery technology to Lead-Acid for example, the most practical and notable difference the user would find is the greater margin in usage they can extract per cycle. In a normal Lead-Acid battery, dropping below 50% SOC increases greatly the possibility of damage to the battery whereas in a LiFePO4 type battery, SOC could drop to 5-15% SOC without significant hinderance. This is an advantage that in terms of capacity per dollar justifies the investment in this type of technology, and in what concerns capacity, there is still progress and margin for improvement (Ahsan et al. (2020)).

Regarding the lifespan of these batteries , there is some divergence on the results, while most paper's claim around 10 years, the fact is that it has not passed that amount of time since the inception of this technology so that value is an estimate derived of cycle stress and durability tests (Zhang et al. (2018)). And when researching literature for this work, the emphasis of research appears to be on storage conditions, as those have the most effect on the quality and durability of these batteries (Molaeimanesh et al. (2021)). In the simulation a mean value of 20ºC was used to compute ageing. The software shares the following estimate based on a 10ºC increment in temperature and its effect on "static" battery life.

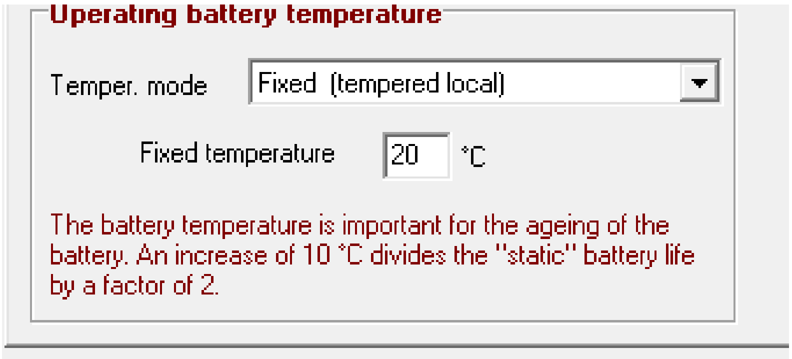

Figure 4.2: PVsyst software - Operating Battery temperature.

To achieve the desired 48V of system voltage two batteries would always be connected in series in all simulations, the only difference as was mentioned before, was capacity, for the goal of maximizing it the Battery pack was assembled with two batteries in series and ten in parallel to add the individual capacity of 180Ah for the "worst-case" simulation. This totals a global nominal capacity of 1800Ah. The difference to the other two simulations, is the under sizing of the battery pack by batteries, for a total of 16 batteries with a global nominal capacity of 1440Ah. Derived from this difference there is a shift in total weigh, from 1100kg to 880kg. This reflects also the change in stored energy from 73.7kWh to 59 kWh at 80% DOD as we can see in the Figures 3.2 and 3.3, among all the differences in simulations.

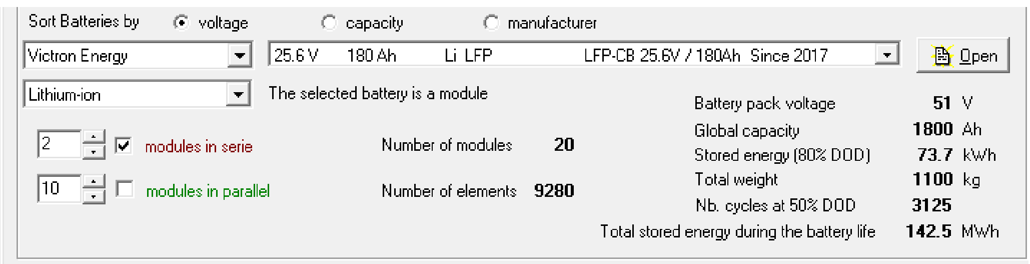

Figure 4.3: PVsyst software - "Worst-case simulation" battery pack characteristics".

The Controller selected was a Universal controller with a DC-DC converter. The goal of the system is that it runs on its entirety with DC current however there is always the possibility placing a capable inverter in this phase, or some punctual inverters for loads that must run on AC. The values for appliances

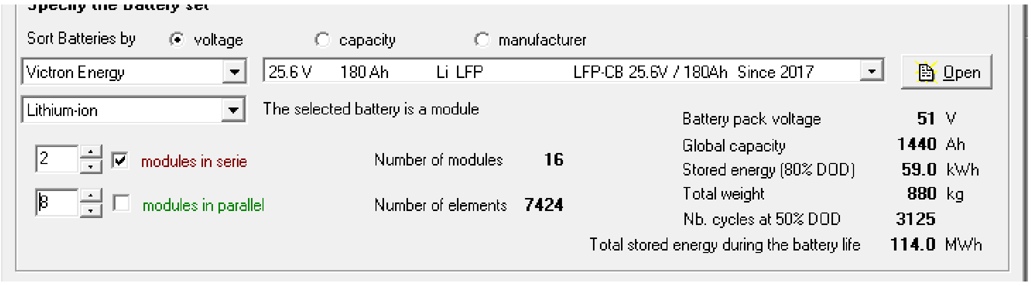

Figure 4.4: PVsyst software - ”Optimized Consumption”/”Monthly Aproximation” simulation battery pack characteristics .

that were computed for both the simulations and excel worksheet were values commonly found on those respective versions of DC run appliances. The Maxi and EURO efficiencies for the converter were 97% and 95% respectively, and as the controller is common to all three simulations there was no difference on those values.

In the user’s needs part of the simulations report is where the core differences that reflect most of the changes between simulations are present. These differences in loads have a direct influence in the sizing of the system and in any user case scenario these will vary greatly depending on each user’s specific needs. As was previously mentioned the “worst case” simulation is the one where the software interprets a daily load with both appliances in the “washing room circuit” being used. The reasoning for that was already explained however a graphical analysis clearly shows the magnitude of the use of those appliances – look in the leftmost part of the graph at the early hours of the day – makes on the daily hourly profile graph (Figure 4.5).

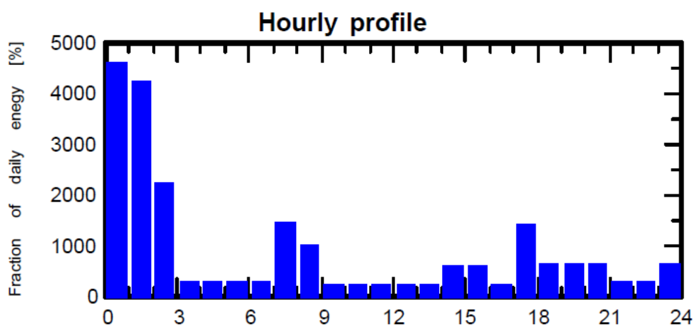

Figure 4.5: PVsyst software - Daily hourly profile graph for the ”Worst-case simulation”.

The report indicates that with this being the daily profile, the average energy consumption throughout the year would be 21.5 kWh/day. That value is calculated based off of the energy consumption made by the appliances that replicate the ones in the Excel spreadsheet – for purposes of validation vice versa - and can be seen in Table 4.1.

The global consumption of energy throughout the year for this system is 7834 kWh/year.

These values contrast greatly with the ones from the “optimized consumption”. Remember that these are the utmost extremes in what regards load demand and strain on the system, in the “worst case sim-

Table 4.1: Annual load values and description "Worst-Case simulation".

	Number	Power	Use	Energy
Lamps (LED or fluo)	7	5 W/lamp	9 h/day	315 Wh/day
TV / PC / Mobile	3	120 W/app	7 h/day	2520 Wh/day
Domestic appliances	2	1200 W/app	1 h/day	2400 Wh/day
Fridge / Deep-freeze	1		24 Wh/day	4800 Wh/day
Dish & Cloth Washers	2		3 Wh/day	10000 Wh/day
Hair Dryer	1	1500 W tot	1 h/day	750 Wh/day
Chargers	1	26 W tot	6 h/day	156 Wh/day
Stand-by consumers			24 h/day	521 Wh/day
Total daily energy				21462 Wh/day

ulation" PVsyst assumes worst possible consumption for each day, and in the "optimized consumption" the software designs the system with the load demand being the smallest possible. Naturally the values from the latter simulation are vastly smaller in comparison. For the average daily consumption that value is almost half of the one from the "worst case simulation" sitting at 10.941 kWh/day. Directly correlated with that, the same applies to the global consumption throughout the year, which is 3993 kWh/year. Below is the annual values for the loads and the hourly profile (bearing in mind the scale change between this graph and the graph for the "worst-case simulation").

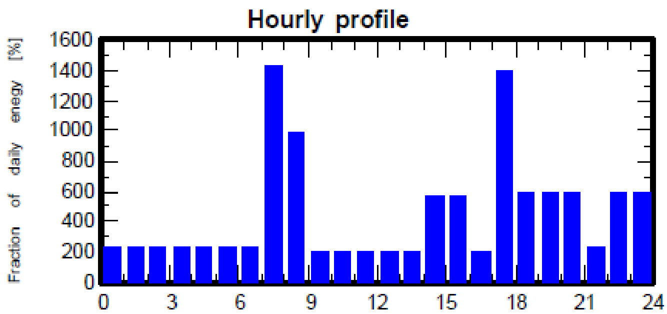

Figure 4.6: PVsyst software - Daily hourly profile graph for the "Optimized consumption simulation".

Table 4.2: Annual load values and description "Optimized consumption simulation".

	Number	Power	Use	Energy
Lamps (LED or fluo)	7	5 W/lamp	9 h/day	315 Wh/day
TV / PC / Mobile	3	120 W/app	7 h/day	2520 Wh/day
Domestic appliances	2	1200 W/app	1 h/day	2400 Wh/day
Fridge / Deep-freeze	1		24 Wh/day	4800 Wh/day
Hair Dryer	1	1500 W tot	1 h/day	750 Wh/day
Chargers	1	26 W tot	6 h/day	156 Wh/day
Stand-by consumers			24 h/day	521 Wh/day
Total daily energy				10941 Wh/day

A rather crucial detail is the fact that only the “optimized consumption simulation” has an excess of unused energy for its system dimension, both the other simulations are sized to a “tight fit” and have their margin for excess energy greatly reduced, however for this simulation an excess of 687 kWh/year remain as unused energy.

4.2 Report final results

The next results to be analyzed are the Normalized Energy Productions of the system and the comparison between Performance Ratio and Solar Fraction. For that we need to define some parameters first according to the Performance Index that is now part of the IEC EN 61724 norm. Beginning with Yr which is the Reference system yield, It is defined by an ideal array yield based on the Pnon and without the effects of losses. The Array Yield Ya, that represents the daily output of energy the system outputs in reference to P_{nom} [kWh/KWp/day]. Collection Loss Lc which is calculated by subtracting the Reference system yield with the array yield Lc = Yr – Ya, represents the array losses including thermal, wiring , module quality and mismatch, shading, dirt and all other inefficiencies regarding the PV array part of the system. The system yield Yf [kWh/KWp/day] is the daily useful energy that is supplied to the user. With those values, Ls which is the System losses can be defined by Ls = Ya – Yf, and this parameter includes the battery inefficiencies. Unused energy (Lu) is the energy that might be available at the array output but can not be used do to system saturation, i.e. full battery or insufficient load of the designed DC system. Finally the Performance Ratio PR = Yf / Yr is the ratio between System Yield and Reference system yield @STC and it represents the global system efficiency pertaining to P_{nom} and incident energy. And contrarily to specific energy production [kWh/kWp/year], PR is not dependent on meteorological input and plane orientation, which allows easy comparison between systems in different locations and with different orientations (PVsyst webgeneve).

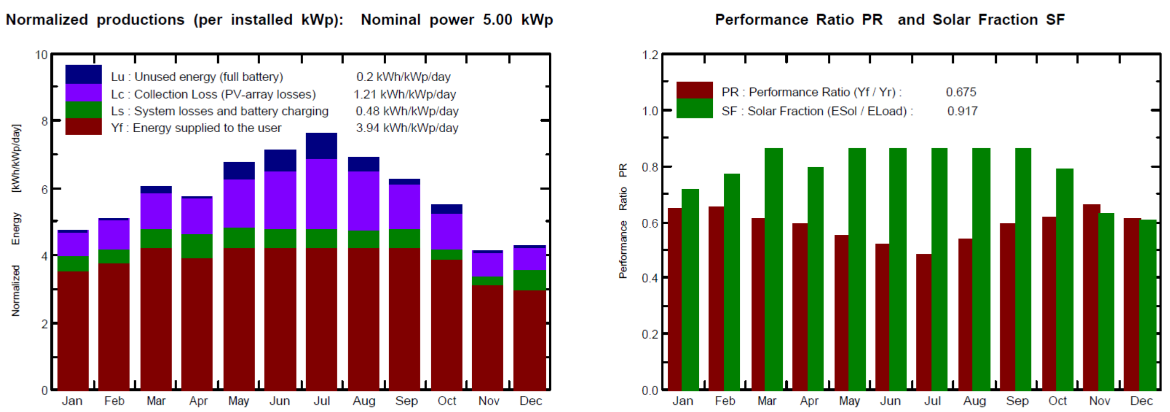

Figure 4.7: PVsyst software - Normal productions and Performance Ratio vs Solar Fraction the ”worst consumption simulation”.

The graphs in Figure 4.7 and Table 4.3 above compute those values on a monthly scale and starting again with the “worst case simulation” although the system is more robust in terms of Nominal Power

Table 4.3: Balances and Main results for the ”Worst-Case simulation”.

	GlobHor kWh/m^2	GlobEff kWh/m^2	E Avail kWh	EUnused kWh	E Miss kWh	E User kWh	E Load kWh	SolFrac
January	78	144.5	84.7	0.011	576.1	83.8	659.9	0.127
February	91.4	138.7	80.6	0	518.1	78	596	0.131
March	145.7	182	103.4	0.005	563.4	96.5	659.9	0.146
April	160.6	166.7	95.5	0	549.8	88.8	638.6	0.139
May	205.3	201.8	111.1	0	551.8	108.1	659.9	0.164
June	215.9	206.6	105.8	0.005	538.1	100.5	638.6	0.157
July	235.1	228.7	110.7	0.005	556.9	103	659.9	0.156
August	201.6	206.8	103	0	561.7	98.2	659.9	0.149
September	161.2	181.4	97.7	0	545.3	93.3	638.6	0.146
October	119.8	165.8	91.9	0	575.1	84.8	659.9	0.129
November	74.9	120.1	69.8	0	572.7	65.9	638.6	0.103
December	66.9	129.1	76.5	0	588.1	71.8	659.9	0.109
Year	1756.3	2072.1	1130.6	0.026	6697	1072.7	7769.7	0.138

(5 kWp) it has small values of Unused energy, roughly 0.2 kWh/kWp/day. As this is the simulation with heavier demand and strain on the system, it is the one where Lu assumes smaller values, and those represent the unused energy per month due mostly to full battery situations, as the load demands in this simulation are more prevalent than in others. Considering the change in-between months of the values of Collection loss, it is apparent that the greater values of lost energy correspond to the warmer months, given how PV panels have reduced efficiency the greater the ambient temperature is (Chandrasiri (2017)).

The system losses Ls are somewhat stable throughout the year, and their greatest value occurs in December due mostly to the fact that it is the month with lowest system yield Yf, and when computing for Ls= Ya-Yf it makes the value for the system losses slightly higher than average. The last parameter from the leftmost graph is Yf, the Energy supplied to the user which assumes the value of 3.94 kWh/kWp/day. Note that it correlates with Solar fraction and the months with more or less available solar energy i.e. Effective Global irradiation.

For the rightmost graph PR and Solar fraction are compared again on a monthly basis. Solar fraction in the context of PVsyst simulations is defined as ESol ou EUser /ELoad which means it is the ratio between energy supplied to the user and the energy needs of the user. Therefore, the closer to unitary value the better – more robust and capable – the designed system is. For the “worst case simulation” the average value for the whole year is 0.917. This means that the system is undersized – albeit slightly – and there is a Missing Energy problem, derived most likely from losses throughout the system or high load demands linked with the number of days of autonomy. Losses that will be analyzed in the end of this chapter for all simulations.

Overall, there are six months of the year where there is a slight problem of missing energy, those months correspond to months where there is less available Solar Energy as can be seen on the table. That effect transposes directly to the Euser column that is the energy supplied to the user, and consequently to the Solar Fraction, that does not a assume a unitary value for those specific months.

For the “optimized consumption” simulation the first notable difference is the fact that the nominal power is reduced from 5kWp to 3kWp. The system has a less intensive demand so the need for excessive nominal power is not justifiable. Aside from that, the same interpretations from the graphs in Figure 4.8 are to be made, the system is pushed to its limits in the period from the 11^{th} month of the year up to the 2^{nd} month of the following year, in the period coinciding with less available solar energy which can be ascertained when looking to the Unused energy Lu in those months, or lack thereof. As for the months with greater solar exposure the Unused energy increases in value due to the increase in availability of solar exposure and accompanying that increase, the factor LC Collection loss also changes to greater values due to the correlation of efficiency vs ambient temperature already mentioned when analyzing the previous simulations for this exact change. And while the energy supplied to the user Yf assumes a more constant pattern throughout the year, system losses (contrarily to the previous analyzed simulation) also follow a more constant pattern and assume a small value per installed kWp, that is 0.48 kWh/kWp/day vs 0.41 kWh/kWp/day, a difference justified by the smaller number of components this simulation presents, the fewer the components the smaller the system losses are.

For the graph that compares SF and PR, in this simulation the values for SF were more constant and closer to unitary value. This reflects that the system is able to better supply the user with their energy needs throughout the course of the year. A value of 0.973 comes from the only 3 months where the simulation runs into a missing energy problem, one that due to the sizing of the system is smaller in scale than the one in the “worst case simulation”. As expected, the values for GlobHor Horizontal global irradiation and GlobEff Effective Global in Table 4.4 are exactly the same between simulations. However, this system supplies roughly 3 kWp less of power to the user and has surplus of almost double the Unused energy when compared to the previous analyzed simulation. In spite of that, the average value for PR was smaller.

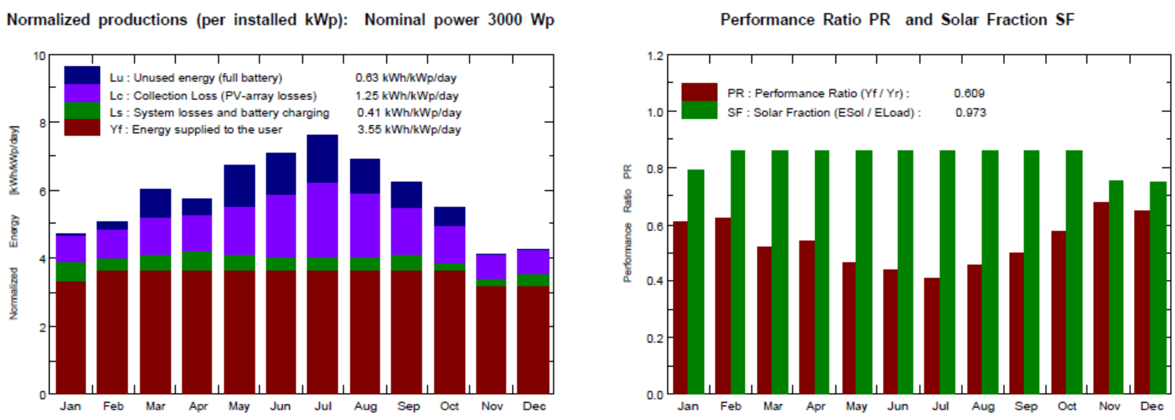

Figure 4.8: PVsyst software - Normal productions and Performance Ratio vs Solar Fraction the ”optimized consumption simulation”.

Finally, the graphs in Figure 4.9 pertain to the “monthly approximation simulation”, these prove most important in order to prove the validity of the system and thereby this work. The first and more apparent

Table 4.4: Balances and Main results for the ”Optimized consumption simulation”.

	GlobHor kWh/m^2	GlobEff kWh/m^2	E Avail kWh	EUnused kWh	E Miss kWh	E User kWh	E Load kWh	SolFrac
January	78	144.5	346	7.8	25.39	313.8	339.2	0.925
February	91.4	138.7	330.8	17.3	0	306.4	306.4	1
March	145.7	182	429.9	73.5	0	339.2	339.2	1
April	160.6	166.7	394.7	39.7	0	328.2	328.2	1
May	205.3	201.8	467.5	111.9	0	339.2	339.2	1
June	215.9	206.6	452.7	110.6	0	328.2	328.2	1
July	235.1	228.7	479.4	124.9	0	339.2	339.2	1
August	201.6	206.8	441.3	89.1	0	339.2	339.2	1
September	161.2	181.4	411.1	66.4	0	328.2	328.2	1
October	119.8	165.8	382.6	45.5	0	339.2	339.2	1
November	74.9	120.1	285.3	0	39.08	289.1	328.2	0.881
December	66.9	129.1	311.3	0	43.22	295.9	339.2	0.873
Year	1756.3	2072.1	4732.6	686.8	107.69	3885.7	3993.4	0.973

change when comparing to the previous simulation’s graphs is that this one has a larger amount of Unused Energy Lu - It can be directly compared to the “worst-case simulation” in terms of energy per kWp as both these systems have a nominal power of 5.0 kWp – it is 1.05 vs 0.2 kWh/kWp/day and shows that this system is considerably more robust and ready to satisfy the user’s needs. Collection loss Lc is exactly the same as expected and the overall system Losses and battery charging assume a lower value due to the fact that the system spends less time charging the batteries due to smaller load demand. For the same reason the energy supplied to the user is slightly lower 3.21 vs 3.94 kWh/kWp/day and also the fact that the battery pack for this system is four modules smaller than for the “worst- case simulation”. However,the Energy available to the user is virtually the same, not exactly due to the nature of the simulation of meteorological data, the difference is approximately 1.3%.

Where this simulation excels is in the Missing Energy parameter as can be seen in Table 4.5, where it is the minimum of all three simulations, and is a good indicator of a well-adjusted system. In this final simulation Missing Energy is 0.069 MWh for the year (compared for example to the “optimized consumption” which is 0.107 MWh/year) and represents only 1.2% of the energy needs of the user assuming a 4-day autonomy value. Again, the correlation of Missing Energy and GlobEff Effective Global Irradiation is verified and only in those months is there an effect of Missing Energy, meaning that a slight adjustment in behavior more than compensates that effect, and this line of reasoning will be further developed in the final part of this Chapter. As expected, that effect translates directly to the analysis of Solar fraction where it does not assume the unitary value precisely on those months.

One of the best features the PVsyst software has is the construction of a Losses diagram where the user has the chance to visually see and understand where their system has the most losses. The three loss diagrams (for the whole year) of the three simulations made: “worst case simulation”, ” optimized consumption simulation” and ”monthly approximation simulation” are present on Figure 4.10, Figure 4.11 and finally Figure 4.12. As expected, since the simulation runs bases on the same meteorological database, some loss parameters pertaining to Irradiance, irradiation and temperature and its effect on

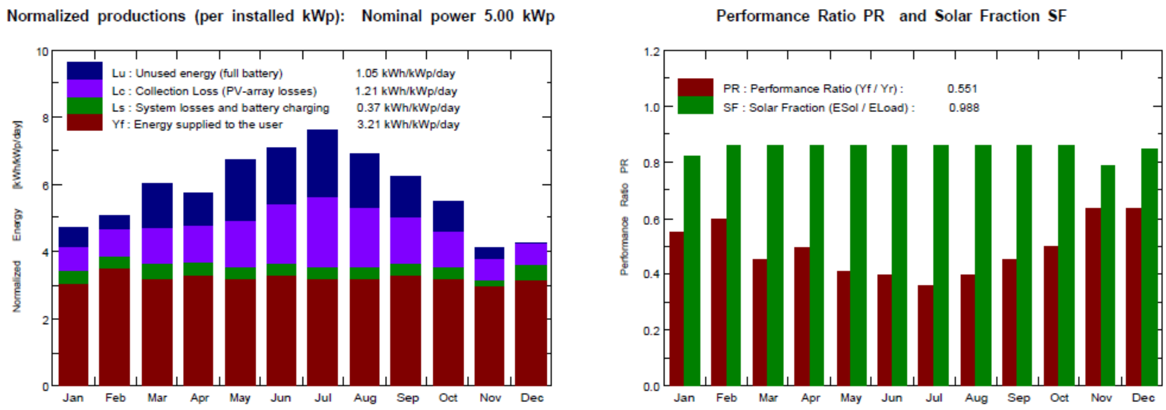

Figure 4.9: PVsyst software - Normal productions and Performance Ratio vs Solar Fraction the ”monthly approximation simulation”.

Table 4.5: Balances and Main results for the ”Monthly approximation simulation”.

	GlobHor	GlobEff	E Avail	EUnused	E Miss	E User	E Load	SolFrac
	kWh/m^2	kWh/m^2	kWh	kWh	kWh	kWh	kWh	
January	78	144.5	584	87.5	21.94	472.1	494	0.956
February	91.4	138.7	555.1	51.1	0	494	494	1
March	145.7	182	725.6	199.6	0	494	494	1
April	160.6	166.7	666.5	147.2	0	494	494	1
May	205.3	201.8	790.6	276	0	494	494	1
June	215.9	206.6	766.3	254.4	0	494	494	1
July	235.1	228.7	814.7	301.3	0	494	494	1
August	201.6	206.8	749.4	236.9	0	494	494	1
September	161.2	181.4	695.3	181.8	0	494	494	1
October	119.8	165.8	645.6	134	0	494	494	1
November	74.9	120.1	479.8	38.5	40.92	453.1	494	0.917
December	66.9	129.1	520.6	0	6.56	487.4	494	0.987
Year	1756.3	2072.1	7993.5	1908.3	69.42	5858.6	5928	0.988

the losses are the same between simulations.

The first loss parameters as can be seen on Figure 4.10 Horizontal global irradiation which are Global incident irradiation on the collector plane, the Incidence Angle Modifier IAM – which in this case is the transmission deficit of irradiance when reaching the solar cell due to the incidence angle on the collector plane - and the PV conversion efficiency are the same, as the panels used were the exact same model between simulations. The notable values are the 2072 kWh/m^2 of Effective Irradiance on the collectors and the panel's efficiency of 15.46%.

The Array Nominal energy @STC is therefore dependent on the area generated by the respective number of panels in each simulation. It is 10.42MWh on the “worst case simulation” and ”monthly approximation simulation”, and 6.2552MWh on the ” optimized consumption simulation”. This difference in value also proves to be a good dimensioning measure to understand the effect that adding a full

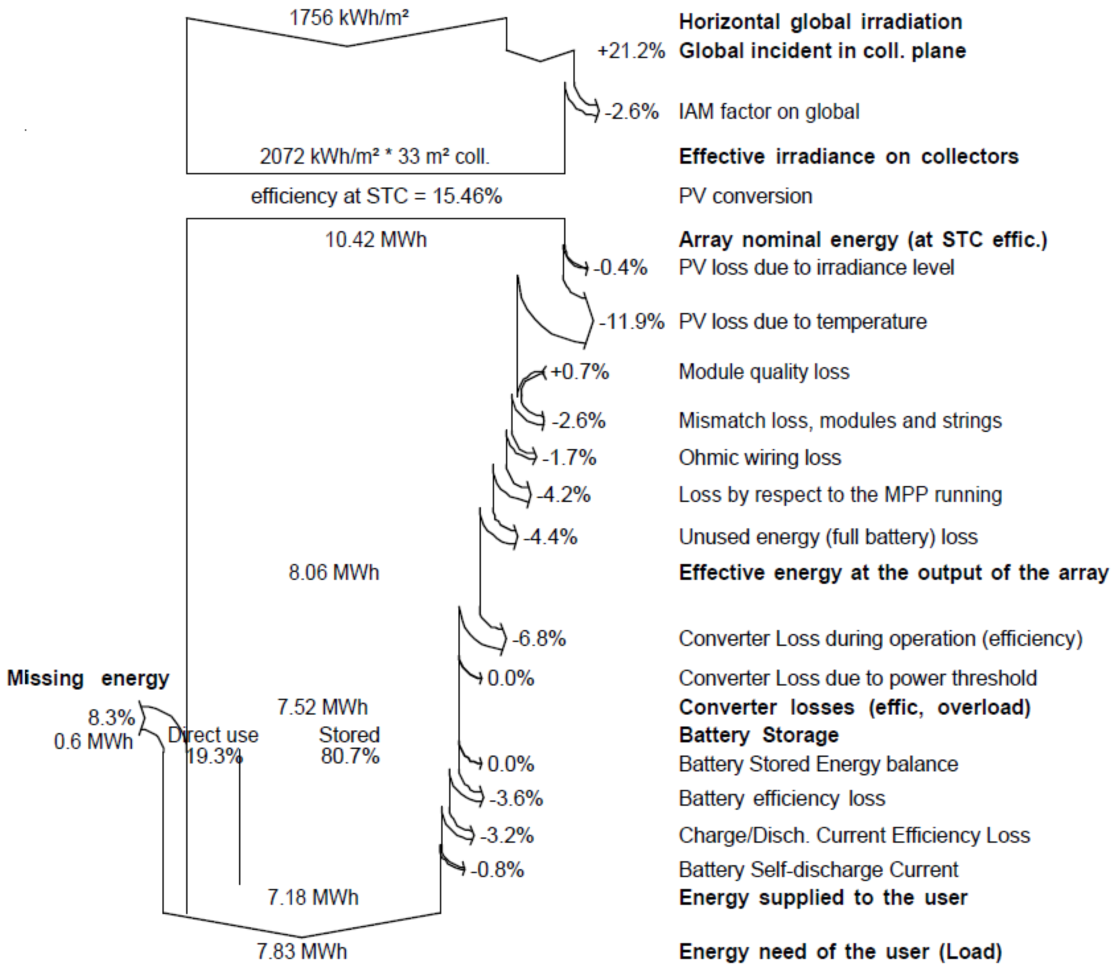

Figure 4.10: PVsyst software - Loss Diagram over the whole year for the ”worst-case simulation”.

string of 4 panels makes on the Nominal energy of an array. The mismatch loss for modules and strings is the same on all three simulations - 2.6% - and the Loss generated by having the MPPT running is 4.2% on the “worst case simulation” and ”monthly approximation simulation”, and -4.7 on the ” optimized consumption simulation”.

Concerning the loss of unused energy due to a state of full battery it is 4.4% on the “worst case simulation” which is expected as the batteries will struggle more often than not to leave bulk charge and achieve float mode. For the “optimized consumption simulation” the value is slightly higher due to a more effective load management and overall system robustness to satisfy user loads – in spite of the inferior energy supply - consequently the battery would stay at maximum SOC more time. Finally, for the “monthly approximation simulation” the loss factor is -22.6% the biggest in proportion out of all the three simulations. This however does not mean the system is oversized, a difference between this factor for the “monthly approximation simulation” and the “worst case simulation” – both have the same nominal power – has also to do with the fact that the former has four less battery modules than the latter which entails less energy to achieve maximum SOC therefore less time to charge in bulk mode which leaves a greater amount of time that the batteries of the "monthly approximation simulation" retain a full SOC.

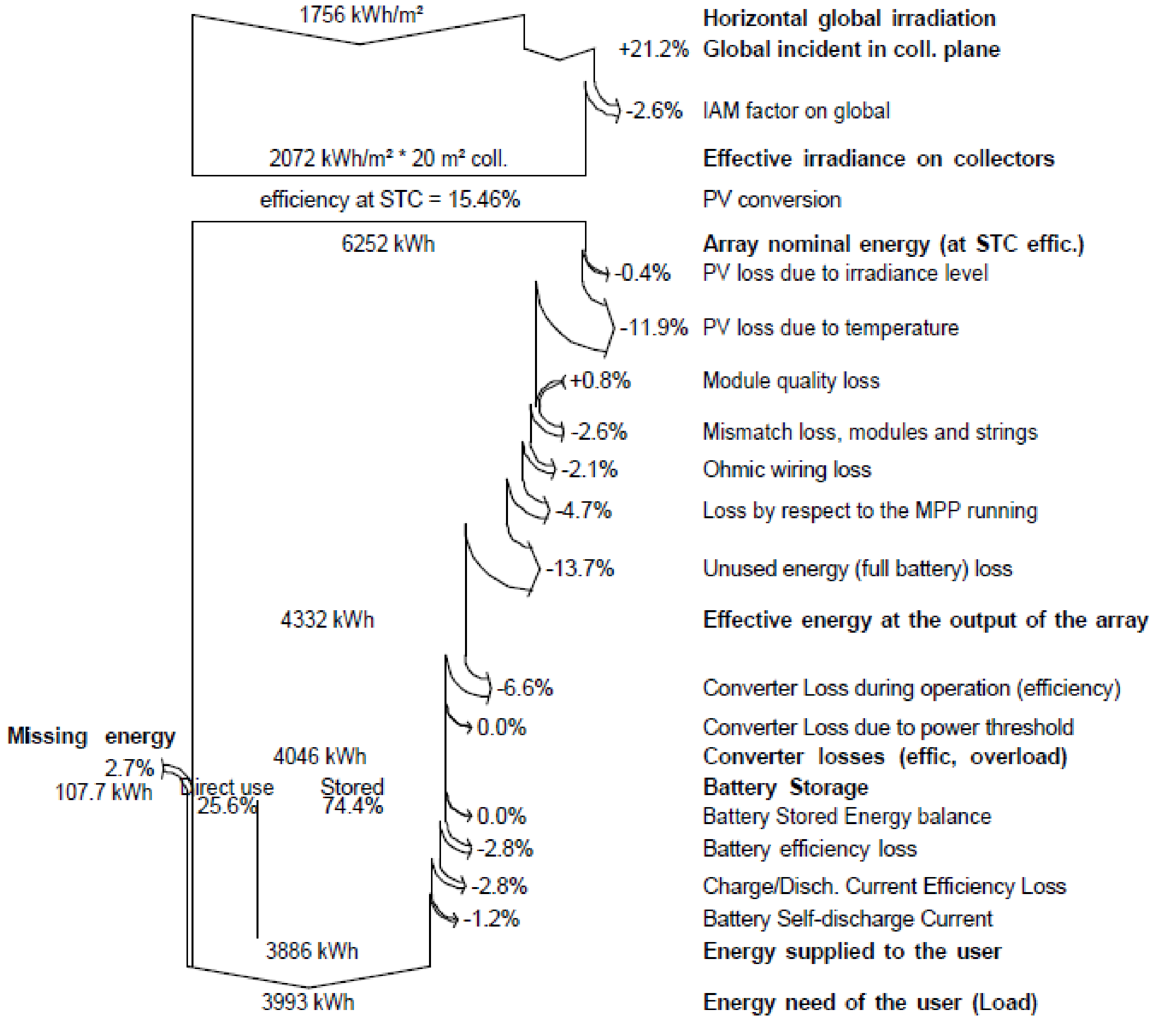

Figure 4.11: PVsyst software - Loss Diagram over the whole year for the "optimized consumption simulation".

The converter loss during operation i.e. the efficiency of the converter and the loss in the converter due to power threshold is the same throughout the simulations as the converter used was the same, and globally did not exceed -7%.

The loss parameters of the battery storage part of the system are similar across the board between simulations, notably higher in the "worst case simulation" given that it implies more SOC fluctuation but not higher than -7.5%.

The separation between Direct use energy and Stored energy is 19.3/80.7% on the "worst case simulation", 25.6/74.4% on the " optimized consumption simulation" and finally 31.2/68.8% on the "monthly approximation simulation". The higher the Direct use Energy percentage is the better dimension a sys-

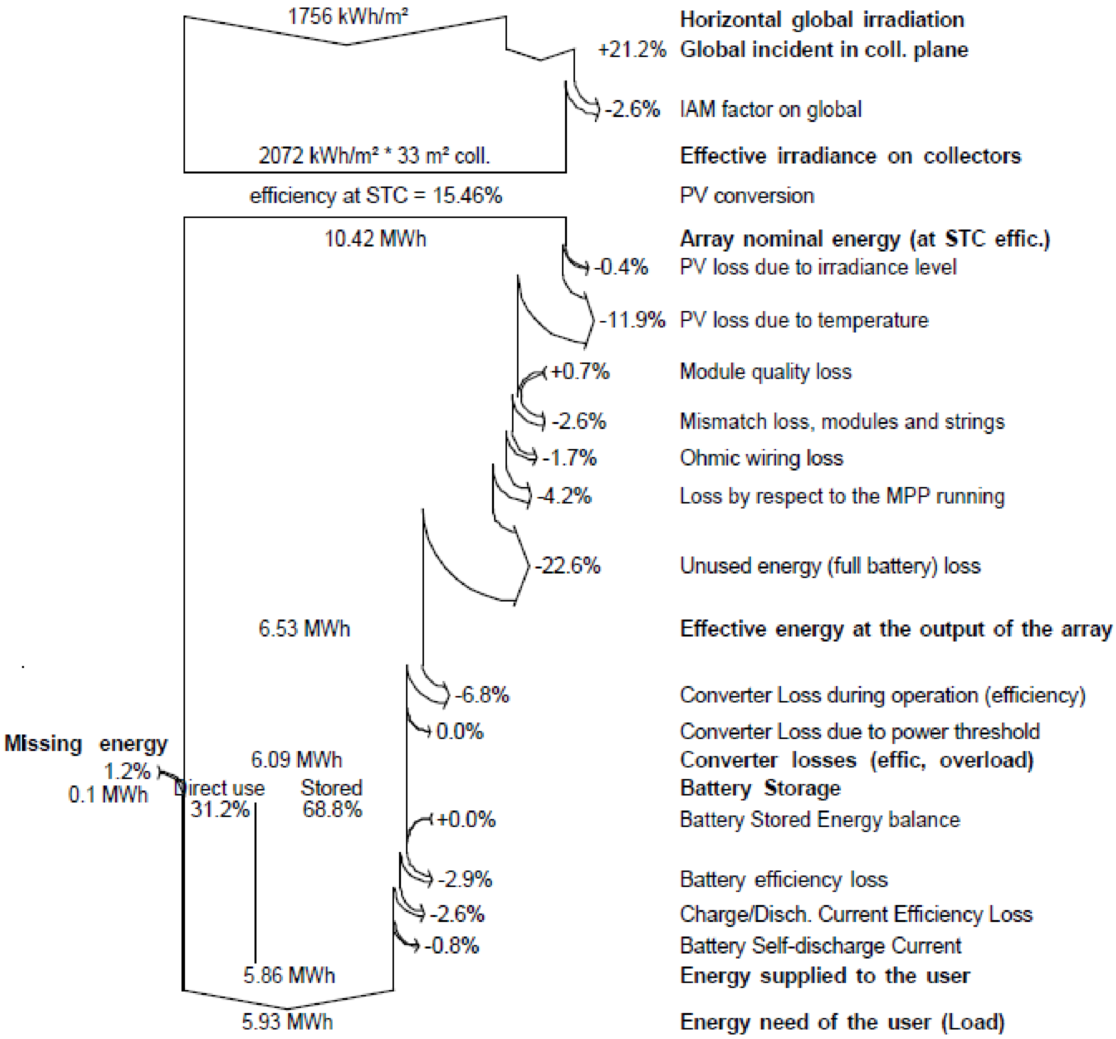

Figure 4.12: PVsyst software - Loss Diagram over the whole year for the "monthly approximation consumption simulation".

tem has.

To conclude this chapter and to what possibly is one of the key indicators of the viability and effectiveness of a system the loss parameter Missing Energy must be addressed. Missing energy, as is, is not a deterrent to a good functioning system, PVsyst indicates a system may be perfectly sized but still Missing energy can occur. It has a direct connection with user loads and availability of stored or direct power. An important note is that these values are for the whole year and with a 5 day autonomy. Therefore theoretically, a user may not even find a problem with missing energy whilst using the system. A Value inferior to less than -5% seems acceptable when putting those factors into perspective, and with fine-tuning load usage that loss parameter can even be thoroughly mitigated. In all the three simulations the worst value for Missing energy was - as expected - the "worst case simulation" where it assumed a value of -8.3% which is almost 7 times the one for the “monthly approximation simulation”. This parameter is calculated by subtracting the energy needs of the user with the final energy supplied to the user after all losses are considered. However, and as was already mentioned, user behavior will define the magnitude of this loss parameter, whether by increase or decrease. Monitoring is key, and the values the simulation extrapolates for load usage and the ones validated in the excel spreadsheet are obviously synthetic approximations of what a real load usage is. No two weeks or even days for that matter will be precisely the same, thus only with close monitoring and effort to maintain the load schedule within its normal operating limits that can be achieved.

Chapter 5

Discussion

5.1 Potential of the work

When designing a system such as the one proposed on this work it is only natural to run into possible constraints and bottlenecks when considering their implementation. Aside from power constrains that were already addressed, the most notable and with higher probability of occurrence is insufficient available area. In the simulations performed the implementation of the panels is to be made on a roof's tilted surface, and those panels would be subject to a seasonal tilt adjustment in order to achieve the better performance possible. As was mentioned, a seasonal tilt adjustment was the broader and more easy methodology to have the panels change their tilt without a tracking system, that choice was made due to the fact that not all roofs would be able to support the added weight of the panels plus the tracking mount system. For the three simulations made, the necessary available area was 32.5m^2 for the simulations that had 20 panels and 19.5m^2 for the simulation that had 12 panels. Note that for roof area we are only considering the part that has good southern exposure i.e. half of the normal total roof area. For a normal Portuguese home, the area values suggested are a tight fit - for example, the house that I live in has half of its roof with direct southern exposure and that half totals to roughly 35m^2. That however might not be the case for other homes, at least not in its entirety. For houses where there is a lack of available roof area other solutions must be devised in other to implement a system capable of supplying the necessary energy to fulfill the user's needs. One of the most promising solutions to address that problem is the implementation of Solar tiles in a BIPV (Building Integrated Photovoltaics) logic whether it being solar roof tiles or even solar facades. Solar roof tiles have the advantage of being able to be deployed on roofs with less loss space in-between cells or even in a building facade (Bahaj and James (1997)).

These solar roof tiles incorporate in their design a PCM (Phase change material) that allows for a boosted electrical output and have an economical payback time of roughly 6 years, improving performance of solar roof tiles by incorporating phase change material (Alim et al. (2020)). However as expected, the efficiency drops when considering a vertical surface as the collecting surface for solar energy but there is still potential to be harnessed and that seems to be the transition when lack of area is applicable to what concerns solar architecture design.

The other implementation tactic is the development of multi purposed solar facades, that in addition to providing an electrical contribution to the building where they are deployed, they can also deal with shading, ventilation and even thermal insulation (Quesada et al. (2012)).

As was mentioned the use of a vertical surface for the collector is less efficient than other parts of the building, to that effect projects and literature are already being made in other to improve that limitation in the form of solar tracking for collectors that are implemented onto a building's facade (Orhon (2016)). To conclude the possible solutions to mitigate the available area problem for collection technologies there is also the development of transparent solar collectors that can be implemented wherever a transparent surface such as window or even full glass wall portion are to be applied. Which is also an area that has enormous potential to grow as the use of those building elements is considered stable trough architectural practices (Husain et al. (2018)).

5.2 Proof-of-Concept - SV Delos (mobile system)

For the proof of concept of this work – and what inspired me to address this topic – a sailing vessel powered mostly by renewable sources was chosen. That vessel is SV Delos (Figure 5.1), star of a YouTube Adventure series where its crew travels around the world to the most remote locations. The focus will be its power generation (solar) and how it is achieved, through a breakdown of its system components and notable loads.

Figure 5.1: SV Delos - Top view. - Photos courtesy of SV Delos

5.2.1 System overview - Generation

Whilst making this work, I was fortunate enough to contact the crew and get extra data concerning power generation and consumption aside from the one made available on their website and videos on the subject. SV delos is a French built 53ft Amel Super Maramu that has a capacity for a 6-person crew. As of making this work SV Delos is equipped with: eight 100Ah DragonFly Energy batteries (in a 400Ah 24V configuration), two 330W Canadian Solar rigid panels on the back of the boat, six flexible panels on the front two 170W and another four 110W which totals to 1440W of nominal solar power, which for a boat – or any system for that matter – is a considerable amount.

Figure 5.2: SV Delos - Turbines and rear mounted 2 X 330W Canadian Solar panels.

Figure 5.3: SV Delos - Center mounted flexible 2 170W and 4 110 W panels.

There are also other means of power generation, as being on a boat the more system redundancy there is the more secure it is for its crew. Those are: 2 wind turbines each 400W, a 8kW Diesel Generator (220 AC), two alternators – a 12V 20A that charges the boat starting battery (which is used for starting the main engine and the 8kW Generator) and a 24V 50A alternator (to charge the Lithium battery bank) which connects to a spike suppressor and then a 24V – 24V DC charger which allows to control and regulate the charging profile of the second alternator – and finally the possibility of connecting to dock power (220/110V AC depending on the part of the world).

Figure 5.4: SV Delos - Victron BlueSolar MPPT.

For the controller side of the renewable power generation, SV Delos is equipped with two Victron BlueSolar 100V 50A MPPTs and a 24V Charger Controller for the Silent Wind turbine (as the other turbine has the controller built in). To control the dock power going into the Lithium battery bank, there are also two Victron Charge Controllers (100A and 70A) and a Master Volt 80A charge controller (these receive 220/110V AC and feed the batteries a controlled 24V DC). These controllers are also key factors in building up redundancy throughout the system, given that having one fail would not leave the crew unable to charge the Lithium battery bank safely. Note that when SV Delos is docked and batteries are at 100% SOC, the MPPT limits the charging current going into the batteries (this will be further analyzed when looking at the monthly solar charger data).

After the Lithium battery bank shown in Figure 5.5, SV Delos has a 3kW inverter that takes either 24V DC from the batteries or 110/220V AC - when the sailing boat is connected to dock power - and feeds 220V AC to all the outlets, electric stove oven, computers, and ice machine.

The remaining loads are 24V DC from the batteries to all electrical boat mechanical loads (such as winches, furler) and also lights and both fridges and freezer. There is also a step-down converter which transforms the 24V DC from the batteries to 12V DC to power Radios, Navigation, Radar and Autopilot. The water maker is usually powered by the diesel generator.

SV Delos underwent a battery pack change from Lead acid to Lithium, and in doing so significantly increased its solar energy production. This was due to the much greater charging efficiency of the Lithium

Figure 5.5: SV Delos - Lithium battery pack.

battery cells (30 to 40% greater than Lead-Acid). Before the change, the solar array was producing roughly 3-3.5 kWh daily and after those values increased to 4kWh which in the words of its Captain was almost like adding a new solar panel and well worth the change. Other effect the crew noticed pertaining to the battery pack upgrade was the reduced time usage of the diesel generator in almost 30% hours. As the batteries charge more efficiently, they stay less time in absorption mode and spend the majority in either bulk charge or float, a factor than when adding the possibility of taking the Lithium battery pack to a much lower SOC than what would be achievable with Lead Acid technology (Lithium can go as low as 5% when Lead Acid should never be below 50% SOC) accounts for a reduction of necessity in running the Diesel-powered Generator. Further proving the viability of such changes and potential lithium has to offer to these types of systems.

5.2.2 Data Analysis

For a closer look and to better understand the dynamics of power generation and consumption Capt. Brian Trautman was kind enough to supply data directly from Victron's VE. Direct Smart phone application. Furthermore the time frame of the supplied data presents the opportunity to make an important analysis regarding the scope of this work, because there is data from when the vessel was connected to dock power and data from when the vessel was travelling high seas. In both Figure 5.6 and Figure 5.7 is the data from the solar chargers, the first from the rigid panels and the second from the flexible ones. Up until the 27^{th} of May SV Delos was connected to dock power in Mexico, then the vessel traveled in high seas to Mexico until arriving there on June 5^{th}. With this data the behavior of the chargers can be compared in a docked situation vs off-grid whilst traveling. In the days the vessel was at sea, the rigid panels were producing approximately 2 kWh however as the vessel is a moving object and in constant motion, exposure is not always constant and therefore not the best at some time periods. An example of that can be seen on May 30th where energy production takes a massive drop compared to the other days at sea – dropping below 0.5 kWh - and that occurred likely because the structure where the panels are house was shaded by the main sail. When analyzing the second graph that corresponds to the flexible panels that are located towards the center of the boat it is possible to see that they suffered no comparable negative effect on their production and remain somewhat constant throughout the duration of the passage. The solar charger graphs also contain the percentage of time in visual form the charge controller is charging the batteries in each respective mode, Bulk, Absorption and Float. It is easily verifiable that when the vessel was connected to the dock the first BlueSolar solar charger maintained the charging profile at float (top portion of each single bar of the graphs) for the majority of the time and the second, although for some reason, possibly a priority setting or a higher cut-off voltage remained charging the batteries albeit slightly, which seems to suggest it is a setting issue within the controller application itself.

The first graph in Figure 5.6 shows the expected data, as Lithium batteries have a higher charging efficiency there's rarely the need for absorption mode. Also, the vast majority of the days at sea was having the controller maintain bulk charge but achieving float for some portion of the day, this indicates robustness of the system but also adequate sizing. The same was not present on the graph of Figure 5.7 for the second controller due to it not achieving float whilst at sea, again this possibly indicates some sort of priority/preference setting for this specific solar charge controller.

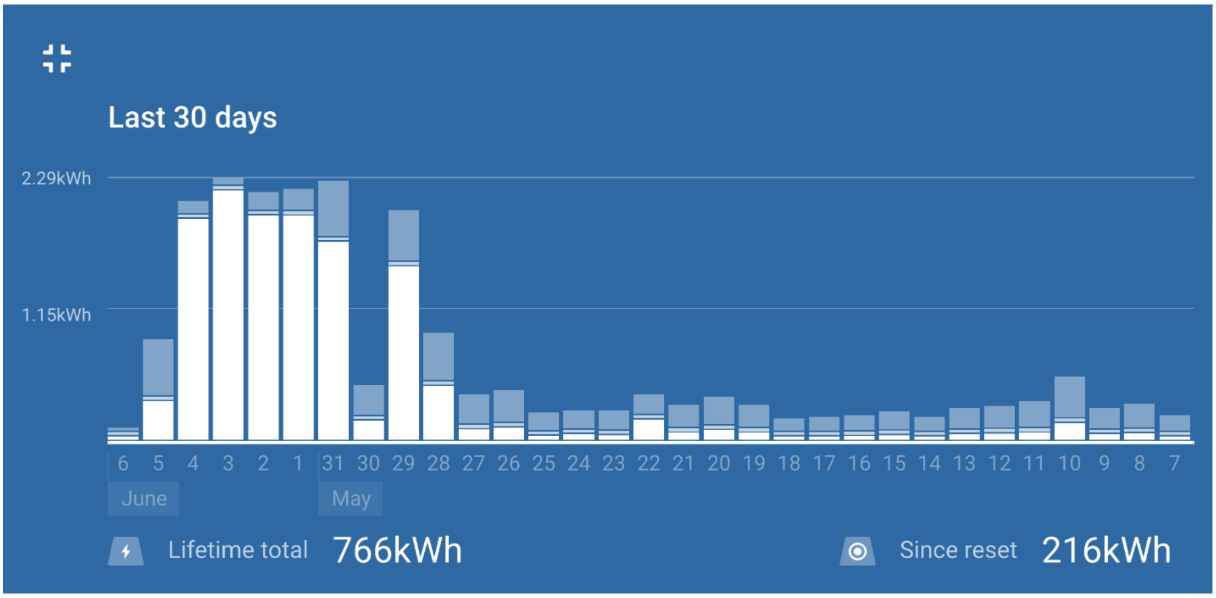

Figure 5.6: SV Delos - Data from the Victron Solar charger - Rigid panels 2 x 330W.

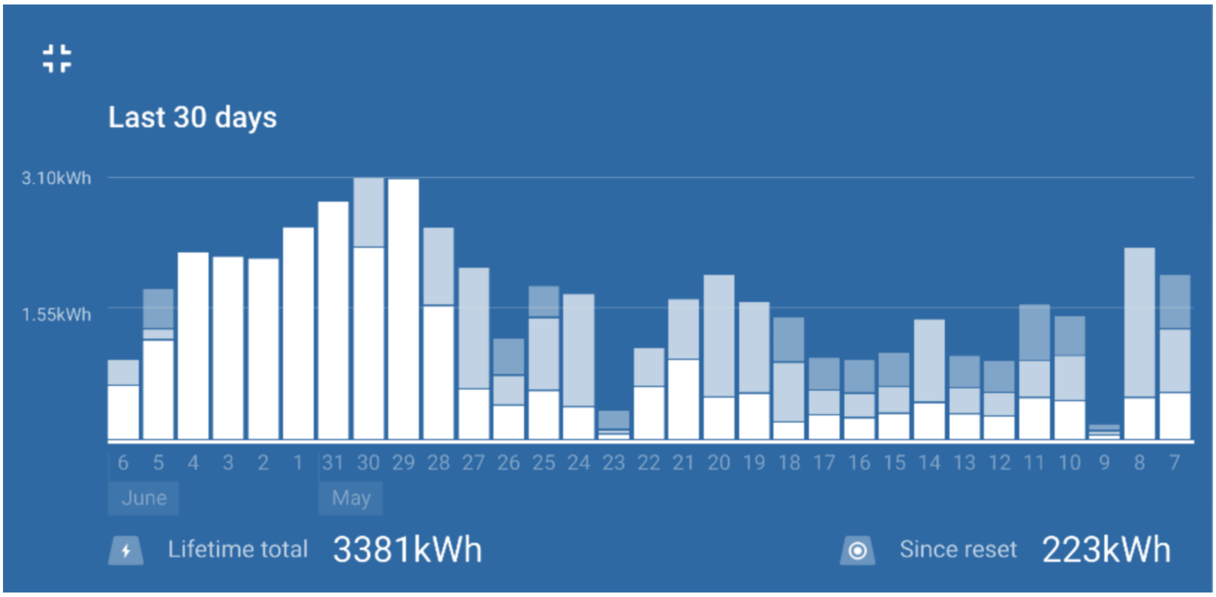

Figure 5.7: SV Delos - Data from the Victron Solar charger - Flexible panels 2 X 170W and 4 X 110 W.

5.2.3 System overview - Capacity and Consumption

Concerning capacity and consumption, SV Delos' captain also supplied data extracted from the Victron Energy Smart Battery Monitor BMV-712 via the smartphone application. The battery monitor connects via Bluetooth to whichever device the user chooses. In the screenshot from the application (Figure 5.8) the data regarding consumption (discharge) is present. As was previously mention the overall Lithium battery bank capacity of the vessel is 400Ah. The information in the screenshot shows that the average discharge is 220Ah which is around 55% of the overall capacity. This means that this system, for the loads the crew subjects the system to, is robust. Then considering the deepest discharge data which reveals that the most strained discharge of the system was 354Ah – 88% of overall capacity – shows that in addition to being a robust system, it is also a well sized system that allows considerable margin to the crew to add more demand on the batteries beyond their average use.

Globally, in terms of energy since system implementation, the system charged the batteries with 3366.6 kWh of energy, and 3236.5 kWh of energy were discharged from the batteries. Naturally this has to be a positive ratio, since there can not be more discharged energy from the lithium battery back than the energy which the battery pack received, however the margin difference between the two values shows that the system was never pushed to its limit and is performing within expected behavior. This battery monitoring system is also equipped with low and high voltage alarms. So far, the minimum voltage value the batteries had was 0.03V – more than likely for the calibration process after the first recommended full discharge - and the maximum voltage was 29.7V, well within normal parameters for a 24V system. Overall and since its deployment, the lithium battery pack went through 269 charge cycles, so in what concerns the possible life-cycle of the system is it still rather young.

The second stage in Figure 5.9 shows a photograph like state of the battery at 9 A.M. (before the majority of solar energy charging occurs) and it shows the SOC at 36% and the battery pack voltage

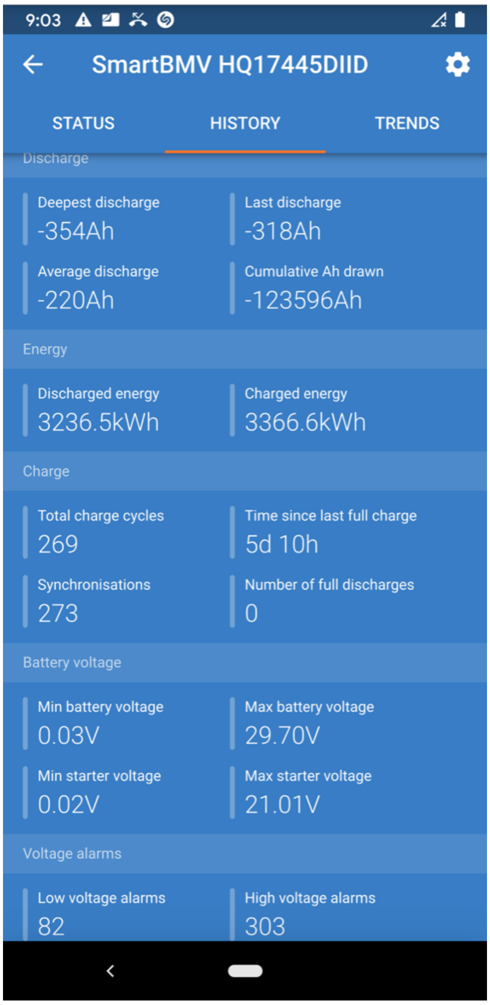

Figure 5.8: SV Delos - Data from the VictronConnect smartphone application - History.

at 25.83V. At that precise moment, there were 31.4A being drawn from the batteries and a consumption of 811W of power. Finally since the last charge the system had discharged 259.4Ah of capacity, approximately 64.85% of overall capacity.

In conclusion SV Delos in my opinion is the perfect vessel for a proof of concept such as this. It is well sized and has a heavier load demand than usual for vessels of its class, the multitude of energy inputs and redundancy the system has offer greater security for its crew in what are more perilous and straining conditions than would be expected for systems such as these. It also provides manufactures of products such as batteries, solar panels and controllers valuable data for what kind of stress - whether high heat in the tropics where SV Delos usually sails, or the highly saline environment of a sailing vessel - their products can withstand. The ease of access to energy related data the Victron Energy products provide also made this proof of concept that more reliable in what concerns analyzing the intricacies of how the system performs.

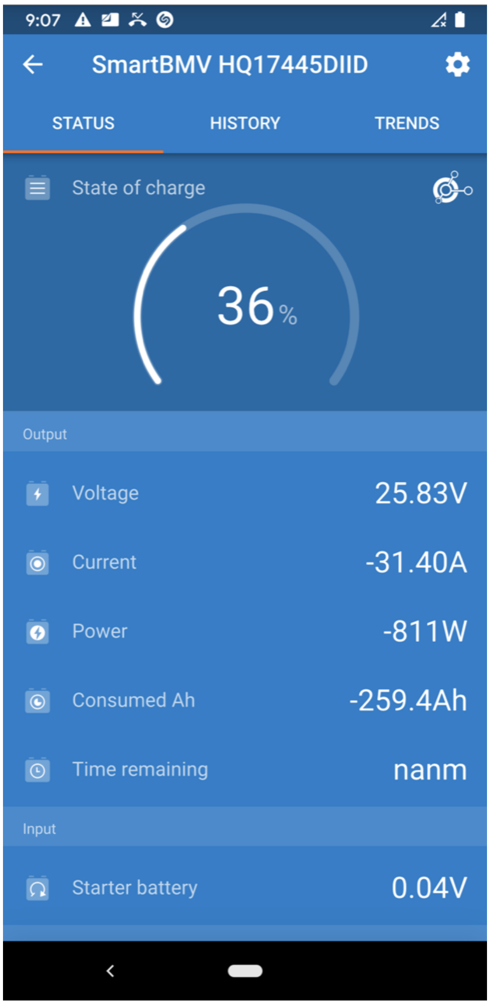

Figure 5.9: SV Delos - Data from the VictronConnect smartphone application - Status.

Chapter 6

Conclusions

The implementation of a system designed to work independently from the power grid inherently places itself in the minority of electrical domestic systems. Due to the sheer nature of what off-grid means, a system designed to work solely by itself subjects the user to different types of possible hindrances, but it also provides advantages. As with any alternative to the norm, there must be a purpose for its existence, whether it being providing a solution where there is an impracticability to implement the norm, or providing different advantages that the norm simply by design can not offer. Therefore, to the perspective of the user, each case will have its pros and cons. In this case the norm as was mentioned is having a grid connected system, and the alternative – among many as they include any power delivery solution other than solely grid connected – is any other devisable power delivery system. In the case of this work the alternative is a completely off-grid power delivery system, but there are also PV grid connected systems, localized microgrids and so on. The core advantage this work focuses on for Off-Grid PV powered systems with Lithium battery banks is autonomy. Whether it being a system deployment in an area where power grids are not available, emergency deployment situations or the ability to roam and travel with the normal luxuries of a 21^{st} century home by land or by sea, this work proves the viability of that choice. The main disadvantage will always be connected to available area, but this work shows that with normal roof area in an average sized home, this systems can be deployed. At first it may seem nonsensical to focus the missive of a work on an idea such as this, however there is a lack of literature supporting it, consequentially there is lack of information dissemination on a topic that in practical terms is being adopted by a younger generation unable to attain housing at affordable prices, people with the desire to travel and work remotely or even ONGs faced with emergency energy needs in a world where populations migrations are becoming more common due to war or climate alterations.

When considering future work, the direction where there seems to be a void in literature is the topic of mobile off-grid homes. The Proof-of-Concept of this work validates the feasibility of such systems and how they can thrive in a multitude of conditions. Therefore the logical step is to find the limit of those conditions by designing - and optimising - new systems based on real data from practical cases all around the world. Possibly cases where the system is already being pushed to the limits with fewer solar exposure or even harsher conditions such as arctic travel.

Bibliography

Irena 2019 renewable energy statistics 2019, 2019. URL `https://www.irena.org/publications/2019/Jul/Renewable-energy-statistics-2019`.

Z. Ahsan, D. Bo, Z. Cai, C. Wen, W. Yang, Y. Ma, S. Zhang, G. Song, and M. S. Javed. Recent progress in capacity enhancement of lifepo4 cathode for li-ion batteries. *Journal of Electrochemical Energy Conversion and Storage*, 18:1–54, 05 2020. doi: 10.1115/1.4047222.

A. Al-Akori. Pv systems for rural health facilities in developing areas. *Report on International Energy Agency Photovoltaic Power Systems Programme (IEAPVPS) T9-15*, 2014.

M. A. Alim, P. Z. Tao, M. Abden, A. Rahman, and B. Samali. Improving performance of solar roof tiles by incorporating phase change material. *Solar Energy*, 207:1308–1320, 09 2020. doi: 10.1016/j.solener.2020.07.053.

T. Ayodele, T. Mosetlhe, A. Yusuff, and A. Ogunjuyigbe. Off-grid hybrid renewable energy system with hydrogen storage for south african rural community health clinic. *International Journal of Hydrogen Energy*, 46(38):19871–19885, 2021. ISSN 0360-3199. doi: https://doi.org/10.1016/j.ijhydene.2021.03.140. International Journal of Hydrogen Energy Special Issue devoted to the 32nd International Conference ECOS 2019.

A. Bahaj and P. James. Photovoltaic roof tiles: Design and integration in buildings. 02 1997.

T. Castillo-Calzadilla, A. Macarulla, O. Kamara-Esteban, and C. Borges. Analysis and assessment of an off-grid services building through the usage of a dc photovoltaic microgrid. *Sustainable Cities and Society*, 38, 04 2018. doi: 10.1016/j.scs.2018.01.010.

S. Chandrasiri. Temperature effect on solar photovoltaic power generation. 01 2017. Uni-In Alliance Symposium 2017 - University of Sri Jayewardenepura, Sri lanka.

M. De Carli, S. Graci, Y. Natalini, L. Tônus, and P. Agostini. Energy self-sufficiency and sustainable development in a closed mountain area. *Renewable Energy and Power Quality*, pages 1288–1293, 04 2012. doi: 10.24084/repqj10.679.

Y. Garcia, O. Daniel, D. Castillo, L. Luz´angela, C. Pardo, L. Fernanda, and S. Pérez. Performance study of monocrystalline and polycrystalline solar pv modules in tropical environments. 01 2020.

P. Huber, M. Gerber, A. Rumsch, and A. Paice. Prediction of domestic appliances usage based on electrical consumption. *Energy Informatics*, 1, 10 2018. doi: 10.1186/s42162-018-0035-1.

A. A. Husain, W. Z. W. Hasan, S. Shafie, M. N. Hamidon, and S. S. Pandey. A review of transparent solar photovoltaic technologies. *Renewable and Sustainable Energy Reviews*, 94:779–791, 2018. doi: https://doi.org/10.1016/j.rser.2018.06.031.

S. H. A. Kaboli, J. Selvaraj, and N. Rahim. Long-term electric energy consumption forecasting via artificial cooperative search algorithm. *Energy*, 115:857–871, 2016. ISSN 0360-5442. doi: https://doi.org/10.1016/j.energy.2016.09.015.

S. Khan and A. Rahman. The efficiency of thin film photovoltaic paint: A brief review. *International Journal of Recent Technology and Engineering*, 7:163–169, 04 2019.

O. Longe, K. Ouahada, H. Ferreira, and S. Chinnappen. Renewable energy sources microgrid design for rural area in south africa. 02 2014. doi: 10.1109/ISGT.2014.6816378.

D. MacPherson, B. Gushulak, and L. Macdonald. Health and foreign policy: influences of migration and population mobility. *Bulletin of the World Health Organisation*, 85:200–206, 03 2007. doi: 10.1590/S0042-96862007000300013.

M. McAuliffe, A. Kitimbo, A. M. Goossens, and A. A. Ullah. Chapter 7 – understanding migration journeys from migrants' perspectives. *World Migration Report*, 2018(1):e00007, 2018. doi: https://doi.org/10.1002/wom3.7.

T. Michalakopoulos and V. Perraki. Effect of solar radiation incidence angle and module tilt angle on the pv module perfomance: Modeling for mediterranean sites. 01 2014.

G. R. Molaeimanesh, S. M. Mousavi-Khoshdel, and A. B. Nemati. Experimental analysis of commercial lifepo4 battery life span used in electric vehicle under extremely cold and hot thermal conditions. *Journal of Thermal Analysis and Calorimetry*, 143(4):3137–3146, 2021.

M. Mouheb, A. Hamidat, and L. Loukarfi. Impact of pv compensation in improving the voltage drop in electrical networks lv. *Energy Procedia*, 18:751–761, 12 2012. doi: 10.1016/j.egypro.2012.05.091.

A. Oliver-Smith. Debating environmental migration: society, nature and population displacement in climate change. *Journal of International Development*, 24(8):1058–1070, 2012. doi: 10.1002/jid.2887.

R. Opoku, E. A. Adjei, G. Yaw Obeng, L. Severi, and A.-R. Bawa. Electricity access, community healthcare service delivery, and rural development nexus: Analysis of 3 solar electrified chps in off-grid communities in ghana. *Journal of Energy*, 2020:1–10, 03 2020. doi: 10.1155/2020/9702505.

A. Orhon. A review on adaptive photovoltaic facades. 12 2016.

P. Ortega-Arriaga, O. Babacan, J. Nelson, and A. Gambhir. Grid versus off-grid electricity access options: A review on the economic and environmental impacts. *Renewable and Sustainable Energy Reviews*, 143(C), 2021. doi: 10.1016/j.rser.2021.11086.

R. Perez, P. Ineichen, R. Seals, J. Michalsky, and R. Stewart. Modeling daylight availability and irradiance components from direct and global irradiance. *Solar Energy*, 44(5):271–289, 1990. ISSN 0038-092X. doi: https://doi.org/10.1016/0038-092X(90)90055-H.

R. Perez, P. Ineichen, E. Maxwell, R. Seals, and A. Zelenka. Dynamic global-to-direct irradiance conversion models. *ASHRAE Transactions*, 98:354–369, 01 1992.

PVsyst webgeneve. Pvsyst. URL `https://www.pvsyst.com/`.

G. Quesada, D. Rousse, Y. Dutil, and B. Messaoud. A comprehensive review of solar facades. opaque solar facades. *Renewable and Sustainable Energy Reviews*, 16, 06 2012. doi: 10.1016/j.rser.2012.01.078.

T. Salihu, M. Akorede, A. Abdulkarim, and A. Abdullateef. Off-grid photovoltaic microgrid development for rural electrification in nigeria. *The Electricity Journal*, 33:106765, 2020. doi: 10.1016/j.tej.2020.106765.

M. S. Uddin, M. M. Ahmad, and P. Warnitchai. Surge dynamics of disaster displaced populations in temporary urban shelters: future challenges and management issues. *Natural Hazards: Journal of the International Society for the Prevention and Mitigation of Natural Hazards*, 94(1):201–225, 2018. doi: 10.1007/s11069-018-3383-z.

V. Vega-Garita, A. Hanif, N. Narayan, L. Ramirez-Elizondo, and P. Bauer. Selecting a suitable battery technology for the photovoltaic battery integrated module. *Journal of Power Sources*, 438:227011, 2019. ISSN 0378-7753. doi: https://doi.org/10.1016/j.jpowsour.2019.227011. URL `https://www.sciencedirect.com/science/article/pii/S0378775319310043`.

L. H.-p. Yin-Quan. Charging method research for lithium iron phosphate battery. *Procedia Engineering*, 15:4367–4371, 2011. ISSN 1877-7058. doi: https://doi.org/10.1016/j.proeng.2011.08.820. CEIS 2011.

R. Zhang, B. Xia, B. Li, L. Cao, Y. Lai, W. Zheng, H. Wang, and W. Wang. State of the art of lithium-ion battery soc estimation for electrical vehicles. *Energies*, 11(7), 2018. ISSN 1996-1073.

G. Zubi, R. Adhikari, N. Sánchez, and W. Acuña-Bravo. Lithium-ion battery-packs for solar home systems: Layout, cost and implementation perspectives. *Journal of Energy Storage*, 32:101985, 12 2020. doi: 10.1016/j.est.2020.101985.