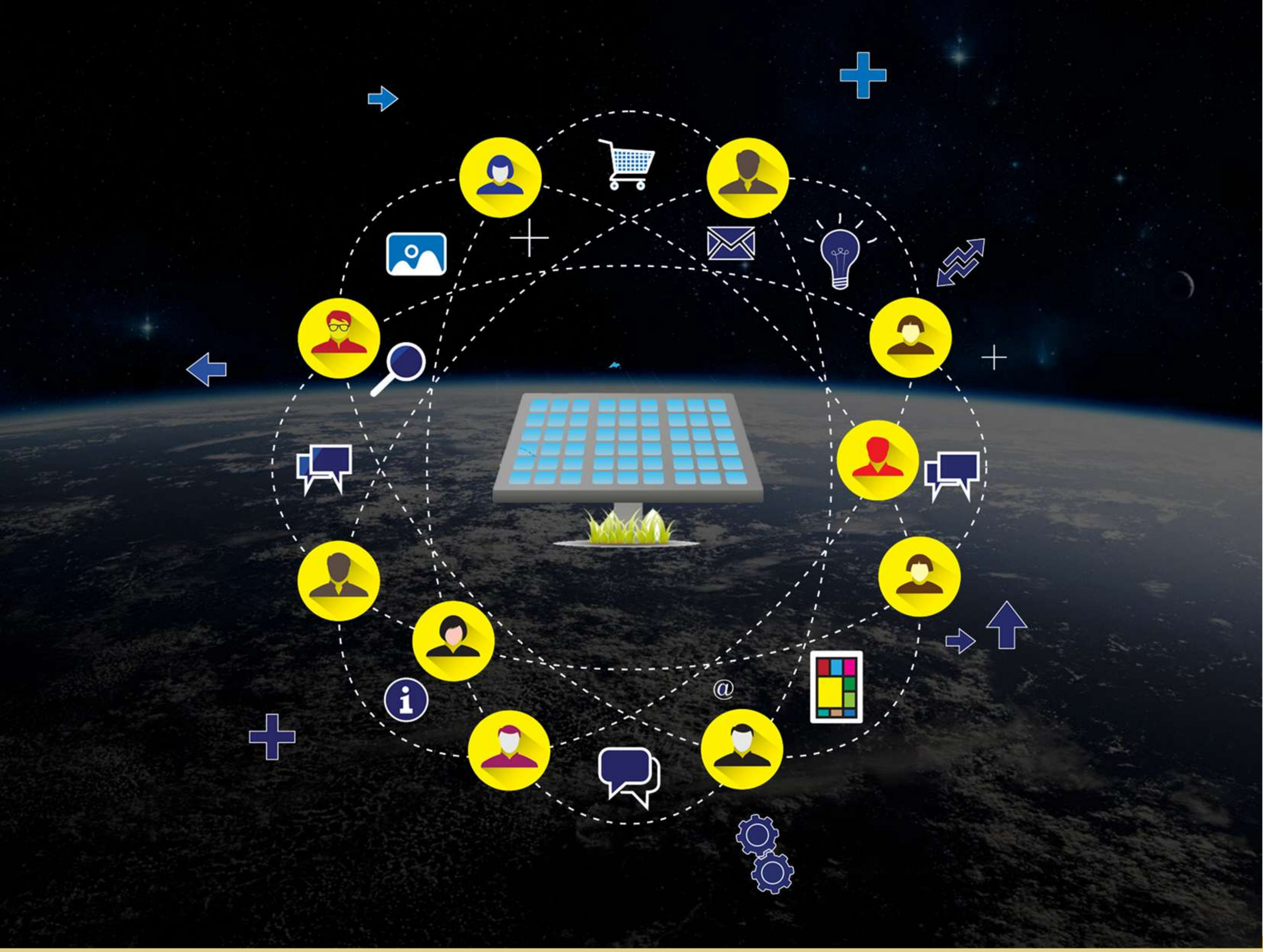

João Pedro Antunes Clemente

The OffGridder:
An Interactive Platform for Designing and Purchasing Off-Grid Solar Photovoltaic Systems

Integrated Master's in Electrical and Computer Engineering

September 2016

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Universidade de Coimbra

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THE OFFGRIDDER: AN INTERACTIVE PLATFORM FOR DESIGNING AND PURCHASING OFF-GRID SOLAR PHOTOVOLTAIC SYSTEMS

BY

JOÃO PEDRO ANTUNES CLEMENTE

DISSERTATION

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of the Czech Technical University in Prague

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"I learned this, at least, by my experiment: that if one advances confidently in the direction of his dreams, and endeavors to live the life which he has imagined, he will meet with a success unexpected in common hours."

— Henry David Thoreau, ***"W**alden"*

ABSTRACT
(ENGLISH)

We live in a decade that where we need fast solutions to the environmental concerns that surround. In this day and age global scientists have already given various warnings about how society is transgressing a number of planetary boundaries. In the meantime, it has been proven time and time again that capitalising on information technologies is often the way to offer critical solutions in a timely manner. Following this line of thought this dissertation aims to create a project that thrives on the high-tech global economy by utilising information technologies in order to rev up the implementation of one of the most prominent solutions to global warming – off-grid solar photovoltaic systems – thus fostering a society that is economically, socially and environmentally viable.

The project is entirely based on an interactive platform developed in Microsoft Excel 2016 that deals with the design and consequent purchase of the main components of off-grid solar PV systems. It automatizes several processes such as load analyses and the sizing of solar arrays, battery banks, charge controllers, and inverters in the context of off-grid solar photovoltaic systems, while maintaining a business standpoint by creating an extra interactive tool that deals with the purchasing of those devices.

In order to provide timely solutions, though, technology is often not enough. That is why the dissertation's final product, entitled *The Offgridder,* also becomes a prospective business venture by being summarised in a framework called a *business model canvas*, which is essentially a diagram of how a company creates value for itself and its customers.

KEYWORDS

Solar energy

Off-grid systems

Photovoltaic systems

Interactive platform

Business planning

RESUMO
(PORTUGUÊS)

Vivemos numa década onde precisamos de soluções rápidas para os problemas ambientais que nos rodeiam. A comunidade científica global comunica frequentemente vários avisos sobre como a nossa sociedade está a ultrapassar vários limites ecológicos. Entretanto, já foi provado vezes sem conta que utilizar tecnologias de informação compõe frequentemente uma maneira de oferecer soluções rápidas, importantes e oportunas. É com esta linha de pensamento que esta dissertação tem como objetivo o de desenvolver um projeto com a capacidade de prosperar tanto no mundo da alta tecnologia, como na economia contemporânea através da utilização de tecnologias de informação para a implementação de uma das mais eminentes soluções para combater o aquecimento global – os sistemas de painéis fotovoltaicos isolados – fomentando assim uma sociedade economicamente, socialmente e ambientalmente viável.

O projeto é completamente baseado numa plataforma interativa desenvolvida no Microsoft Excel 2016 que lida com o design e consequente compra dos principais equipamentos que compões os sistemas de painéis fotovoltaicos isolados. Esta plataforma automatiza vários processos ligados aos sistemas isolados, tais como os de análise de cargas e os de dimensionamento de bancos de baterias, painéis solares, controladores de carga e inversores, enquanto mantém também um ponto de vista empreendedor ao criar uma ferramenta interativa extra que lida com a compra dos equipamentos selecionados no processo de design.

No entanto, soluções oportunas muitas vezes requerem mais do que tecnologia. É por este facto que o produto final desta dissertação – intitulado *The OffGridder* – é também sumarizado num breve modelo de negócios baseado no método "Lean", que é essencialmente um diagrama de como uma empresa pode gerar valor para si mesma e para os seus clientes.

PALAVRAS-CHAVE

Energia solar
Sistemas de energia isolados
Sistemas fotovoltaicos
Plataforma interativa
Plano de negócios

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LIST OF ACRONYMS

Acronym (A-Z)	Definition
A	Amps
AC	Alternating current
BatteryDb	Battery Database
DC	Direct Current
DE	Distributed Energy
DESS	Distributed Energy Storage System
DoA	Days of Autonomy
DoD	Depth of Discharge
DR	Digital Revolution
EU	European Union
ICTs	Information and Communication Technologies
IT	Information Technology
Li-ion	Lithium-ion
MVP	Minimum Viable Product
OG	Off-Grid
PV	Photovoltaic
ROI	Return On Investment
MPPT	Maximum Power Point Tracking
PWM	Pulse Width Modulation
PanelDb	Solar Panel Database
InverterDb	Inverter Database
ChargeDb	Charge Controller Database

Chapter 1: Introduction

1.1. Background

For fifteen thousand years not much changed about the way people acquired clothing, located drinking water, produced food, or travelled around. From the 18th to the 19th centuries, however, the Industrial Revolution unfolded, marking a major turning point in human history. Predominantly agrarian and rural societies became industrial and urban, and a great deal of commodities available today – from seemingly simple ones such as blueberries in February to the more complex such as the automobile – can be attributed to progress that had its roots in this period of time. Yet while the Industrial Revolution dramatically improved major aspects of human life, it also ended up becoming a double-edged sword, marking an additional turning point in Earth's ecology and humans' relationship with their environment (McLamb, E. 2011).

Perhaps the most astonishing evidence of the Industrial Revolution's impact on the modern world is seen in the worldwide human population growth. While at the dawn of the Industrial Revolution in the mid-1700s the world's human population grew by about 57 percent to 700 million, the twenty-first century hadn't yet become a dozen years old when global population surpassed the 7 billion mark. This is a massive problem because human population growth is ineradicably tied together with increased use of natural and man-made resources, energy, land for growing food and for living, and waste by-products (McLamb, E. 2011,). This dependence on limited resources, namely the fossil fuels that nourished the Industrial Revolution, came at staggering costs to our environment.

In the meantime, humans have already gone through yet another revolution – the Digital Revolution (DR), where technological development shifted from analog electronic and mechanical devices to the digital technology available today, marking the beginning of the Information Age. Information and communication technologies (ICTs) have since become the driving force of social evolution (Hilbert, M. 2015), paving the way to the creation of a knowledge-based society surrounded by a high-tech global economy. In a commercialised society, the information industry allows individuals to explore their personalised needs, therefore simplifying the procedure of making decisions for transactions and significantly lowering costs for both the producers and buyers (Masud, K. 2014). This has been key to solving numerous modern-day predicaments.

The truth of the matter is: when it comes to environmental issues, we need solutions fast. In fact, in this day and age global scientists have already given various warnings about how society is transgressing a number of planetary boundaries. And as it has been proven time and time again, capitalising on DR's by-products is often the way to offer critical solutions in a timely manner.

Following this line of thought, this thesis aims to create a project that thrives on the high-tech global economy by utilising Information Technology (IT) in order to rev up the implementation of one of the most prominent solutions to global warming – solar photovoltaic systems – thus fostering a society that is economically, socially and environmentally viable.

Welcome to The Age of Sustainable Development.

1.2. Overview and Thesis Statement

December 1, 1913: Henry Ford installs the first moving assembly line for the mass production of an entire automobile. His innovation reduced the time it took to build a car from more than 12 hours to 2 hours and 30 minutes. In doing so, Ford converted the automobile from an expensive curiosity into a practical commodity that would profoundly impact the landscape of the 20th Century. Ford's Model T had already been introduced in 1908 and was simple, sturdy and relatively inexpensive – but not inexpensive enough for the American industrialist, who was determined to build "motor car[s] for the great multitude." Ford was somehow obsessed with providing inexpensive goods to the masses: "When I'm through," he said, "about everybody will have one." In order to lower the price of his cars, Ford figured, he would just have to find a way to build them more efficiently (History.com Staff. 2009).

Fast forward to the twenty-first century, where as the economy shifts from carbon-emitting sources to greener options, the new reality is that the cost of electricity produced from renewable energy sources has finally reached grid parity or dropped below the cost of fossil fuels for various technologies in many parts of the world. Such is the case of solar photovoltaic (PV) modules, whose costs – much like the Model T – have been decreasing astronomically, precisely due to their rise in demand and manufacturing volume increases.

In fact, there's now frequent talk of a "Moore's law" in solar energy. In computing, Moore's law dictates that the number of components that can be placed on a chip doubles every 18 months. More practically speaking, the amount of computing power a consumer can buy for a dollar has roughly doubled every 18 months, for decades (Naam, R. 2011). And much like the computer chip manufacturers, solar cell manufacturers have been learning how to further reduce the cost to fabricate solar, alongside improving solar cell efficiency, thus plummeting the cost per watt of silicon PV cells from $76 in 1977 to less than $0.30 in 2015 (as can be observed in Figure 1).

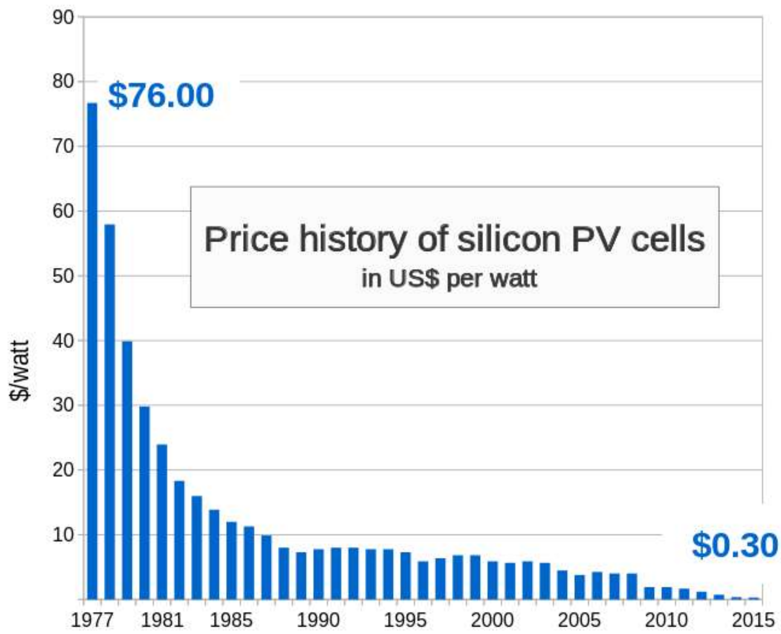


Figure 1: Price history of silicon PV cells from 1977 to 2015.
Source: Bloomberg, New Energy Finance & pv.energytrend.com

But while manufacturers are doing a fantastic job by providing consumers with increasingly affordable solar cells, for utility-scale applications solar modules constitute no more than one component in a complex system. In fact, module prices now make up less than half of the price of solar PV systems, whereas the planning and design, remaining equipment and installation and permit costs take up a much greater share of the budget pie (see Figure 2). Expertise is expensive. The design and installation of solar PV systems requires a lot of research, but the fact that the great majority of these tasks is exclusively entrusted to solar companies significantly inflates the price of PV system adoption, especially when compared to a more "information-based" approach.

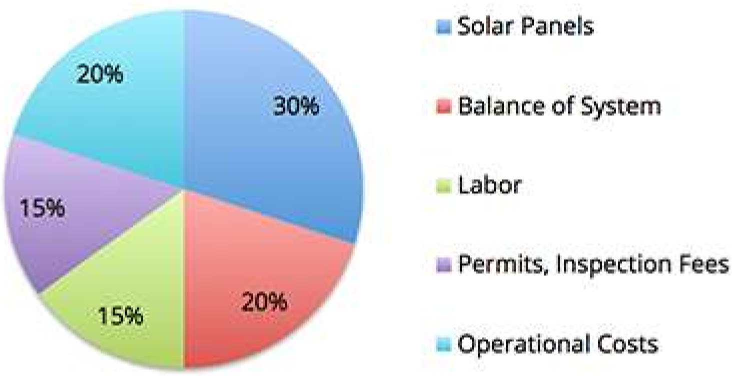


Figure 2: Solar PV system costs.
Source: energyinformative.org

However, the complexity of the process of getting up and running on solar PV systems is far from a showstopper for everyone. On the contrary, this type of renewable energy systems has actually been a driving force behind many changes to lifestyle a great many people have been putting into effect for decades. As it happens, a certain movement has been lurking in the eco-fringe, continuously growing in size as the conditions for its development became more and more favourable, and is now gaining such outstanding momentum that it is starting to border on mainstream – introducing: the off-the-grid movement.

Off-the-grid stands for both a lifestyle and a system (Vanini, P. 2014) designed to help people function without depending on remote infrastructure, such as an electrical grid. As this thesis aims to defend, this approach – whether by providing electricity to one household via a stand-alone power system or to a community via a microgrid – is far more than the root of modern electrification; it is a prospective solution to many present-day predicaments, such as global carbon-related emissions and energy poverty in third world countries.

So just like Henry Ford did in 1913 with the automobile, is it possible to break down the process of designing and acquiring off-grid solar PV systems into automatable steps, thus creating a "moving assembly line" that facilitates the implementation of this type of technologies? As many other solutions developed during this day and age, I believe the answer lies in IT – the application of computers and internet to store, retrieve, transmit, and manipulate data (Daintith, John, 2009). For example, if a company wants to get rid of its filing cabinets, a computer system is effortlessly able to allow the digitalisation of its company records. The company saves some precious office space, lowers its rent, adds new convenient features to its now digital records – such as search optimisation – and consequently saves a great deal of money.

In a similar fashion people have been using IT to transform much more complex concepts into commodities and business opportunities: online shopping websites like Amazon free consumers from buying products exclusively in brick-and-mortar stores by allowing them to buy directly from a seller over the internet, and services like Uber provide an alternative to hiring a taxicab by connecting paying passengers with drivers who provide the transportation on their own non-commercial vehicles. Both solutions are implemented through a computing platform which creates an online marketplace. These solutions slice down costs for both consumers and producers or service providers, allow both parties to overcome barriers of distance and extend their reach of doing business, and wrap these concepts in a layer of computational intelligence that, to top it all off, learns specific tasks from data or experimental observation and continuously improves user experience.

In a decade where renewable energy adoption is rapidly growing and information technology is booming, the time has come to identify what exactly can be done in order to skilfully integrate the two of them and, from a business standpoint, investigate how to turn the product of this combination into a profitable business that brings value to people's lives and fosters environmentally-friendly practices. This dissertation intends to do just that by developing a lean business plan based on an interactive platform that deals with the design and consequent purchase of the main components of an off-grid solar PV system.

However, turning a complex concept such as this one into a digital tool *and* business venture is no easy task. Isn't a business plan a complicated document that involves years of financial projections, thorough market analyses and detailed strategies that aim to achieve carefully calculated objectives? How can an electrical and computer engineering student intend to include all of this information in a dissertation whose main focus is supposed to be in scientific knowledge? To answer the question, turns out the key word here is "lean."

Launching a new enterprise – whether it is a tech start-up, a small business, or an initiative within a large corporation – has always been a very unpredictable proposition. According to traditional business formulas, one writes a business plan, pitches it to investors, assembles a team, introduces a product, and starts selling as hard as he can. However, odds are apparently against entrepreneurs from the start: new research by Harvard Business School shows that 75% of all startups fail. Yet recently an innovative methodology emerged called the "The Lean Startup," created by Eric Ries, which favours experimentation over meticulous planning, customer feedback over intuition, and iterative design over traditional "big design up front" development. The method was first proposed in 2008 and its popularity flourished rapidly, mainly due to the success of Ries' best-selling book, *"The Lean Startup: How Today's Entrepreneurs Use Continuous Innovation to Create Radically Successful Businesses,"* whose concepts have since quickly taken root in the start-up world. In fact, they have been so effective that even business schools have already begun adapting their curricula to teach them (Blank, S. 2013).

Therefore, instead of writing an intricate business plan, it is by following lean startup's principles that I intend to expose the future of my current hypothesis – i.e. Is it possible to create an interactive platform that not only designs customisable off-grid systems, but also helps people find and purchase their major components on various online marketplaces? – in a framework called a *business model canvas*, which is essentially a diagram of how a company creates value for itself and its customers (Blank, S. 2013). This interactive platform itself is intended to be a *minimum viable product* (MVP): a development technique in which a new product or website is developed with sufficient features to satisfy early adopters.

In other words, by the end of this dissertation I plan to have created an endeavour similar to a pilot experiment where I can start testing my hypothesis and find out if the interactive off-grid solar PV platform is a service that costumers would be ready and willing to use, and therefore a proper core for a prosper business venture. Furthermore, considering that all projects must have names, I will from this subchapter on proceed to call this one by its own – *The OffGridder*, a name which I believe accurately represents the subject of this venture while being catchy and easy to pronounce. As a matter of fact, I have already acquired the following domain: theoffgridder.com, which by the time this dissertation is defended it will already feature some quality content.

However, *The OffGridder*'s MVP – this dissertation's prime accomplishment – will not be a full-blown online tool just yet. Instead, in order to speed up the platform's development, the MVP will be entirely built in the spreadsheet-based software Microsoft Excel 2016. Its primary focus for now will be on load analyses and the consequent sizing process of all major components of an off-grid PV system – battery bank, solar array, charge controller, and inverter. Nevertheless, this does not mean that the platform will be completely disconnected from the web; as we will see, the MVP will still feature connections to online tools and marketplaces. In fact, based on its own spreadsheet intelligence it will not only guarantee that any user can design a stable, reliable off-grid PV system – it will also provide links to online platforms where the user can subsequently purchase all the selected, fully-compatible equipment.

1.3. Research Questions

In this subchapter I will list the main questions this dissertation aims to answer, preceding each one of them with a brief introductory paragraph.

Planning and designing off-grid solar photovoltaic systems varies from case to case, but it is fundamentally an application of scientific concepts that can therefore be subjected to the scientific method. Systematic observation helps identifying patterns that work better than others, while constantly formulating, testing and modifying hypotheses helps fostering progress. In order to create a platform that simulates these procedures it is therefore crucial to comprehend:

1. What common traits do most procedures of designing off-grid solar PV systems share?
2. How can one structure the whole design process into a step-by-step guide that covers as many cases as possible?
3. What should be prioritised in order to create a *minimum viable product* based on this information?

Lastly, as stated before, in order to formulate a *business model canvas* this project will have to grasp how it will create value for itself and its customers. Now, the platform is intelligibly what will provide value to its customers, but its financial sustainability will rely on the purchasing of off-grid solar PV systems feature, which has its own set of questions in need of answers:

4. How can *The OffGridder* integrate the services it provides (designing the system) with the purchasing of off-grid solar PV systems in order to achieve financial prosperity? In what way could information technologies perfect the experience of acquiring all the

needed equipment to start harvesting energy from the sun from stand-alone energy systems?

1.4. Outline of the Following Chapters

This dissertation is composed by six main chapters, including this one. This introductory chapter is followed by Chapter 2: one dedicated to comparing the three main types of solar PV systems – grid-tied, hybrid and off-grid – which also serves as an outlook on why off-grid PV systems matter and how if properly fostered they could greatly benefit the world.

After the systems comparison chapter comes the section where all the theory related to the design process of any off-grid PV system is going to be exposed. The design process is going to be divided into five steps, each one related to one of the main components that constitute the system, and in the end answers to research questions 1, 2 and 3 are going to be provided. A practical example is also going to be studied throughout this very important chapter as a way to solidify all knowledge acquired in every step that composes the design process.

Subsequently, Chapter 4 is where all theory turns into action. Relying on every step described in chapter two, I am going to explain how I developed an interactive platform in Microsoft Excel 2016 that speeds-up the process of designing an off-grid PV system. I will also demonstrate how the platform can be applied to real-life cases by using the example featured in the previous chapter. This platform is, in turn, *The OffGridder's minimum viable product.*

Afterwards, in Chapter 5 the entrepreneurship dimension of this dissertation is going to come to life. This is where research question 4 will be answered and where, through a *business model canvas,* I am going to make the case of how *The OffGridder* could indeed become a prosperous business venture.

Finally, Chapter 6 is where I am going to include both the "Discussion" and "Conclusion" sections. In the former, I am going to comment on my results, interpret them in a wider context and point out the limitations of my research while raising questions for future directions. I will discuss how my hypothesis has been demonstrated and then show how the field's knowledge has been changed by the addition of this new data. The latter is where I am going to conclude this dissertation by making concise statements about my main findings, as well as about what I learned, what were the hardest parts, to what extent I achieved my objectives, and where future research should go from here.

Chapter 2: Photovoltaic Systems Comparison

2.1. Overview

A photovoltaic system converts the sun's radiation into usable electricity. Photovoltaic devices generate electricity directly from sunlight via an electronic process that occurs naturally in certain types of material, called semiconductors. Photons strike and ionize semiconductor material on the solar panel, causing outer electrons to break free of their atomic bonds. Due to the semiconductor structure, the electrons are forced in one direction creating a flow of electrical current that can be induced to travel through an electrical circuit, powering electrical devices or sending electricity to the grid (Seia.org Staff). The systems consist of the solar PV array as well as balance of system components, such as inverters, charge controllers, batteries, and others, which can be assembled in several ways depending on their desired purpose.

PV systems can be categorised by various characteristics, such as their level of centralisation, utility or residential application, or mounting and building integration. This dissertation focuses on a very significant distinction between solar PV systems, which is whether or not they are connected to the electrical grid.

While grid-tied (grid-connected) and off-grid (stand-alone) PV systems are the two major types that constitute whether a system has an established connection to the utility grid, hybrid (battery backup) systems combine both of these approaches in order to come up with its own original set of advantages. Solar power in general offers many benefits to home and property owners, particularly a reduction in electricity costs. However, there are other benefits that are dependent on the type of system one chooses, and it is important to weigh the pros and cons in order to make accurate decisions. Let us now go through a brief overview of what devices constitute each of these types of systems and evaluate their unique benefits

2.2. Grid-Tied PV Systems

Grid-tied PV systems are by far the most common of all, require the least maintenance and are the most inexpensive of the three. Grid-tied installations include the possibility to earn, sell, and generate revenue from the electricity the PV system generates. They are extremely convenient because the utility company will provide either money for excess power generation, or supply electricity for whenever the solar array is not generating enough energy to power the home. This is especially appropriate for people who may not have enough sun exposure or space on their property for all of the panels required to power their home since they can still discount their current electricity rates (Cole, S. 2013). However, the owner of a grid-tied system is still as dependent on the grid as any other energy consumer, and may be disconnected from it in the event of a power outage.

In a grid-tied system, solar energy harvested by the system's solar panels flows straight into a grid-tied inverter, which fundamentally changes the direct current (DC) input voltage from the PV to alternating current (AC) voltage for the grid and certain appliances (see Figure 3). The inverter sits between the solar array and the grid, monitoring grid voltage, waveform and frequency, and drawing energy from both sides (Majumdar & Ramteke. 2016). The key distinction when compared to the remaining configurations is that the purpose of monitoring the grid is ultimately to decide if the solar energy should or should not pass along the inverter based on conditions imposed by the grid itself (e.g. if the grid is dead or straying too far out of its nominal specifications, energy flow will be cut).

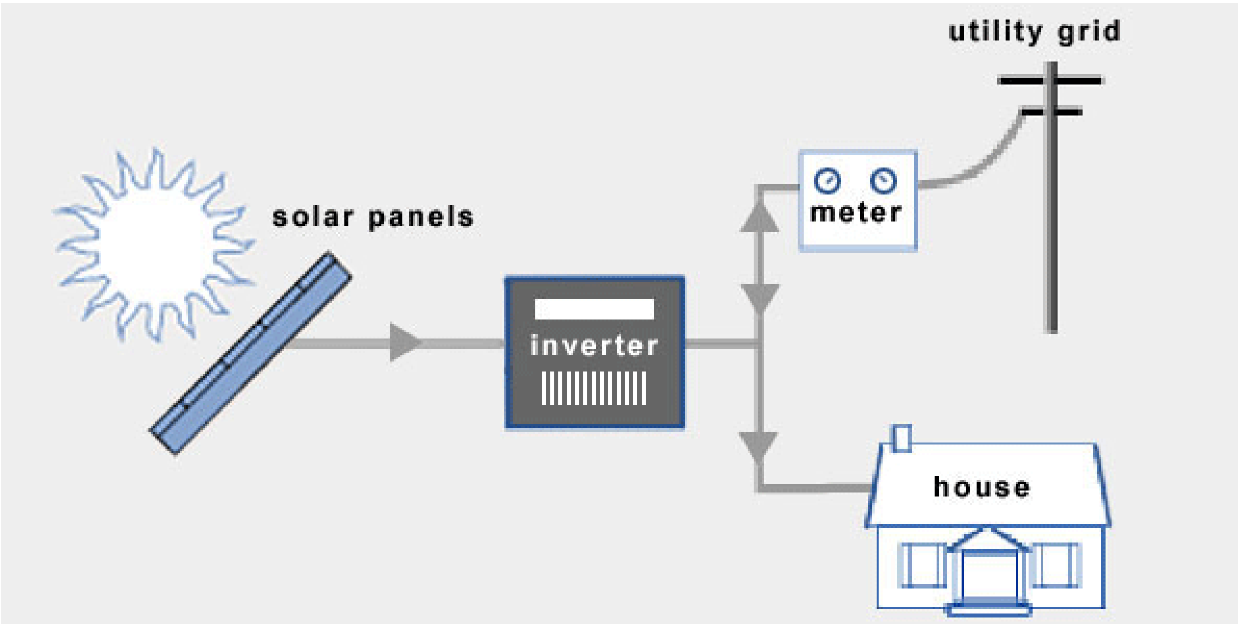


Figure 3: Basic schematic of a grid-tied solar PV system. Source: energyinformative.org

2.3. Off-Grid PV Systems

Off-grid PV systems are solar electric systems that are not connected to the electrical grid. While in a grid-tied scenario the system could shut off during a power outage for safety reasons, in an off-grid system the power will remain on for the household or building due to its complete independence from the grid. This sort of self-sufficiency has always been a great desire for many people, and the rise of distributed energy (DE) – smaller power-generation systems for homes, businesses and communities (Brief, B. 2013) – has significantly contributed to its astronomical rise in popularity.

Instead of relying on the utility grid, the system relies on batteries and other stand-alone equipment to store the electricity generated by the solar panels in order to combat their intermittency, i.e., to be able to use stored energy when the system is not generating enough to sustain household functions (as in at night, for example). These devices are mandatory for a fully functional off-grid solar system and add to costs as well as maintenance, making off-grid solar systems generally harder to install and more expensive.

Nevertheless, whether to gain more independence from centralised models, aspiring to assume as much responsibility as possible for their ecological footprint, wanting to avoid the high cost of extending a utility line, creating self-sufficient community, or simply for having a silent, emission-free energy source with a decade-long warranty, many people are attracted to off-grid systems and general lifestyle. But besides the creation of more locally centred, self-sufficient economies and communities that promote a sustainable approach to living, there are other significant reasons to foster off-grid energy generation. One of them is that while power deficits remain a powerful showstopper for economic growth and poverty reduction, around a billion people worldwide have no access to reliable and affordable energy, and changing these circumstances is an absolutely necessary condition for every aspect of human development. This is recognised in the sustainable development goals, or SDGs, which set a target of universal access to modern energy by 2030 (Watkins, K. 2015). Taken from World Bank's database, Figure 4 showcases the decadent state of access to electricity, namely in the African continent.

Figure 4: Access to electricity map (% of population). Source: Sustainable Energy for All (SE4ALL) database from World Ban

While some off-grid solar energy initiatives have been criticised for diverting attention from the urgent need to develop large-scale power infrastructures, this provision of renewable energy for rural populations living beyond the reach of national grids might just be the right choice to combat energy poverty in a politically instable continent. In fact, large-scale power infrastructures have their own sets of big disadvantages and developed countries spend huge sums of money every year on their development and maintenance – sums of money which are evidently out of reach for their developing counterparts. Fostering off-grid generation and consumption in developed countries could help drive down the costs of implementation *globally* for various stand-alone renewable technologies, which could in turn provide a timelier solution to people who either have no access to electricity or have to rely on costly, inefficient and polluting sources of energy. Furthermore, off-grid systems could provide energy to millions of people while more large-scale infrastructures are being built; besides, there is nothing preventing renewable solar power users from subsequently connecting to a prospective grid (Watkins, K. 2015).

As for system design, Figure 5 showcases the components that constitute an off-grid PV system. Key differences from grid-tied PV systems are the need of a distributed energy storage system (DESS), where the most commonly used are rechargeable battery technologies such as lead-acid or lithium-ion (Li-ion) batteries. There is also a consequent need for a charge controller, a device that nurses the DESS by limiting the rate at which current is added to or drawn from the battery bank, thus preventing unwelcome situations such as overcharging or voltage spikes and power surges. A charge controller may also prevent the complete discharge of a battery, or perform controlled discharges to protect battery life. Lastly, albeit fundamentally optional, an extra generator is sometimes coupled with an off-grid PV system to act as a backup supply of electricity for whenever the solar array is not generating enough energy to meet its owner's needs. However, as technologies develop the need to integrate polluting and inefficient sources of energy into renewable energy systems is becoming a thing of the past.

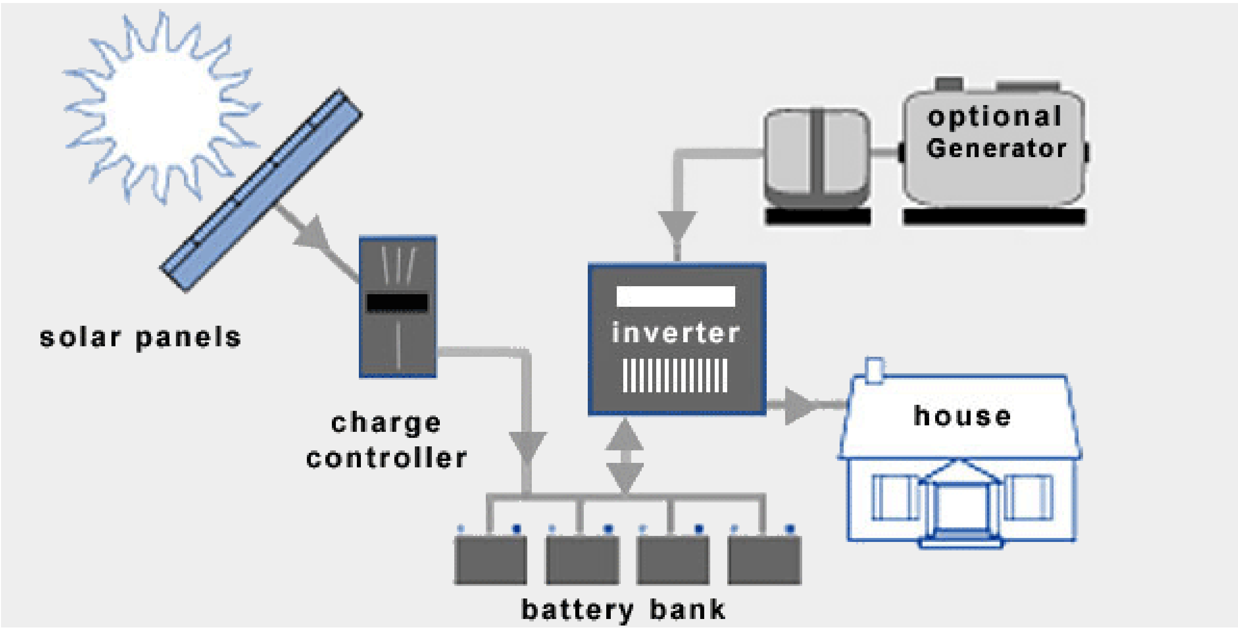


Figure 5: Basic schematic of an off-grid solar PV system. Source: energyinformative.org

In the meantime, solutions to the biggest bottleneck in off-grid PV systems – our ability to store power – are now gaining a considerable amount of momentum. The shared need for reliable energy storage by the transport, energy and infrastructure industries creates a potentially lucrative market for those that succeed in their efforts to deal with current DESS shortcomings (Gibbs, S. 2016), which consequently promises to soon plummet the market price of the one component that makes the costs of relying on an off-grid PV system skyrocket.

2.4. Hybrid PV Systems

Last but not least, hybrid PV systems combine the best of both grid-tied and off-grid PV systems, thereby counteracting many of the setbacks seen on those remaining configurations. These systems can either be described as off-grid solar with utility backup power, or grid-tied solar with extra battery storage (Maehlum, 2013), making them the most flexible of the three types. As it can be observed in Figure 6, a hybrid system still relies on a battery bank to store energy for times when the solar panels are not producing enough, but it also relies on the grid to supply electricity in such cases. Consequently, this setup completely eliminates the need of a backup generator, survives grid power outages by using its battery backup, and is considerably less expensive than an off-grid PV system due to the fact that not only the battery bank can be downsized, but surplus electricity can still be sold to the grid, thus contributing to a better return on investment (ROI).

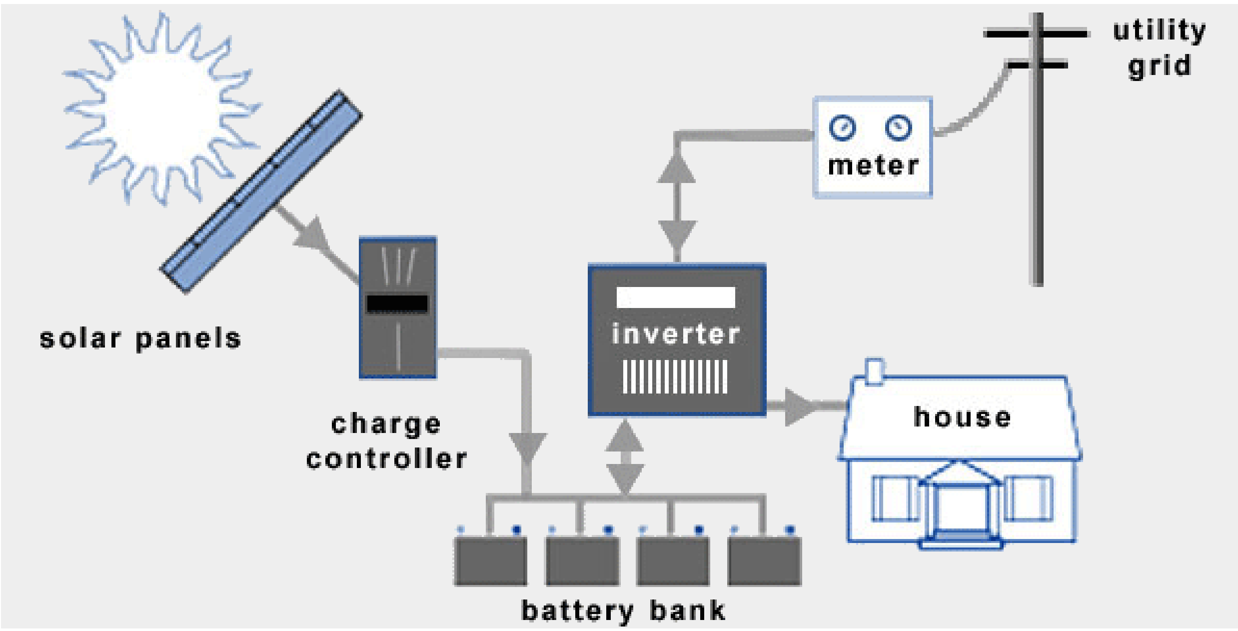


Figure 6: Basic schematic of a hybrid solar PV system. Source: energyinformative.org

Chapter 3: Designing an Off-Grid PV System

3.1. Layout

Cutting the utility grid's umbilical cord is not an easy task. Without the grid providing a supplemental electricity source, an off-grid system requires a lot of methodical planning and constant participation from any owner – besides maintenance and equipment servicing, this often means living within the original design's energy budget, planning for future growth, and having a backup energy source for times of high energy usage or low solar production (Weis, C. 2013). All of these stringent requirements make the process of designing an off-grid PV system a very delicate one, but also one of paramount importance.

What better place to start than by understanding the roles of all major constituents of any off-grid PV system? The first step I took in order to pursue this venture was to redesign the basic schematic observed in countless sources throughout the web (such as the one in Figure 5), while identifying and colouring the components which appeared to be of utmost noteworthiness to the functionality of the off-grid PV system. Figure 7 showcases said schematic, which will from now on just be referred to as "the Off-Grid (OG) schematic" and will function as the core layout in which both the theoretical and methodological parts of this dissertation will be based upon. Although present in the schematic, the components represented in grey will not be included.

The OffGridder's steps will subsequently be developed based on the following five components: load (green), battery bank (orange), solar array (blue), charge controller (yellow), and inverter (pink), together with an additional final step that will deal with the purchasing of all devices on the supply side (i.e. all but the load) selected by the user during the interactive design process. Let us first start with the demand side.

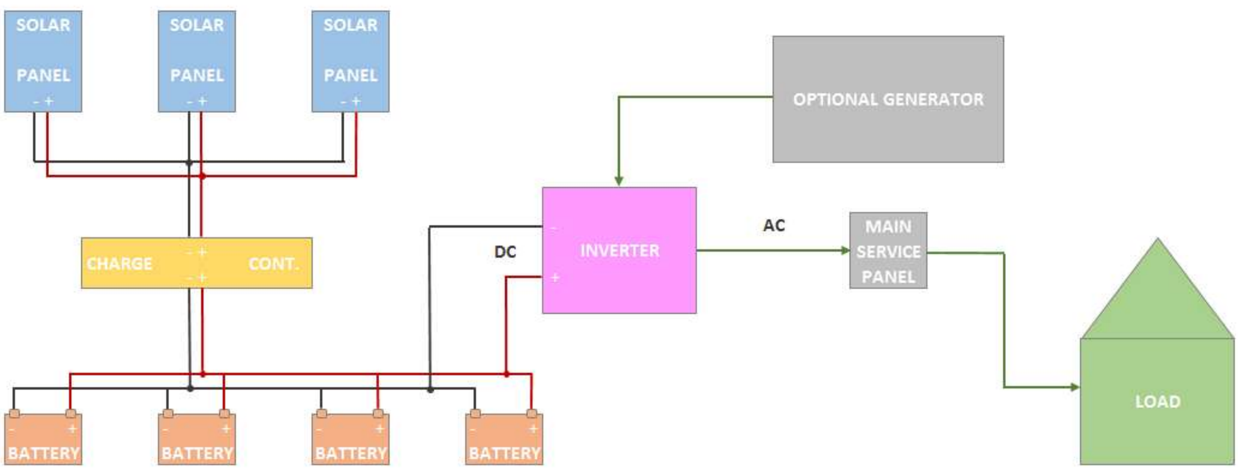


Figure 7: Coloured schematic of an off-grid PV system ("the OG schematic"). Source: Author's own figure

3.2. Step One: Load Analysis

When designing an off-grid PV system it is of foremost importance to have an accurate estimate of how much energy one will need. While on the grid-tied side a yearly average of power consumption is often sufficient to assess how much power a property requires, it is indispensable to perform a more thorough analysis and get to know all devices one will plug into a system in order to achieve self-sufficiency. This can be accomplished by completing a *load analysis*, which corresponds to the green part of the OG schematic (see Figure 8) as well as step one in the process of designing an off-grid PV system.

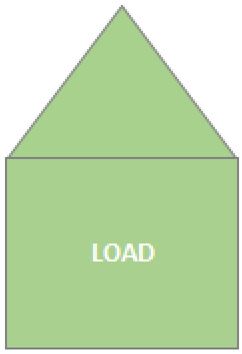


Figure 8: Load analysis in the OG schematic. Source: Author's own figure

A *load analysis* calculates the energy consumed by each appliance, with the ultimate goal of determining the total average daily energy consumed by all loads. This daily consumption value is then used to design a battery bank large enough to store that energy each day and a PV array large enough to produce the energy (Weis, C.). So as to protect the PV system and size the inverter, it is also crucial to distinguish between AC and DC loads, know what devices will be on at the same time, and keep track of possible power surges that some appliances may cause. This analysis usually has the form of a table where each line represents a group of identical devices.

To calculate the total average daily energy consumed by all loads (E_D), which is expressed in Watt-hours per day, we need to know how much power each load consumes (P_L– expressed in Watts), how much time per day each load will be on (t_L – expressed in hours per day) as well as the number of identical loads (n) in order to group them in the same line/equation. The product of these three variables gives us the final result, as can be observed in Equation 1.

$$E_D = \sum_L n_L * P_L * t_L$$

(Watt-hours per day), where L = each individual load that composes the system

Equation 1: Total average daily energy consumed

In order to compile all detailed information into a single table, I create one with eight distinct columns, as can be seen in Table 1.

Table 1: Load Analysis. Source: Author's own table

Quantity	Load name / Appliance	On at Same Time?	AC Watts	DC Watts	AC Surge	Hours on per day	Watt-hours/day
		☑					

[Underlined text marks the passage to an example]

Let us now construct a demonstration that will serve us as an example for the rest of the dissertation. It should include loads of different kinds, DC and AC, with different power surges and different levels of control over which of them are on simultaneously. Please observe Table 2.

Table 2: Load Analysis input data example. Source: Author's own table

Quantity	Load name / Appliance	On at Same Time?	AC Watts	DC Watts	AC Surge	Hours on per day	Watt-hours/day
1	Dishwasher	☑	356		400	1	356
1	LED light bulb	☐	7		7	12.5	88
2	DC light bulbs	☐		40		1	80
1	DC fan	☑		60		1	60
1	Fridge	☑	600		2000	2	1200

3.3. Step Two: Battery Bank Sizing

On the power supply side, the first step is to use the final average daily load value – along with a variety of other variables – in order to calculate battery bank requirements. Sizing the battery bank is perhaps the most crucial step in the process of designing an off-grid PV system insomuch as it not only requires an information input from the load side, which naturally imposes that the batteries must be sized accordingly, but its results will also affect every design calculation for every component that constitutes the system. This process is represented by the colour orange in the OG schematic (see Figure 9).

Figure 9: Battery bank sizing process in the OG schematic. Source: Author's own figure

Given the predominant role these devices have in the design process and the radical alterations that are currently unfolding in the battery industry, before proceeding with the sizing of battery banks I believe it is important to distinguish some of the main battery technologies available nowadays, as well as investigate the potential opportunities the energy storage market is offering at the present time.

3.3.1. Lead-Acid vs. Lithium-Ion

Lead-acid and lithium-ion batteries are the two main players in the battery market. However, even though lead-acid has been the standard in batteries for decades, it compares very poorly in various aspects when compared to lithium-ion technologies. So I will take this opportunity to compare these two energy storage options and justify why *The OffGridder's* battery database (BatteryDb) will be entirely composed of lithium-ion batteries while dismissing their lead-acid counterparts.

Depth of Discharge (DoD) is perhaps one of the most crucial battery specs people refer to when comparing the two main battery technologies used in off-grid PV systems. While cycle life is greatly affected by higher levels of discharge in lead-acid batteries, lithium-ion batteries are much less affected by it. In fact, most lead-acid manufacturers do not even recommend more than 50% DoD (Messina, C. 2015), which greatly reduces the value of the capacity a person pays for. On the other hand, Li-ion batteries do allow discharging 100% of the energy, athough for general applications a DoD of 80% is recommended (GWL Power Staff, 2015), which still composes a huge difference. Manufacturer-supplied specification sheets also show that lead-acid batteries can typically be expected to last only 200-300 standard cycles at 100% DoD before degrading to 80% capacity (the standard measure of end-of-life), whereas Li-ion cells fade to 80% capacity only after more than 500 cycles (Krieger, Cannarella & Arnold. 2013). Furthermore, if only partial discharges are considered then the gap becomes much wider: as can be observed in Figure 10, at lower DoDs Li-ion batteries cycle more than 2000 times whereas lead-acid technologies drop to 250-500 cycles of battery life.

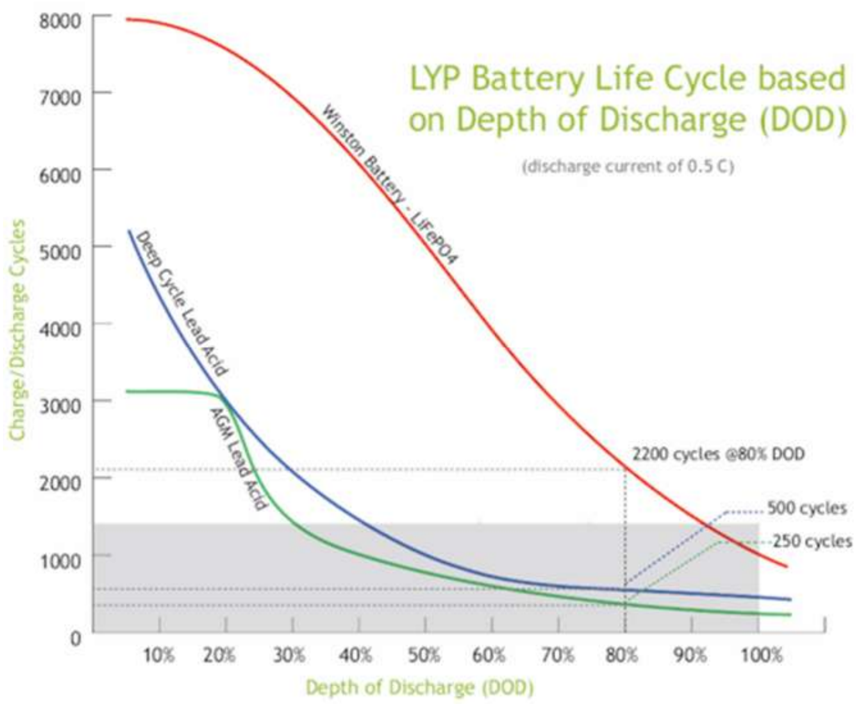


Figure 10: Battery cycle life comparison. Source: GWL/Power – Product Information and Technical Support Blog

This has huge repercussions for the true cost of ownership of these technologies. Despite the higher upfront cost of lithium-ion batteries, the true cost of ownership is far less than lead-acid when considering life span and performance, as can be observed in Figure 11.

COST SAVINGS	LEAD ACID	LITHIUM ION
Life Span (in daily cycles)	300	5000
Amp Hours	110	100
Cost	$339.71	$1,299.99
Batteries needed x 10 Years	11	1
Total cost for 10 years spend	$3,736.81	$1,299.99
Total Savings	$0.00	$2,436.82

Figure 11: Lithium-ion vs lead-acid cost analysis. Source: Bean, R. (2016) "Lead acid vs Lithium-ion batteries"

But cycle life and ownership cost are not the only specifications where lead-acid batteries fall behind. Lithium-ion batteries are one-third the weight of lead-acid batteries and are nearly 100% efficient in both charge and discharge (Messina, C. 2015), while their lead-acid counterparts waste as much as 15% of the energy put into them via inherent charging inefficiency (Bean, R. 2016). Over and above, Li-ion batteries maintain their voltage throughout the entire discharge cycle, which allows for greater and longer-lasting efficiency of electrical components. On the other hand, lead-acid voltage drops consistently throughout the discharge cycle. Besides, although the first 80% of a lead-acid battery can be "bulk charged" by a smart three-stage charger quickly, during the final 20% an "absorption" phase begins and the charging current drops off dramatically. Li-ion batteries are also fairly maintenance free, where a "balancing" process to make sure all the cells in a battery bank are equally charged can be easily achieved by a Battery Management System (BMS) (Bean, R. 2016), while lead-acid battery users constantly need to keep track of battery voltage, water levels, overcharge functions, and routine electrolyte maintenance (Gretz, A. 2016).

Moreover, on top of all those significant discrepancies comes the fact that lead-acid batteries compare very poorly to lithium-ion with regards to environmental friendliness. Lead-acid batteries require many times more raw material than lithium-ion to achieve the same energy storage, making a much larger impact on the environment during the mining process. The lead processing industry is also very energy intensive, leading to large amounts of pollution (Albright, Edie, Al-Hallaj. 2012). They also contain sulphuric acid, which is extremely corrosive, as well as large amounts of lead which is a highly toxic metal that produces a range of adverse health effects, particularly in young children (Zafar, S. 2016).

Deciding to leave out lead-acid technologies from *The OffGridder* is therefore about more than just efficiency. These environmental and health effects go completely against what this project stands for, so it would not make sense to include such primitive and hazardous technologies when there are much better alternatives available in the battery market.

3.3.2. The Lithium-Ion Opportunity

As briefly mentioned before, various industries (such as the electric vehicles') are now invested in driving down the costs of batteries by ramping up lithium-ion battery production, which could be excellent news for the off-grid world, as well as an outstanding business opportunity for anyone who can grab early shares in this rather untapped market. That is something to keep in mind for the business plan I will present later, but let us take a brief look at the numbers first. Nykvist and Nilsson recently published a study in Nature Climate Change saying that if battery prices fell to less than US$150 per kWh, electric cars would be cost competitive with combustion cars. In turn, Elon Musk – CEO of Tesla Motors, Inc. – predicted that the Gigafactory – a massive lithium-ion battery factory under construction and already in production, primarily for Tesla Motors – could reach $100 per KWh by 2020, beating industry projections by about five years (Coren, M. 2016). These predictions do not seem to be all that far-fetched considering studies like the one represented in Figure 12, which showcases data compiled by Bloomberg New Energy Finance about the estimated range for future costs for lithium-ion battery packs.

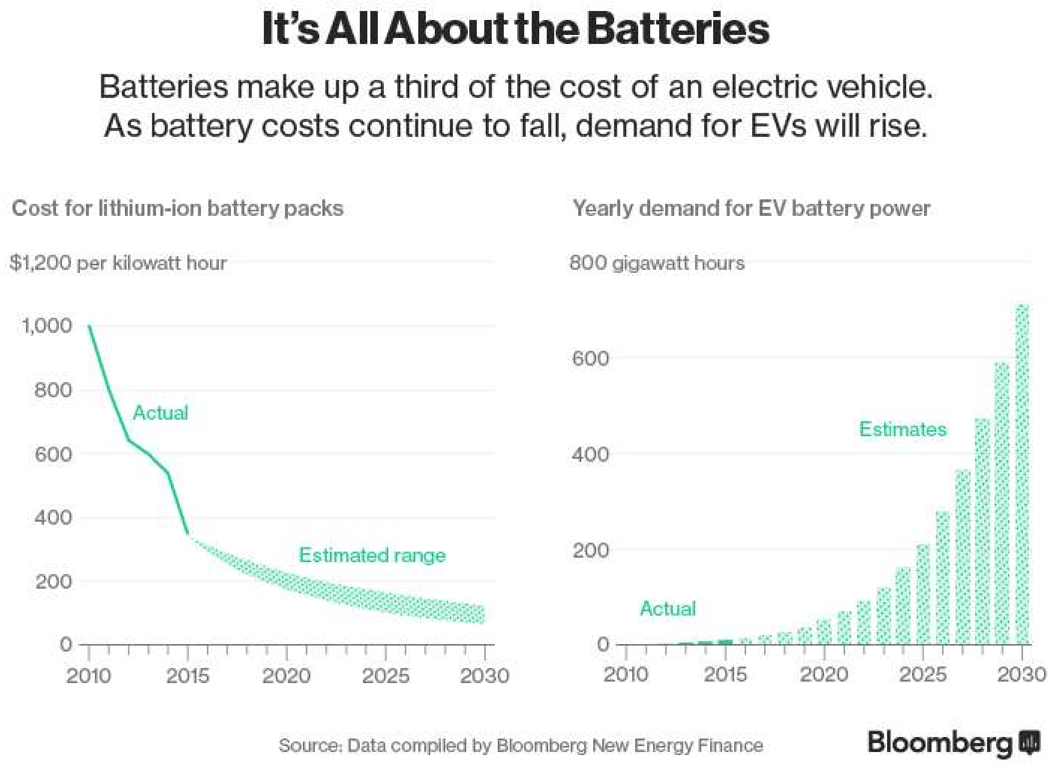


Figure 12: Cost for lithium-ion battery packs. Source: Data compiled by Bloomberg New Energy Finance

Now according to the World Energy Council's Energy Efficiency Indicators, the European Union (EU)'s average electricity consumption per electrified household was 3600 kWh/hh (kilowatt hour per household) in 2014. If the aforementioned predictions were to become true and considering energy efficiency measures and sizing calculations, this could mean that lithium-ion battery banks could indeed become very cost-effective and in turn provide a proper alternative to grid-tied living in the near future, thus making the present moment a very exciting and prosperous time to take on ventures related to off-grid living.

Given all those important considerations, let us now resume the process of sizing a battery bank for off-grid PV systems. Values that are to be taken into consideration before selecting a battery bank are the number of Days of Autonomy (DoA), maximum Depth of Discharge (DoD), battery bank's ambient operating temperature multiplier (T_B), and the desired system voltage (V_{system}).

Days of Autonomy dictates how many days (in a row) the battery bank will need to sustain the average daily load when there is little or no sunshine to recharge it. It is a compromise between having energy during overcast spells and the added cost of a larger battery bank. Generally, three to five days of autonomy provides a good balance. The more days of autonomy desired, the larger the battery bank, and in turn the larger the PV array will need to be to recharge the bank sufficiently on a regular basis (Munro, K. 2010).

Besides *DoA*, *maximum DoD* is also a very dominant criterion for sizing battery banks as it will greatly affect their cost. This is due to the fact that, as we have seen, the number of cycles deep-cycle batteries can provide over their lifetime is inversely proportional to the deeper they are discharged on a regular basis. As mentioned, this is also a value that is highly dependent on the type of batteries chosen to compose the bank. When considering a maximum DoD, another compromise between longevity, cost, and the inconvenience of replacing the bank has to be considered. DoA and DoD will often multiply the amount of capacity needed for energy storage, but keep in mind that off-grid PV systems must *always* be carefully planned taking worst-case scenarios into account.

Ambient operating temperature is also known to affect battery capacity. These two variables are directly proportional, given that a decrease in temperature reduces battery life. In order to properly estimate how a certain battery will deal with the ambient temperature in a specified location, a battery temperature multiplier table is usually provided by battery manufacturers. The buyer should therefore retrieve the multiplier from the table while taking into consideration the coldest indoor or outdoor temperature of his current area – depending on where the batteries will be placed.

Lastly, there are important considerations one has to take into account when choosing his *system voltage*, which will consequently be defined by chosen battery bank voltage. The higher the system voltage the more flexibility as to how far away one can place the solar array from the battery bank: for a given power output, a higher system voltage reduces amperage flow which allows the owner to use a smaller and less expensive gauge wire throughout his solar panels, battery and inverter wire runs (altE Staff). While in the past it was common practice to reduce the cost of an off-grid system by limiting its size through the use of 12V appliances and lighting that did not require an inverter, today most systems are 24V or 48V and include a 230V AC inverter. We need to adapt to this progress and take into account that inverters and solar panels have become more efficient and a lot more affordable, making off-grid systems increasingly qualified to accommodate more power consumption and scalability (Rainbow Power Company Staff).

Now that we have pinpointed all these variables, it is time to calculate the size of an arbitrary battery bank. Equation 1 gives us E_D, i.e. the total average daily energy consumed by all loads. But in order to size the battery bank, we need to distinguish between AC loads – where we have to take into account the efficiency of the inverter by respectively dividing one by the other – and DC loads that pull power directly from the DC system, bypassing the inverter. Equations 2 and 3 calculate the total average daily energy consumed by AC loads (without considering inverter's efficiency), as well as by DC loads, respectively.

$$E_{D_{AC-noinverter}} = \sum_{L_{AC}} n_{L_{AC}} * P_{L_{AC}} * t_{L_{AC}}$$

(Watt-hours per day), where L_{AC} = each AC load

Equation 2: Total average daily energy consumed by AC loads (without considering inverter's efficiency)

$$E_{D_{DC}} = \sum_{L_{DC}} n_{L_{DC}} * P_{L_{DC}} * t_{L_{DC}}$$

(Watt-hours per day), where L_{DC} = each DC load

Equation 3:Total average daily energy consumed by DC loads

Considering the efficiency of the inverter ($\eta_{inverter}$), we can now calculate the total average daily energy consumed by AC loads (see Equation 4):

$$E_{D_{AC}} = \eta_{inverter} * E_{D_{AC-noinverter}}$$

(Watt-hours per day)

Equation 4: Total average daily energy consumed by AC loads

Now in order to get the total load as seen by the battery bank we add the AC and DC figures together (see Equation 5).

$$E_{B_{bank}} = E_{D_{AC}} + E_{D_{DC}}$$

(Watt-hours per day)

Equation 5: Total load as seen by the battery bank

Next, we need to multiply $E_{B_{bank}}$ by desired days of autonomy, divide it by chosen depth of discharge and multiply it by the ambient temperature multiplier in order to obtain the daily minimum Wh capacity of the battery bank (see Equation 6).

$$E_{BFINAL} = \frac{E_{B_{bank}} * DoA}{DoD} * T_B$$

(Watt-hours)

Equation 6: Minimum Watt-hour capacity of the battery bank

However, battery capacity is usually expressed in Amp-hours (Ah), so according to Ohm's law we need to divide the result obtained in Watt-hours (Wh) by the desired system voltage in order to obtain a result in Amp-hours (see Equation 7).

$$C_{B_{bank}} = \frac{E_{BFINAL}}{V_{system}}$$

(Amp-hours)

Equation 7: Minimum Amp-hour capacity of the battery bank

Now that we have reached the Ah capacity that will give us the total needed storage, it is important to keep in mind that it is best to keep the number of parallel strings of batteries to three or fewer when wiring the battery bank. This is due to the fact that batteries are prone to be unevenly charged, which in turn shortens their life. For future calculations we need to keep in mind the basic principles of electric circuit connections which tell us that when batteries are cabled together in series the voltage is additive and Ah capacity remains constant, while when batteries are connected in parallel the voltage remains constant and the Ah capacity is additive (Btek Staff).

The batteries the future owner selects must meet both his system voltage requirements as well as the Ah capacity we calculated divided by the *maximum number of parallel strings* ($\mathrm{n_{pstrings}}$), which will in turn give us our minimum daily Amp-hour capacity per battery (C_B) that will compose the battery bank (see Equation 8).

$$C_B = \frac{C_{B_{bank}}}{n_{pstrings}}$$

(Amp-hours)

Equation 8: Minimum Amp-hour capacity per battery that constitutes the battery bank

Finally, given a battery with an arbitrary voltage ($V_{battery}$) and capacity in Ah ($C_{battery}$), the following calculations should be made in order to calculate the number of batteries in each series string ($n_{batteriesperstring}$) (see Equation 9).

$$n_{batteriesperstring} = \frac{V_{system}}{V_{battery}}$$

Equation 9: Number of batteries in each series string

Equation 9 will make sure the bank meets the system voltage's requirements. In turn, the capacity of each battery should be greater than the minimum daily Amp-hour capacity value:

$$C_{battery} > C_B$$

Lastly, the product between the chosen number of parallel strings and the number of batteries in each series string gives us the total number of batteries needed to compose the battery bank ($n_{totalbatteries}$), as can be observed in Equation 10.

$$n_{totalbatteries} = n_{pstrings} * n_{batteriesperstring}$$

Equation 10: Total number of batteries needed to compose the battery bank

Carrying on the example set in Table 2, in order to make the battery bank sizing math clearer let us start by taking a look at Table 3:

Table 3: Load calculations and battery bank sizing input data example

Input data	
V_{system}	48V
E_D	$\sum_L n_L * P_L * t_L$ = 1784 Wh/day
AC Loads ($E_{D_{AC-noinverter}}$)	$\sum_{L_{AC}} = n_{L_{AC}} * P_{L_{AC}} * t_{L_{AC}}$ =1644 Wh/day
DC Loads ($E_{D_{DC}}$)	$\sum_{L_{DC}} = n_{L_{DC}} * P_{L_{DC}} * t_{L_{DC}}$ =140 Wh/day
DoA	3 days (minimum recommended)
DoD	80% (wishes to acquire Li-ion batteries)
Minimum temperature estimated	10ºC
$\eta_{inverter}$	92% (typical)
$n_{pstrings}$	2 (recommended)

Question: How many identical batteries would it take to compose a battery bank that would properly accommodate those system specifications?

Total load as seen by the battery bank:

$$E_{D_{AC}} = \eta_{inverter} * E_{D_{AC-noinverter}} = 0.92 * 1644 = 1748.58\ Wh/day$$

$$E_{B_{bank}} = E_{D_{AC}} + E_{D_{DC}} = 1888.58\ Wh/day$$

Minimum Watt-hour capacity of the battery bank:

$$E_{BFINAL} = \frac{E_{B_{bank}} * DoA}{DoD} * T_B = \frac{1888.58 * 3}{0.8} * 1.08 = 6373.95\ Wh$$

Minimum Amp-hour capacity per battery that constitutes the battery bank:

$$C_{B_{bank}} = \frac{E_{BFINAL}}{V_{system}} = \frac{6373.95}{48} = 132.79\ Ah$$

Minimum Amp-hour capacity per battery that constitutes the battery bank:

$$C_B = \frac{C_{B_{bank}}}{n_{pstrings}} = \frac{132.79}{2} = 66.40\ Ah$$

So if we selected the following battery:

Table 4: Battery specifications for battery bank sizing example. Source: lithiumion-batteries.com

Type	Name	$V_{battery}$	$C_{battery}$	T_B at 10ºC
Li-ion	Smart Battery 12V 75Ah	12 V	75 Ah	1.08

Which passes the $C_{battery} > C_B$ test, we would need a battery bank with the following number of batteries in each series string:

$$n_{batteriesperstring} = \frac{V_{system}}{V_{battery}} = \frac{48}{12} = 4$$

Answer: In order to satisfy a total load of 1784 Wh/day with 1644 Wh/day coming from AC loads and 140 Wh/day coming from DC loads, the total number of Smart Battery 12V 75Ah batteries needed to compose a battery bank with a minimum of 2 parallel strings and a system voltage of 48V would be:

$$n_{totalbatteries} = n_{pstrings} * n_{batteriesperstring} = 4 * 2 = 8$$

3.3. Step Three: Solar Array Sizing

Now that we have calculated the loads' energy needs and the necessary storage to withstand them, the next step is to find out how to calculate the number of PV modules needed for any off-grid PV system. Just like for batteries, *The OffGridder* will feature a solar panel database (PanelDb), as well as a database for the remaining components as well. The array calculations must include Wh per day (calculated from the average daily load), the location's solar resource expressed in daily peak sun-hours (worst-case scenario), as well as a system efficiency factor that accounts for all loses, such as battery and charge controller efficiency losses (even with Li-ion batteries which are almost 100% efficient), module temperature losses and a conservative derate multiplier to account for things like wire losses, module soiling, and production tolerance. According to Affordable Solar, this system efficiency factor (η_{system}) is usually estimated between 0.65 – 0.7 for stand-alone systems (0.55 – 0.6 for systems with a non-MPPT charge controller). The factor is lower than the ones used for sizing grid-tied solar arrays, especially due to the addition of a battery bank and charge controller, as well as because of the differences in inverters between grid-tied and off-grid systems (which I will mention later). The solar array sizing process is represented by the colour blue in the OG schematic, as can be observed in Figure 13.

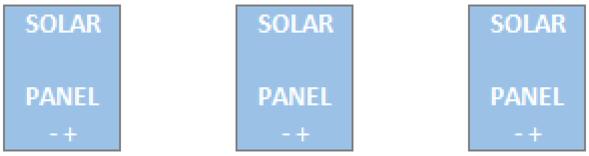


Figure 13: Solar array sizing process in the OG schematic. Source: Author's own figure

3.3.1. Sun-Hours and Minimum Solar Array Power Output

While the amount of daylight hours in any given location is a convenient thing to know, a more accurate representation of the amount of energy an array can produce is given by peak sun-hours (Solar Power Authority Staff). But in order to understand what a sun-hour is, we must first think of solar irradiance – the output of light energy from the entire disk of the Sun, measured at the Earth (Zell, H. 2008). Solar irradiance has a SI unit of Watt per square metre (W/m^2) and varies based on the sun's position in the sky, clouds, and other atmospheric conditions. Integrated over time it gives us solar insolation, which according to the Sandia National Laboratories is a measurement of the cumulative [solar] energy measured over some area for a defined period of time. In turn, by adding up the various amounts of solar insolation over the course of a day and counting them as units equivalent to 1 solar-noon midsummer hour (1,000 watts per square meter for 1 hour), we get a very useful comparison number – the peak sun-hour (Huffman, J. 2007).

Fortunately, there are many tools online that can help us find the amount of solar energy an arbitrary location receives on an average day during the worst month of the year. Again, as the off-grid PV system must be prepared to handle absolute worst-case scenarios we want to find out which one is the worst day of the year in terms of amount of solar energy and use it for our calculations. As we will see in the developing part, *The OffGridder* will incorporate a small latitude and longitude interactive database that can be used along with NASA's *Surface meteorology and Solar Energy* tool to retrieve the worst-case scenario peak sun-hours (h_{minsun}) for an arbitrary location

All variables needed to calculate the minimum solar array power output that satisfies the calculated load's energy needs (P_{array}) are now identified: the total average daily energy consumed by all loads (E_D), system efficiency factor η_{system} and worst-case scenario peak sun-hours (h_{minsun}). The final calculation is the expressed in Equation 11:

$$P_{array} = \frac{\frac{E_D}{h_{minsun}}}{\eta_{system}} \text{ (Watts)}$$

Equation 11: Minimum power the array must generate in order to satisfy the load's energy needs

Given this calculation, we can now move on to the sizing of the solar array.

First of all, we need to make sure that the number of panels that will compose the array will allow us to wire them so that the nominal voltage of the panels either matches or is higher than the voltage of the battery bank (V_{system}). This requirement will define the minimum number of panels in each series string ($n_{panelsperstring}$) and can be easily satisfied by looking at a solar panel's specification sheet, finding its nominal voltage ($V_{N_{panel}}$), and dividing it by the system voltage, as represented in Equation 12. This number needs to be an integer, but in this early version of *The OffGridder* there is no need to round it up because the $V_{N_{panel}}$ of the solar panels featured in the PanelDb so far are all multiples of the V_{system} options which will be available (12/24/48V).

$$n_{panelsperstring} = \frac{V_{system}}{V_{N_{panel}}}$$

Equation 12: Minimum number of panels in each series string

Another product information listed in every solar panel specification sheet is the maximum power it is able to generate ($P_{panelmax}$), expressed in Watt-peak (Wp). In order to find out the minimum number of panels that must compose the array in order to satisfy the load's energy needs (n_{panels}), one can simply divide P_{array} and $P_{panelmax}$, as shown in Equation 13:

$$n_{panels} = \frac{P_{array}}{P_{panelmax}}$$

Equation 13: Total number of panels that must compose the array in order to satisfy the load's energy needs

Now that we know the number of panels that goes in each series string and the total number of panels that will compose the array, it is trivial to calculate the integer number of strings needed to compose the array ($n_{arraystrings}$). Equation 14 does that by rounding up the division between n_{panels} and $n_{panelsperstring}$:

$$ROUNDUP(n_{arraystrings}) = ROUNDUP(\frac{n_{panels}}{n_{panelsperstring}})$$

Equation 14: Number of strings needed to compose the array (rounded up)

If this number is not originally an integer, it needs to be rounded up which in turn might add some extra panels to the array in order to guarantee a balanced system. This will become more obvious in the example I will present subsequently. The final minimum number of panels which must compose the array in order to satisfy the load's energy needs *and* guarantee that the array's voltage is equal or greater than the system voltage ($n_{totalpanels}$) is:

$$n_{totalpanels} = ROUNDUP\left(n_{arraystrings}\right) * ROUNDUP(n_{panelperstring})$$

Equation 15: Final minimum number of panels which must compose the array in order to satisfy the load's energy needs and guarantee that the array's voltage is equal or greater than the system voltage

<u>Once more, let me follow up with an example in order to make the calculations more easily understandable and show how these equations can be applied in real life:</u>

Lisbon's latitude and longitude values are, respectively, 38.72272288 and -9.144866305. If we introduce these values on the following NASA webpage – https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?email=skip@larc.nasa.gov, click on the first parameter named "Average insolation" and click on the submit button, we will see a table named "Monthly Averaged Insolation Incident On A Horizontal Surface (kWh/m^2/day)" for which we can retrieve the number of worst-case scenario peak sun-hours (h_{minsun}). In this case the number is 2.0.

Next, let us continue the example presented in Table 2, where $E_D = 1784$ Wh/day and $V_{system} = 48V$m and suppose that we want to acquire an MPPT charge controller, which will give us a system efficiency factor η_{system} between 0.65 – 0.7 for stand-alone systems (we will consider the average between the two – 0.675). We can now use Equation 11 to calculate the minimum power the array must generate in order to satisfy the load's energy needs:

$$P_{array} = \frac{\frac{E_D}{h_{minsun}}}{\eta_{system}} = \frac{\frac{1784}{2}}{0.675} = 1321.33\ W$$

Supposing that we select the following solar panel:

Table 5: Solar panel specifications for solar array sizing example. Source: ev-power.eu

Name	**Nominal Voltage ($V_{N_{panel}}$)**	**Peak Power ($P_{panelmax}$)**
GWM Sunny Poly 150 Wp 36 cells	12 V	150 Wp

With Equation 12 we can start by calculating the minimum number of panels in each series string (rounded up):

$$n_{panelsperstring} = \frac{V_{system}}{V_{N_{panel}}} = \frac{48}{12} = 4$$

Next, we can now calculate the total number of panels that must compose the array in order to satisfy the load's energy needs (rounded up) by using Equation 13:

$$ROUNDUP(n_{panels}) = \text{ROUNDUP}\left(\frac{P_{array}}{P_{panelmax}}\right) = ROUNDUP\left(\frac{1321.33\ Wp}{150\ \text{Wp/panel}}\right) =$$

$$ROUNDUP(8.81) = 9 \text{ panels}$$

Using this number, we can now calculate the number of strings needed to compose the array (rounded up) via Equation 14:

$$ROUNDUP(n_{arraystrings}) = ROUNDUP\left(\frac{n_{panels}}{n_{panelsperstring}}\right) = ROUNDUP\left(\frac{8.81}{4}\right)$$

$$= ROUNDUP(2.2) = 3 \text{ parallel strings}$$

Lastly, let us use Equation 15 to reach the final minimum number of panels which must compose the array in order to satisfy the load's energy needs *and* guarantee that the array's voltage is equal or greater than the system voltage:

$$n_{totalpanels} = ROUNDUP(n_{arraystrings}) * ROUNDUP(n_{panelperstring}) = 3 * 4 = 12$$

Notice how although power-wise 9 panels satisfy the load's energy needs, they could never be assembled in 3 parallel strings of 4 in order to guarantee that the array's voltage is equal or greater than the system voltage. 9 panels would instead compose 3 parallel strings of 3 panels and would only reach a voltage of 36 V, which would be inferior to the specified 48V system voltage.

Answer: In order to satisfy a total load of 1784 Wh/day with a system voltage of 48V, one could choose to buy 12 GWM Sunny Poly 150 Wp 36 cells panels and compose a battery bank of 3 parallel strings with 4 panels in each series string.

3.4. Step Four: Sizing a Solar Charge Controller

Next in line in the process of designing an off-grid PV system is the task of sizing a solar charge controller. According to solar-electric.com, a charge controller – or charge regulator – is basically a voltage and/or current regulator to keep batteries from overcharging. It regulates the voltage and current coming from the solar panels going to the battery. This process is represented by the colour yellow in the OG schematic, as can be observed in Figure 14.

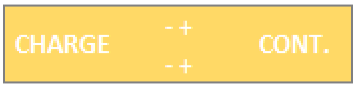


Figure 14: Charge controller sizing process in the OG schematic. Source: Author's own figure

Solar panels greater than 20 W or so generally cannot be directly connected to a load because the voltages they produce are not compatible with most batteries and equipment – a solar panel with a nominal voltage of 12 V can actually go as high as 17-19 volts in bright sunlight. But while an obvious problem exists when a 24 or 48 V solar array powers a 12V load, a well-chosen solar charge controller can ensure proper compatibility. One good analogy is thinking about a solar charge controller as a car's transmission: it provides controlled application of input power (Warren, C. 2015).

Decades ago, the most basic of charge controllers simply monitored the battery voltage and opened the circuit, stopping the charging when battery voltage rises to a certain level. Older charge controllers used a mechanical relay to open or close the circuit, stopping or starting power going into the batteries. Before continuing with the process of selecting a proper charge controller for any off-grid PV system, let us first take a brief look at the two main types of technology on the market nowadays: Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT).

3.4.1. Pulse Width Modulation vs. Maximum Power Point Tracking

PWM is relatively simple and has also been around for decades. One disadvantage is that under most conditions a PWM solar charge controller will not take advantage of the full capacity of the panels (Warren, C. 2015), but instead just slowly lower the amount of power applied to the batteries as the batteries get closer and closer to fully charged (Enerdrive Staff). This is the most common, least expensive, and easiest to deploy solar charge controller technology (Warren, C. 2015). It provides a good low cost solution but typically for use in smaller systems only (where MPPT benefits are minimal).

In turn, MPPT devices are much more sophisticated: although more expensive, they feature on board computers controlling a complex system of semiconductors and gates that convert solar-produced DC to high frequency AC and then back to DC, passing on to the load over 90% of the incoming energy (Warren, C.), thus offering a potential increase in charging efficiency of up to 30% (Enerdrive Staff). They harvest the maximum power from the solar array and then transform this power to supply the varying voltage requirement of both the battery and the loads. This is crucial, for example, when one wants to set a 24 or 48 V configuration for solar panels but still needs to run 12 V loads. Most MPPT units can make the conversion of higher voltages into lower voltages with very little power loss, making MPPT much better for developing far more scalable systems than PWM (Warren, C. 2015). In fact, if there is a possibility that the array could be increased in the future then the controller should be oversized to cater for future growth. Furthermore, the ability to step down a higher array voltage to a lower battery bank voltage helps keep wire size and costs down for long wire runs. It can also reduce the number of series fuses and the size of the combiner box (Munro, K. 2010).

As for the solar charge controller's sizing and selection process, this dissertation's calculations ensure that any PWM or MPPT controller can be properly sized because, as we have seen in the solar array subchapter, there is already a condition imposed in the sizing process that makes certain that the solar array's nominal voltage is always equal or greater than the system voltage (see Equation 12).

The first step is to guarantee that the charge controller supports a nominal battery voltage that is equal to the chosen system voltage. Supported nominal battery voltages of an arbitrary solar charge controller will be denominated $V_{B_i supported}$, where i will vary between 0 and k, k being the total number of supported nominal battery voltages. e.g.: for a controller where k=2, it means that it supports two different system voltages; in this case, for instance, between $V_{B_1 supported} = 24V$ and $V_{B_2 supported} = 48V$ one of them would have to match the system voltage.

Next, damages to the controller must be prevented by also making sure that the total maximum open-circuit voltage of the whole solar array ($V_{oc_{array}}$) never exceeds the charge controller's maximum voltage rating ($V_{maxcontroller}$) (Munro, K. 2010). Therefore, Equation 16 calculates $V_{oc_{array}}$ by multiplying the V_{oc} of the chosen solar panel by the maximum number of panels in each series string that composes the array. Controllers should also be sized so that they are capable of carrying 125% (safety factor – f_{safety}) of the array's short-circuit current (I_{sc}). Furthermore, a second de-rating factor ($f_{derating}$) is usually required: for systems in continuous operation, additional protection must be included to allow for heat and equipment stress. Continuous operation is defined as three hours or longer of continuous use, which would include most PV systems. This factor is also 125% (altE Staff) and must also be applied to I_{sc}.

A proper charge controller for any system must therefore support the chosen system voltage,

$$\text{OR } (V_{B_i supported} = V_{system}), \; i = 0, \dots, k$$

have a $V_{maxcontroller}$ higher than the following voltage,

$$V_{oc_{array}} = n_{panelsperstring} * V_{oc}$$

Equation 16: Maximum open-circuit voltage of the whole solar array

and make sure that the product showcased in Equation 17 – which calculates a new, safe and de-rated short-circuit current ($I_{sc_{total}}$) – does not surpass the maximum short-circuit current value of the charge controller ($I_{maxcontroller}$). Remember: $n_{arraystrings}$ is the number of strings needed to compose the solar array, a value that was already calculated in Equation 14 which is crucial to define the total short-circuit current flowing through the charge controller.

$$I_{sc_{total}} = ROUNDUP(n_{arraystrings}) * I_{sc} * f_{safety} * f_{derating}$$

Equation 17: Minimum solar charge controller size

Just like with other electronic devices, there is always the possibility to connect various identical charge controllers in series or parallel, thus multiplying their capability of respectively withstanding open-circuit voltage or short-circuit current values.

<u>Let us now go back to our example and see how the following charge controller:</u>

Table 6: Charge controller specifications for charge controller sizing example. Source: ev-power.eu

Type	**Name**	$V_{maxcontroller}$	$I_{maxcontroller}$	$V_{B_i supported}$			
				i=1	i=2	i=3	i=4
MPPT	TriStar-MPPT-45	150 V	45 A	12 V	24 V	36 V	48 V

satisfies all of the conditions listed above.

First we need to go back to our solar panel's specification sheet and retrieve its I_{sc} and V_{oc} values:

Name	V_{oc}	I_{sc}
GWM Sunny Poly 150 Wp 36 cells	22 V	8.41 A

As can be observed in Table 6, $V_{B_4supported} = 48V = V_{system}$.

Furthermore, $V_{oc_{array}} = n_{panelsperstring} * V_{oc} = 4 * 22 = 88V < V_{maxcontroller} = 150V$, which satisfies Equation 16's condition. As for Equation 17:

$I_{sc_{total}} = ROUNDUP(n_{arraystrings}) * I_{sc} * f_{safety} * f_{derating} = 3 * 8.41 * 1.25 * 1.25 = 31.54A$, which is lower than $I_{maxcontroller} = 45A$.

Answer: The TriStar-MPPT-45 would be a proper choice to satisfy all of the system requirements of our example. For bigger systems, if two TriStar-MPPT-45s were put in series they would be able to withstand up to 300 V of an array's open-circuit voltage, and if put in parallel they would be able to withstand up to 90 A of an array's short-circuit current.

3.5. Step Five: Sizing an Inverter

There is only one major component of a typical off-grid PV system left to design, and that is the inverter. The primary job of an inverter is to convert the DC power from the battery bank or solar panels into AC power that can be fed into a commercial electrical grid or used by a local, off-grid electrical network. In order to do that, it must take the constant DC voltage and change it to a sine wave curve that goes above and below 0 volts (Beaudet, A. 2015). There are two major ways inverters do this: via modified sine wave or via pure sine wave technologies.

Much like PWM and MPPT charge controllers, modified sine wave inverters are based on older, simpler technology whereas pure sine waves are more recent and sophisticated. However, while *The OffGridder's* charge controller database (ChargeDb) will still feature PWM charge controllers due to the fact that they can still be used for various modern-day smaller applications, its inverter database (InverterDb) will leave out modified sine wave inverters because I believe this type of technology is becoming too obsolete to justify the few upfront savings it might provide. Plus, I want people to build off-grid PV systems with adequate quality to withstand nowadays' devices, which is not the case when modified sine wave inverters are used: their blocky AC signal, which can be observed in Figure 15, causes various problems in a great deal of devices such as laptops, audio equipment, printers, battery chargers, etc. Some equipment may even seem to be working fine, but may run hotter than with a pure sine wave; a condition that can shorten its lifespan (Beaudet, A. 2015). In turn, pure sine waves inverters' close to perfect curve is much preferred for many electronics.

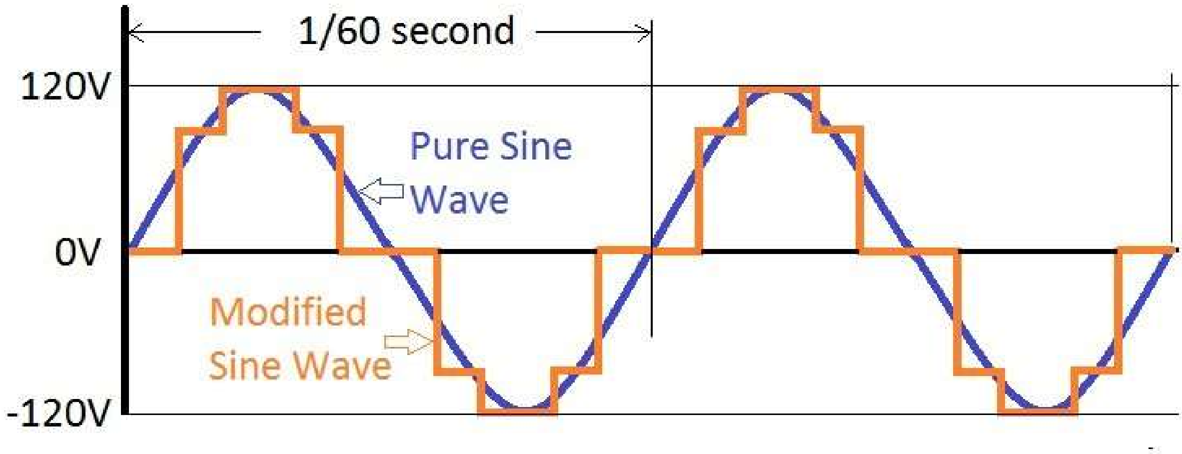


Figure 15: DC voltage, modified sine wave and pure sine wave. Source: altestore.com

The process of sizing an inverter for an arbitrary off-grid PV system is represented by the colour pink in the OG schematic, as can be observed in Figure 16.

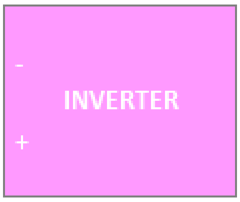


Figure 16: Inverter sizing process in the OG schematic. Source: Author's own figure

Before moving on to the process of sizing a proper inverter for any type of off-grid PV system, though, it is also important to distinguish between three broad types of inverters that exist, considering that the differences are crucial to define what any PV system can actually do. Inverters can be classified as stand-alone, grid-tie or battery backup inverters, just like the types of PV systems presented in chapter 2, and differ in the way they interface (or not) with the utility grid.

Grid-tie inverters are designed specifically for grid-connected applications that do not require a battery backup system. They convert DC power directly from a PV array to AC power to supply to electrical appliances and sell excess power back to utility grid. Stand-alone inverters, or off-grid inverters, are designed for remote stand-alone applications or off-grid power systems with battery backup where the inverter draws its DC power from batteries charged by a PV array and converts it into AC power. For the best output, the pure sine inverter is required (Leonics Staff). They do not interface in any way with the utility grid. Lastly, hybrid inverters can operate as either a stand-alone inverter or a grid-tie inverter. They connect to a battery bank just like off-grid inverters and are designed to draw energy from it, but can also export excess energy to the utility grid. *The OffGridder's* MVP inverter database (InverterDb) will be exclusively composed of off-grid inverters.

In order to properly size an inverter, there are three values we must first take a close look at. First of all, choosing the right inverter for an off-grid system is based on accurately calculating electrical loads and usage patterns. This assessment needs to be done very carefully and with absolute honesty to oneself so that the entire system is sized correctly and will function without failure. The size is based on what is called the sum of all "peak-load" requirements (Pinkham, L.) – all the AC loads that could be turned on at the same time (P_{AC}), which in turn have a dedicated column in the load analysis table as can be observed in Table 1. This value can be calculated by using Equation 18.

$$P_{AC} = \sum_{i} P_{L_{AC-ON_i}}$$

(Watts), where L_{AC-ON} defines an AC load that has the box in the column to its left checked for "On at Same Time" and i varies from first to last table row

Equation 18: Sum of all AC loads that could be turned on at the same time

The second value is the sum of all AC surges that could be turned on at the same time (P_{surge}), which is demonstrated in Equation 19. Some devices, such as the ones with a motor, require an initial surge of power to start up. For example, a certain appliance may have a "continuous power" attribute of 2000 W and a "peak surge" of 4000 W. This means that the appliance will require 4000 W of power to start up (usually for a few seconds), but once started it will require less power to continue to operate (a maximum of 2000 W). For determining power surge requirements, one has to see each device manufacturer's specifications, or measure the surge with an ammeter. If absolutely necessary one could also multiply the continuous Watts times three (although the surge can sometimes be as much as seven times) (Pinkham, L.).

$$P_{surge} = \sum_{i} P_{surge_{AC-ON_i}}$$

(Watts), where $surge_{AC-ON}$ defines an AC surge from a device that has the box in the column to its left checked for "On at Same Time" and i varies from first to last table row

Equation 19: Sum of all AC surges that could be turned on at the same time

These values are crucial for sizing any inverter because the inverter must be able to deal with both the sum of continuous AC loads and the sum of peak surges for a certain amount of time. The inverter's maximum continuous output power ($P_{inv_{cont}}$) and surge output power ($P_{inv_{surge}}$) are usually specified in the device's specifications sheet. Furthermore, the usual condition of matching the device's voltage with the system voltage also applies here. The inverter's voltage is given by its nominal DC input voltage ($V_{inverter}$).

And so we are left with the three conditions expressed in Equations 20, 21 and 22. Just like charge controllers, inverters can also be wired in parallel or in series in order to multiply their voltage or current, respectively.

$$P_{inv_{cont}} > P_{AC}$$

Equation 20: Comparing the inverter's maximum continuous output power to the sum of all "peak load" requirements

$$P_{inv_{surge}} > P_{surge}$$

Equation 21: Comparing the inverter's maximum surge output power to the sum of all AC surges that could be turned on at the same time

$$V_{inverter} = V_{system}$$

Equation 22: Condition of equality between the nominal DC input voltage of the inverter and the system voltage

Let us now end the design of the example started in Table 2 by first calculating the sum of all AC loads and surges that could be turned on at the same time through Equations 18 and 19:

$$P_{AC} = \sum_i P_{L_{AC-ON_i}} = 356 + 600 = 956\ W$$

$$P_{surge} = \sum_i P_{surge_{AC-ON_i}} = 400 + 2000 = 2400\ W$$

Considering the inverter presented in the following table (Table):

Type	**Name**	**Nominal DC input voltage**	**Continuous output power**	**Surge output power**	**Peak efficiency**
Pure	Cotek SK3000-248	48 VDC	3000 W	6000 W	94%

We need to make that it will be able to deal with both the sum of continuous AC loads and the sum of peak surges, as well as that its nominal DC input voltage matches our system voltage. As seen before, this can be accomplished by verifying the conditions set in Equations 20, 21 and 22:

$$P_{inv_{cont}} = 3000\ W > P_{AC} = 956\ W$$

$$P_{inv_{surge}} = 6000\ W > P_{surge} = 2400\ W$$

$$V_{inverter} = V_{system} = 48\ V$$

Answer: We can conclude that the Cotek SK3000-248 would be compatible with all the devices chosen for the off-grid system design set in the example.

3.6. Final Design Considerations

This is it. We have successfully sized all major components of an off-grid system that satisfies the energy needs of the loads presented in Table 2. All components should by now be compatible with one another and function in a proper way. *This* is the painstaking process that every person must go through, one way or another, in order to properly size the major components of an off-grid PV system. There are evidently many other minor components needed to compose a complete system such as breakers, cables, breaker boxes, etc., but all the steps up until here already compose a significant commence.

The first two research questions – i.e. 1. “What common traits do most procedures of designing off-grid solar PV systems share?” and 2. “How can one structure the whole process into a step-by-step guide that covers as many cases as possible?” – has hereby a set of answers:

1. All processes of designing off-grid PV systems have to first deal with a load analysis, followed by the sizing of a battery bank, solar array, charge controller, and finally of an inverter. These devices are all of critical importance to the functioning of most off-grid PV systems.
2. The whole process can therefore be structured into five main steps, each one dealing with each one of the procedures mentioned above. This will guarantee the conception of a guide that covers the majority of cases.

However, here is the catch: a minor change in the load could jeopardise the stability of the whole system. Off-grid systems have to be meticulously planned. One more appliance connected to the devices and the battery bank, solar array, charge controller or inverter could fail to meet the newly instituted energy demands. This would send the prospect *off-gridder* back all the way to the beginning of the calculations, where he would have to thoroughly design a compatible system all over again. Furthermore, so far we have only been dealing with design calculations and have not even brought the aforementioned purchasing dimension into the picture, which is also a critical one in the implementation of off-grid PV systems.

As we will see in the next chapter, this is where *The OffGridder* comes into play. Spread throughout the web there are indeed some tools that can help anyone calculate their load energy demands or size a solar array, but as far as I could tell after months of research I could not find a design tool – much less a platform – that not only considers *all* of the calculations we have done above, but also responds to any changes in real-time. This is what *The OffGridder*’s MVP will do.

So to bring this chapter to a conclusion, I would like to answer the third research question: “What should be prioritised in order to create *The OffGridder’s minimum viable product*?”.

3. Although there are other minor components that play a role in the design of off-grid PV systems, I believe the ones featured in the already established steps should be prioritised in order to create *The OffGridder’s minimum viable product*. As stated in Chapter 1, a MVP stands for a new product or website that has sufficient features to satisfy early adopters. It is my position that the subsequent interactive platform, which will be created to deal with all the previously exposed procedures in an intelligent, user-friendly way meets those expectations while enabling experimentation and customer feedback and giving the means to future design iterations.

Chapter 4: Developing the Platform for Designing and Purchasing Off-Grid PV Systems

4.1. "*The OffGridder*" – An Interactive Platform

Welcome to the set of chapters where I will detail everything I did in order to create an interactive platform that not only designs customisable off-grid systems, but also helps people find and purchase their major components on various online marketplaces. *The OffGridder's minimum viable product* was fully developed in Microsoft Excel 2016 and consists of a single Microsoft Excel Worksheet file (.xlsx) where all calculations were based on the previously presented content. Let us start by describing its first worksheet – the Main Menu, which can be observed in Figure 17.

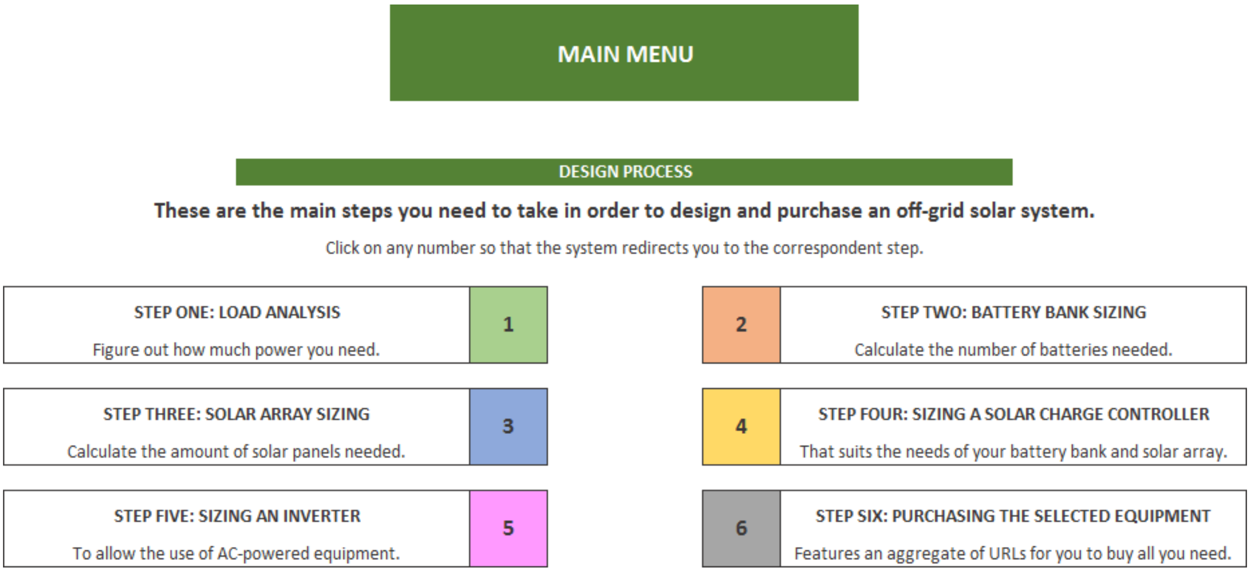


Figure 17: The OffGridder's main menu. Source: Author's own figure

Naturally, this menu allows users to navigate throughout all the steps that compose the interactive platform. We are already familiarised with all of the exposed steps except for the sixth, which will be studied in the end of this chapter as stated in the outline given in Subchapter 1.4. Step six will basically provide users with URLs to online marketplaces where anyone can purchase all of the selected, guaranteed-to-be-compatible equipment.

4.1.1. Important Remarks

→ .xlsx is the default Excel 2007 and later workbook format, so a compatible Microsoft Excel version must be used in order to ensure that there are no compatibility issues. I hereby abdicate responsibility from any compatibility issues caused by the use of early Microsoft Excel versions or other types of spreadsheet software such as LibreOffice or Apache OpenOffice.

→ At the time when this dissertation is being submitted, the official domain of the project – www.theoffgridder.com – has just been acquired and is still under construction. Therefore, all of the Excel cells that say "Click here to visit our website" or "Click here to learn more about…" are not yet programmed into the attached *OffGridder* software version. Nevertheless, the purchasing feature that lists URLs to buy the selected products in different online marketplaces is fully functional and ready to satisfy early adopters.

Let us now go through all the programmed versions of the designed steps developed in Chapter 3.

4.2. Step One: Load Analysis

Table 1 represents the exact load analysis' table implemented in the platform, the considerable difference being all the intelligence programmed into the Excel version. In turn, Figure 18 showcases a screenshot of the programmed table featuring the example set in Table 2 already incorporated. Pay close attention to the basics of Excel, where the rows are numbered and each column is represented by a letter – this will be paramount to all future calculations.

	D	E F G H	I	J K	L M	N O	P Q	R S
88–89	Quantity	Load name / Appliance	OAST?	AC Watts	DC Watts	AC Surge	Hours on per day	Watt-hours/day
90	1	Dishwasher: F&P DD24DCTX7	☑	356 W		400 W	1.00 h	356 Wh/day
91	1	LED Light Bulb	☐	7 W		7 W	12.50 h	88 Wh/day
92	2	DC Lightbulbs	☐		40 W		1.00 h	80 Wh/day
93	1	DC Fan	☑		60 W		1.00 h	60 Wh/day
94	1	Fridge	☑	600 W		2000 W	2.00 h	1200 Wh/day
95			☐					Insert wattage
96			☐					Insert wattage
97			☐					Insert wattage
98			☐					Insert wattage
99			☐					Insert wattage
100			☐					Insert wattage
101			☐					Insert wattage
102			☐					Insert wattage
103			☐					Insert wattage
104			☐					Insert wattage
105			☐					Insert wattage
106			☐					Insert wattage
107			☐					Insert wattage
108			☐					Insert wattage
109			☐					Insert wattage
110			☐					Insert wattage
111			☐					Insert wattage

Figure 18: The OffGridder's load analysis' table (featuring the example set in Table 2)

As seen in chapter 3, the following are the values we need to extract from this table because we are going to need them in the remaining steps of the design process:

i. **Total average daily energy consumed (Equation 1):** This very significant value is calculated by simply utilizing the function SUM:

$E_D = \sum_L n_L * P_L * t_L = SUM(R90{:}S111)$ (Watt-hours per day), where L = each load that composes the system

Equation 23: Total average daily energy consumed (Excel version)

ii. Total average daily energy consumed by DC loads (Equation 3): This value is not so easy to obtain. First of all, a function named ISBLANK has to verify which rows in the "DC Watts" column actually have received an input. This function returns a TRUE value if the cell is empty and a FALSE value if the cell has any content, and since we want to count cells that are *not* empty we need to invert the ISBLANK by using the function NOT. Next, we need to convert the Boolean values into ones and zeros. This can be used by typing the command "--" before the NOT function. So far we have "--NOT(ISBLANK(L90:M111)", which retrieves a column of ones and zeros depending on the input of DC values (or lack of it). Finally, as we can see in Equation 24, we can multiply each of one of the values in this new column by their correspondent "Watt-hours/day" values (R90:S111) and sum them all up by using the function SUMPRODUCT.

$$E_{D_{DC}} = \sum_{L_{DC}} n_{L_{DC}} * P_{L_{DC}} * t_{L_{DC}} =$$

$$= SUMPRODUCT\big(- - NOT\big(ISBLANK(L90{:}\,M111)\big), R90{:}\,S111\big)$$

(Watt-hours per day), where L_{DC} = each DC load

Equation 24:Total average daily energy consumed by DC loads (Excel version)

iii. Total average daily energy consumed by AC loads (without considering inverter's efficiency) (Equation 2): This value can now be obtained more easily than in Equation 2 by simply subtracting $E_{D_{DC}}$ from E_D, as can be observed in Equation 25.

$$E_{D_{AC-noinverter}} = \sum_{L_{AC}} n_{L_{AC}} * P_{L_{AC}} * t_{L_{AC}} = E_D - E_{D_{DC}}$$

(Watt-hours per day), where L_{AC} = each AC load

Equation 25: Total average daily energy consumed by AC loads (without considering inverter's efficiency) (Excel version)

iv. Sum of all AC loads that could be turned on at the same time (Equation 18): This value can be obtained through the same function applied in Equation 24, only here we are converting the TRUE and FALSE values inputted via the checkboxes in the "On at Same Time" column to ones and zeros. No NOT function needed here (see Equation 26). Note that (Load!I90:I111) stands for the "On at Same Time" column, whereas (Load!J90:J111) stands for the "AC Watts" column.

$$P_{AC} = \sum_{i} P_{L_{AC-ON_i}} = SUMPRODUCT(- - (Load!\,I90{:}\,I111), Load!\,J90{:}\,J111)$$

(Watts), where L_{AC-ON} defines an AC load that has the box on the left checked for "On at Same Time" and i varies from first to last table row

Equation 26: Sum of all AC loads that could be turned on at the same time (Excel version)

v. Sum of all AC surges that could be turned on at the same time (Equation 19): This value is calculated very similarly to the previous one, only instead of (Load!J90:J111) standing for the "AC Watts" column, we need (Load!N90:N111) to point at the "AC Surge" column (see Equation 28).

$$P_{surge} = \sum_{i} P_{surge_{AC-ON_i}} = SUMPRODUCT(--(Load!I90:I111), Load!N90:N111)$$

(Watts), where $surge_{AC-ON}$ defines an AC surge from a device that has the box on the left checked for "On at Same Time" and i varies from first to last table row

Equation 27: Sum of all AC surges that could be turned on at the same time (Excel version)

As we already know, while the result of Equation 23 – E_D – will be used in the solar array sizing step, the results $E_{D_{DC}}$ and $E_{D_{AC-noinverter}}$ (from Equations 24 and 25, respectively) will in turn be used in the battery bank sizing step and the results P_{AC} and P_{surge} (from Equations 26 and 27, respectively) will be used to size the inverter.

4.2. *The OffGridder's* Database Technology

In order to be able to build a tool capable of sizing a customisable off-grid PV system in accordance with the inputs typed in the Load Analysis worksheet, *The Offgridder* utilizes Excel spreadsheet technology to retrieve and manipulate data related to any battery, solar panel, charge controller or inverter listed respectively in its various databases (BatteryDb, PanelDb, ChargeDb, and InverterDb).

To do that, it relies on one of Excel's most powerful fixtures: the ability to nest formulas. Using a function as one of the arguments in a formula that uses another function is called nesting (support.office.com). In *The OffGridder,* a powerful combination between the two following functions basically creates a search engine within the Excel file: the INDEX function nested with the MATCH function.

Simply put, INDEX takes a cell range and returns a cell within that range based on a count provided by the user. The formula looks like this: "=INDEX(range, row_or_column)". In other words, it counts the number of cells we specify in our row_or_column parameter and outputs what it finds at the end of its search. By combining it with the MATCH function, which returns the position of a cell within an array by matching against a criteria string, we create a search engine. The way it works is that we use MATCH to tell Excel how many cells it should count into INDEX's range, based on a given value matched against a separate array (deskbright.com Staff). This will become clearer once we get to the first example in the battery bank sub-chapter, but by matching the inputted name of a battery, panel, charge controller or inverter with the correspondent name featured in a database, the system can then use the INDEX function to retrieve as many parameters as necessary.

4.3. Step Two: Battery Bank Sizing

From this step forward the user does not have to type any more values. Instead, the user can use the drop-down lists placed all over the platform in order to select the input information he wants to introduce. The only exception to this will be in the Peak Sun-Hours tool, which has to outsource the Sun-Hours calculation to NASA's website by providing latitude and longitude inputs.

In order to recognise drop-down lists, whenever an input is needed there is always a drop-down title preceding the cell where the input must be introduced. These drop-down titles always feature the following symbol in the end – **[v]** – so that the user knows that a certain input is required. Figure 19 showcases some cells in the battery bank sizing process where we can observe if an input is needed or not.

What is the voltage you want your system to have? [v]	48 V

Click to see considerations for selecting a 12, 24 or 48 Vdc battery bank.

How many days of autonomy do you want to have? [v]	2.5 days
What is the yearly minimum temperature at the exact place where your batteries will be placed? (Round it down to the nearest ten; e.g. 15ºC = 10ºC) [v]	10 ºC

Maximum number of parallel strings: [v]	2

Click to learn more about the number of parallel strings.

Depth of Discharge (DoD): [v]	80%

Click to learn more about Depth of Discharge.

	Typical	Selected
Inverter efficiency:	92%	94%

Figure 19: Input values in the battery bank sizing process. Source: Author's own figure

I have explained each and every one of these values in Chapter 3. Notice how 48 V of system voltage, a DoA of 2.5 days, a minimum ambient temperature of 10º C, a maximum number of parallel strings of 2 and 80% of DoD are all values introduced by the user, while the inverter efficiency table at the bottom lists both the typical efficiency and the selected inverter's efficiency and requires no input.

After the input information, the user finds a sections where all the battery sizing calculations that we have studied in the previous chapter are made. Observe Figure 20 to see all calculations from our previous example being made. Everything is carried out exactly like previously stipulated in Equations 4, 5, 6, 7, and 8, with the little tweak of using the exact inverter efficiency retrieved from future step five (in the case that no inverter was yet chosen, the system just assumes the typical inverter efficiency of 92% which can be seen in Figure 19).

SIZE YOUR BATTERY BANK

Let us first calculate the energy required to be supplied to the inverter from the battery bank:

While for our AC loads we have to take into account the efficiency of the inverter by respectively dividing one by the other, DC devices pull power directly from the DC system, bypassing the inverter, so our calculations must distinguish between the two of them.

AC Loads = 1644 Wh/day
DC Loads = 140.00 Wh/day

Daily battery load (energy) from AC loads = 1748.58 Wh/day

Now to get the total load as seen by the battery, we add the AC and DC figures together:

1888.58 Wh/day

Wh/day x Days of autonomy = 4721.45 Wh
/ DoD = 5901.81 Wh
x Temp. multiplier = 6373.95 Wh
/ System voltage = 132.79 Ah
/ Max nr parallel strings = 66.40 Ah minimum battery capacity

Figure 20: The OffGridder's battery bank sizing calculations. Source: Author's own figure

I would like to stress that, just like everything I am presenting in this chapter, all of these calculations respond in real time to any changes made in *The OffGridder's* load analysis table (the one featured in Figure 18).

Next, as can be observed in Figure 21, comes the interactive battery selection tool. This tool is based on the system's search engine I have previously described, which in turn is based on both INDEX and MATCH functions. In this section the system looks for an input in both the minimum ambient temperature cell and battery model selection cell, matches them with their correspondent data present in the BatteryDb, and later manipulates that retrieved data not only by applying Equations 9 and 10, but also by verifying if the condition $C_{battery} > C_B$ is true (in this case, as seen before in the example 75 Ah > 66.40 Ah, so the system prints a message saying that the chosen battery fits the user's needs).

BATTERY SELECTION

Choose your battery: [v]
Smart Battery 12V 75AH LITHIUM ION BATTERY

TYPE	NAME	PRICE	NOMINAL VOLTAGE	CAPACIT Y (Ah)	CAPACIT Y (Wh)
Li-Ion	Smart Battery 12V 75AH LITHIUM ION BATTERY	$999.99	12 V	75 Ah	900 Wh

Temperature multiplier at 10ºC:
1.08

Congratulations! The battery you chose fits your needs.

System voltage / Single battery nominal voltage = 4 batteries in each series string

Number of parallel strings x Number of batteries in each series string = 8 total batteries

Figure 21:The OffGridder's interactive battery selection tool. Source: Author's own figure

To end the battery bank sizing step, the system also calculates the total costs of the designed battery bank. This is a tool that is featured in every step from now on, which will be presented at the end of this chapter when we deal with “step six: purchasing the selected equipment”.

4.4. Step Three: Solar Array Sizing

Right after clicking on the “NEXT →” button at the end of the battery bank sizing worksheet, the user is directed to the solar array sizing one. The first thing the user encounters – right after the usual OG schematic highlighting the devices we are dealing with at the moment – is a tool that provides the latitude and longitude values for any desired city within the “LOCATION” database. For the effect, a cascading drop-down list had to be programmed.

Drop-down lists are an important feature in *The OffGridder* and are programmed through the “data validation” tool. For the effect, a whole column within a worksheet (either the same or a separate one) must be dedicated to the creation of the list. In turn, a cascading (dependent) drop-down list is achieved via the INDIRECT function typed into the data validation tool. Each item listed in the first column (in this case the country column) needs a column of its own where in turn the dependent attributes will be listed below (in this case the cities column). This way when we select the country “Portugal” we will only see Portuguese cities listed on the second drop-down list. Subsequently, by using the INDEX MATCH formula combination yet again, the correspondent values of latitude and longitude can be retrieved from the database. Right after this the instructions written on the platform must be followed so that the worst-case scenario peak-sun hours can be retrieved from NASA’s website. The whole process – including instructions – can be read in Figure 22.

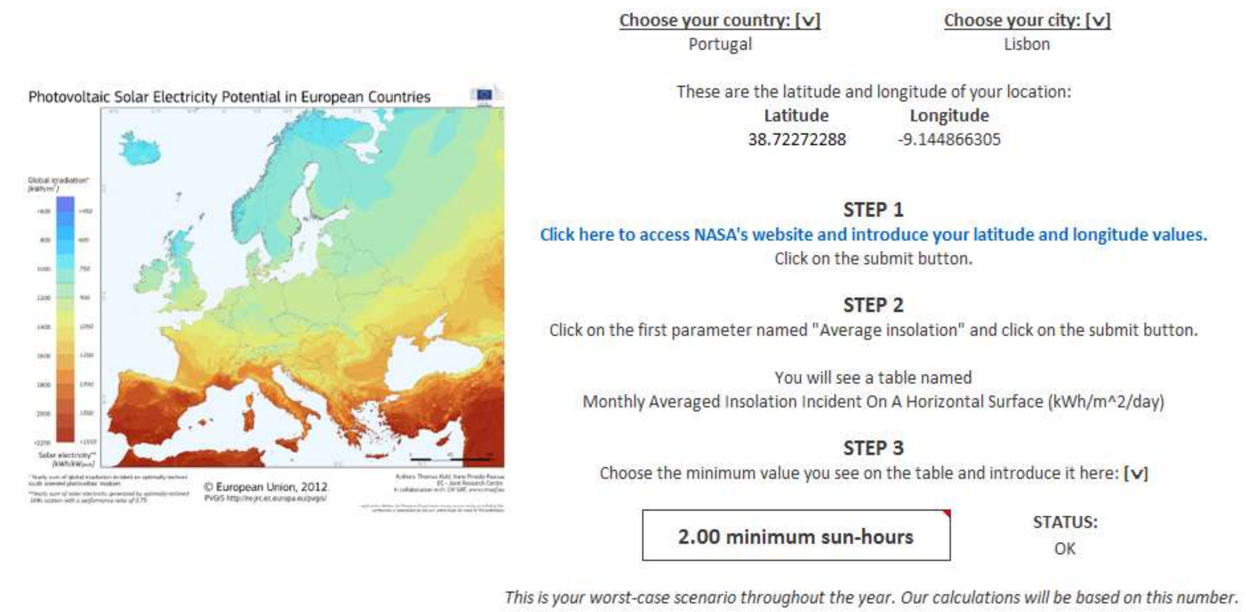


Figure 22: The OffGridder’s peak sun-hours interactive tool. Source: Author’s own figure

After this outsourced peak sun-hours tool, the system moves on to the calculation of minimum power the array must generate in order to satisfy the load’s energy needs, which was expressed in Equation 11: $\boldsymbol{P_{array}} = \frac{\frac{E_D}{h_{minsun}}}{\eta_{system}}$ (Watts). This calculator puts the worst-case scenario peak sun-hours (h_{minsun}) inputted above to use and also features an interactive calculation of the system efficiency factor η_{system}, where it uses an IF function to decide between the values 0.675 (midpoint in the 0.65 – 0.7 range) and 0.575 (midpoint in the 0.55 – 0.6 range), depending on the type of charge controller which will be chosen on the next design step (MPPT or PWM, respectively).

Subsequently, a solar panel selection tool – which is based on the same procedures as the battery selection tool – comes into play, as can be observed in Figure 23.

Choose a solar panel: [v]
GWM Sunny Poly 150 Wp 36 cells

TYPE	PRICE	# OF CELLS	NOMINAL VOLTAGE	OPEN CIRCUIT VOLTAGE (Voc)	SHORT-CIRCUIT CURRENT (Isc)	PEAK POWER	EFFICIENCY
Poly	$99.68	36	12 V	22.20 V	8.41 A	150 Wp	15%

Figure 23: The OffGridder's interactive solar panel selection tool. Source: Author's own figure

The selection tool is in turn followed by the sizing calculations expressed in Equations 12, 13, 14 and 15, as demonstrated in Figure 24.

Minimum number of solar panels per string:	
System voltage / Nominal panel voltage =	4.0 panel(s) in each series string

Power considerations:

Power needed / Maximum power per panel =

8.81 Panels

Configuration:

Total number of panels needed / Number of panels per series string =	2.2 parallel strings

Rounding up the number of parallel strings:	
Integer:	3 parallel strings
If the number of parallel strings isn't an integer, you might have to add extra panels in order to design a balanced system.	

Total number of panels needed:

12

Figure 24: The OffGridder's solar array sizing calculations. Source: Author's own figure

Other than these calculations, there are no other condition verifications featured in this step.

4.5. Step Four: Sizing a Solar Charge Controller

Next in line comes the sizing and selection of the solar charge controller. This step starts by providing information about the safety and de-rate factors, followed by the showcasing of the previously selected solar panel's model as well as all data related to it that will be used in the sizing process of the charge controller: namely its open-circuit voltage, short-circuit current and number of panels in each series string of the already-composed array. Before proceeding to the selection process, the system then calculates the minimum solar charge controller size by multiplying the short-circuit current of the selected panel by the number of parallel strings of the array and the mentioned factors, just as seen in the Equation 17.

Subsequently comes the selection tool represented in Figure 25. All charge controller's data is retrieved from *The OffGridder's* ChargeDb as usual via the INDEX MATCH function combination. As seen before, there are three conditions the charge controller has to meet in order to be of proper use to the established system's requirements: its maximum solar open-circuit voltage needs to be higher than the product calculated in Equation 16 (the maximum open-circuit voltage of the whole solar array), one of its supported nominal battery voltages needs to match the chosen system voltage, and its maximum short-circuit current needs to be higher than the product from Equation 17.

Select your PWM/MPPT charge controller: [v]
TriStar-MPPT-45

TYPE	NAME	PRICE	MAXIMUM SOLAR OPEN-CIRCUIT VOLTAGE	MAXIMUM SHORT-CIRCUIT CURRENT	SUPPORTED NOMINAL BATTERY VOLTAGES			
MPPT	TriStar-MPPT-45	$368.65	150 V	45 A	12 V	24 V	36 V	48 V

One of the supported nominal battery voltages has to match your system voltage.

Choose how many controllers you want to buy: [v]	Series/Parallel? [v]
1	Parallel

Chosen system voltage:
48 V

Total current:	45 A			
Total voltage:	12 V	24 V	36 V	48 V

Evaluating open-circuit voltage compatibility...	Excellent! Your charge controller is able to withstand the array's total open-circuit voltage.
Evaluating system voltage compatibility...	Good! Your charge controller design is compatible with your system voltage.
Evaluating controller's size...	Well done! Your charge controller design has enough current.

Figure 25: The OffGridder's charge controller selection tool. Source: Author's own figure

As for the tool on the left that says "Choose how many controllers you want to buy", it is basically a multiplier which will also be seen in the inverter sizing process: by choosing more than one charge controller and by wiring them in series or parallel, the user can create a "bank" where either the total current or voltage supported increases accordingly. Through experimentation, though, I am finding out that there is a wide range of charge controllers and inverters out there, so this tool might not be featured in future versions.

All these conditions are assessed intelligently by the system, which compares all data retrieved from its databases with data previously inputted by the user via an IF function. While the open-circuit voltage and short-current conditions composed by a simple “>” comparison, the system uses the MATCH function linked to an IF function through an ISNUMBER Boolean test in order to confirm if one of the charge controller’s supported voltages matches the chosen system voltage. The way this works is because the MATCH function either returns a number (e.g. 48 V) if it finds a matching nominal voltage, or non-numerical data (“#N/A”) if a matching voltage is not found. By using the ISNUMBER test the system checks whether the MATCH function’s output is numerical or not and returns a Boolean value to the IF function which in turn delivers a message to the user which either confirms or disproves system compatibility.

4.5. Step Five: Sizing an Inverter

The final step featured in the platform for designing customisable off-grid PV systems – sizing an inverter – goes straight to the selection tool. It is very similar procedure to the one featured in step 4. It retrieves, as usual, data from the correspondent *OffGridder’s* InverterDb and also has a series/parallel multiplier. It evaluates the compatibility of the chosen inverter by evaluating if its nominal DC input voltage matches the system voltage and if its continuous and surge output power are greater than the sum of all AC loads and surges that could be turned on at the same time, respectively, which were calculated in the load analysis step as seen in Equations 26 and 27. The whole procedure can be observed in Figure 26, where the system design example studied in Chapter 3 is concluded.

Select your PWM/MPPT charge controller: [v]
COTEK SK3000-248

TYPE	NAME	PRICE	OUTPUT VOLTAG	NOMINAL DC INPUT VOLTAGE	CONTINUOUS OUTPUT POWER	SURGE OUTPUT POWER	PEAK EFF.	SPECS SHEET
PURE	COTEK SK3000-248	$989.00	230 V	48 VDC	3000 W	6000 W	94%	Click

Chosen system voltage:	Sum of AC Loads on at the same time:	Sum of AC Surges on at the same time:
48 V	956.16 W	2400.00 W

Choose how many inverters you want to buy: [v]	
1	Series/Parallel? [v] Series

Total voltage:	48 V
Total cont. output power:	3000 W
Total surge output power:	6000 W

Evaluating voltage compatibility...	Good! Your inverter's voltage matches your system voltage.
Evaluating inverter's continuous output power...	Well chosen! Your inverter's power is enough to withstand your AC loads on at the same time.
Evaluating inverter's surge output power...	Well done! Your inverter can sustain your AC surges on at the same time.

Figure 26: The OffGridder’s inverter selecting tool and sizing calculations. Source: Author’s own figure

And so we have reached the end of the step-by-step process of developing an interactive platform for designing customisable off-grid PV systems. Unlike the process studied in Chapter 3, any prospect *off-gridder* could use this platform in order to go back and forth in calculations, experimenting with any desired loads and different PV system devices that would satisfy their energy needs. This is a process that would probably take many months of hard work to grasp, especially for a person who is not familiar with electrical engineering concepts. However, rather than being overwhelmed by all the concepts, calculations and different sources, by the time this dissertation is defended, any person can connect to *The OffGridder* and go through the whole design process with a few simple load assessments and clicks of buttons. That is surely something much more user-friendly and appealing to the masses, and I believe it has great potential to foster the implementation of off-grid solar PV systems.

4.6. Conditional Formatting

Before moving on to the platform's purchasing feature, there is one more capability I would like to mention. As one can observe in Figures 21 and 25, cells containing messages confirming the compatibility of system components are filled with green colour. However, this is not always the case: when compatibility is not found, the system formats certain cells and lets the user know where the problem was found. This is achieved through a very useful tool in Excel called *conditional formatting.* This capability can be seen and tested all throughout the system. In step one, if an AC Surge is lower than the AC Watts value for the same load, the system formats the AC Surge cell by filling it with grey in order to warn the user. In turn, the green/red filling of cells can also be seen most of the steps. For example, as it is plain to see in Figure 27, if instead of a TriStar-MPPT-45 charge controller a TriStar-MPPT-30 model was chosen, the system would not only tell the user that the model cannot withstand the calculated short-circuit current, but also fill the cell with red and change the font colour to white.

Select your PWM/MPPT charge controller: [v]
TriStar-MPPT-30

Evaluating open-circuit voltage compatibility...	Excellent! Your charge controller is able to withstand the array's total open-circuit voltage.
Evaluating system voltage compatibility...	Good! Your charge controller design is compatible with your system voltage.
Evaluating controller's size...	Sorry, you need to choose another controller (or buy more units of the same controller) in order to withstand the calculated short-circuit current.

Figure 27: An OffGridder's conditional formatting example. Source: Author's own figure

4.7. Step Six: Purchasing the Selected Equipment

Besides the various levels of interactivity spread throughout the design process, a feature I believe makes *The OffGridder* an outstandingly useful tool is the list of expenses and interactive purchasing tool. This feature will also be the foundation behind *The OffGridder* as a business venture, as we will explore in the business modelling chapter. Listed among all batteries, solar panels, charge controllers, and inverters databases is the price tag for each and every device, as well as the correspondent link to an online marketplace where the user can actually buy the selected equipment. This price data is manipulated by the system and multiplied by the quantity values retrieved from every step of the design process in order to create a list of expenses.

The list is, therefore, completely embedded in the interactive process. Any changes in the selection of equipment applied to any step will change the price tag at the end of each step, and consequently the data presented in the list of expenses. Besides, if any selected device is *not* able to satisfy a systems requirement, the user is told to go back to the correspondent design process This is accomplished by programming all price data in each design step with an IF statement linked to the already discussed conditions imposed by system requirements. If one of the conditions, say for the battery, is not met, then the price for the battery bank does not show up. Consequently, all data related to the battery bank does not show up in the list of expenses either. This guarantees to the user that the equipment that the user *does* purchase is entirely compatible.

As for providing its users with the correspondent URLs to online marketplaces, the system relies – then again – on the INDEX MATCH combination formula. This time, however, this formula has to be nested yet with another function: the HYPERLINK function. The databases are composed by often long, unpleasant URLs. Therefore, to make them more user-friendly and appealing the system uses the HYPERLINK function – a function that creates a jump to a network server while allowing me to control the presentation of the button. As an example, here is code implemented in the "BUY IT HERE" button for the battery section in the list of expenses:

```
=IF(Battery!P103>Battery!P113,"GO BACK", HYPERLINK(INDEX(BatteryDb!G3:G13,
        MATCH(Battery!H109,BatteryDb!B3:B13,0)), "BUY IT HERE"))
```

A good pseudo-code translation for this cell would be: if the minimum Amp-hour capacity per battery that constitutes the battery bank (C_B) is higher than the Amp-hour capacity of he selected model, then the button will tell the user to "GO BACK". If this condition is false, then the system will provide the URL listed in the row that matches the selected battery's name.

APPENDIX A presents a full-page figure with the final solution provided by *The OffGridder* to tackle the loads' total energy needs inputted in step one, which served as an example throughout this whole dissertation. Evidently, all of the data in the appendix can also be observed and studied in greater depth in the main file "theoffgridder_joaoclemente.xlsx", in the worksheet named "Expenses".

Chapter 5: Business Modelling "*The OffGridder*"

I have created this whole project not just with an engineering mindset, but also with an entrepreneurial one. The truth is, I honestly think that *The OffGridder* can indeed provide value to people and communities who want to become self-sufficient but are struggling to find proper information about off-grid solar PV systems. Even though I have been learning all about electrical and computer engineering during all these years in my integrated master's, this process was still very hard to assemble. So as to officialise my attempt to propose *The OffGridder* not only as an interactive platform created for a dissertation project but as a prospect business venture as well, I would like to describe how this business venture could indeed become profitable.

As seen throughout the dissertation, the prices of all main equipment are fairly affordable except for the ones for distributed energy storage systems, namely the battery bank. However, as I also mentioned before, the next four years are promising to lower those costs in an astronomical manner, while the costs for solar panels will also continue to become more and more affordable. This is the perfect opportunity to create a full-blown online interactive platform *and* marketplace, which not only helps people deal with the design of their off-grid PV systems, but also helps them find a great variety of equipment to service all their needs.

Although I wrote that the key word for this business plan was "lean", that does not mean I did not do any market analyses. I spent months working on this platform, and as can be seen in the references a lot of material was actually gathered from online marketplaces that also feature some information about how the design of PV systems is to be performed. They actually helped me writing this dissertation. However, I also believe that while there are many people out there who would like to become self-sufficient, many of them still discard this idea because they feel very overwhelmed when they see all the effort required and things that need to be learned.

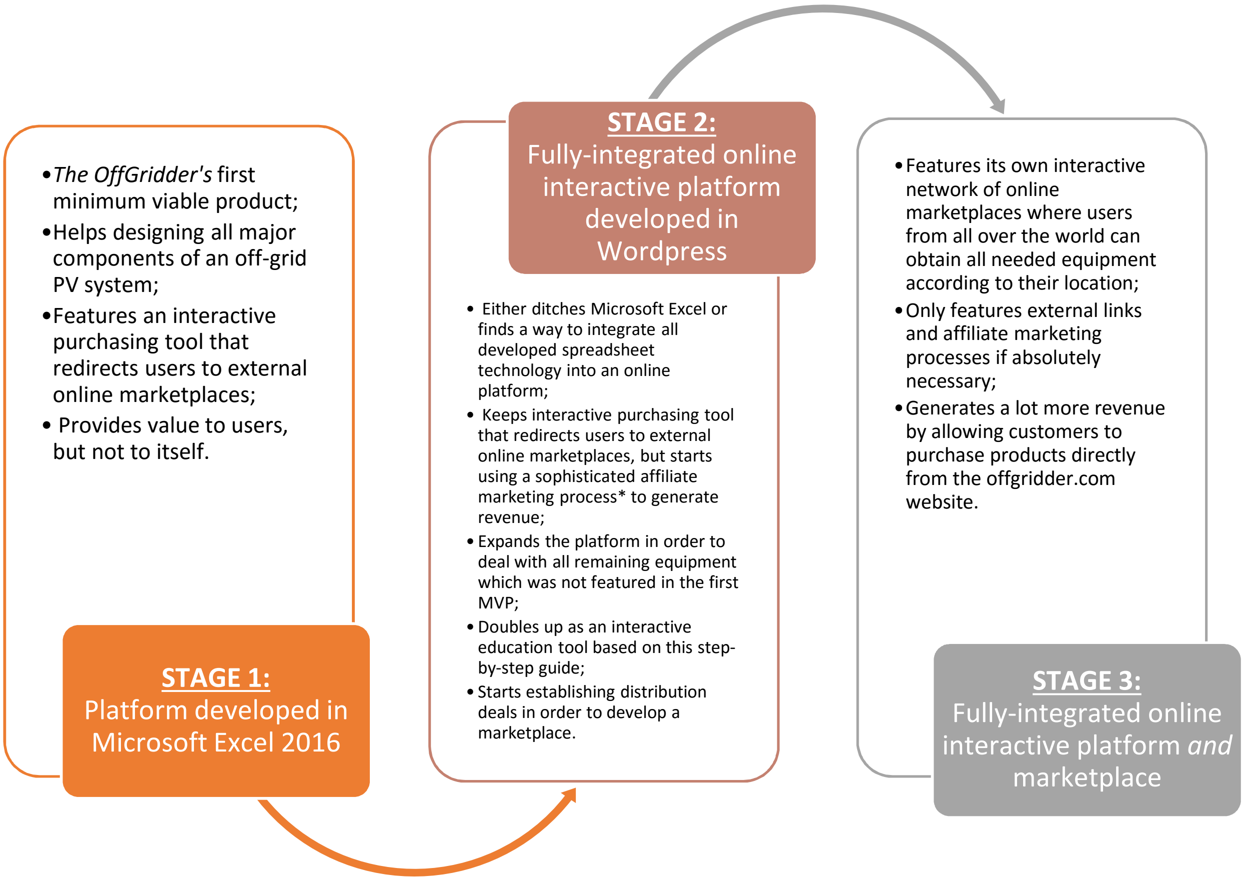
Considering the environmental concerns I wrote about in Chapter 1, it is my stand that renewable energy systems *need* to be targeted at the masses. We need solutions that provide the user-friendliest, most interactive tools possible in order to convince people that although getting up and running on renewable energy is a complex task, it can still be done by the average Joe with little to no previously obtained knowledge of how electrical circuits or renewable energies work.

We need to *empower* the masses and let everyone know that becoming energy independent is something attainable – an available option to every individual. The products are out there and they are becoming much cheaper; now we only need to develop tools to get those products into the hands of consumers and teach them how to assemble them in a way that saves them money and our planet as well. Win-win. The technologies that can enable the development of these tools are also out there as well – as stated in Chapter 1, we are surrounded by information technologies every day of our lives. Now we just need to bring more of those technologies into the renewable energy world in order to free ourselves of ancient, harmful ways of satisfying our energy needs.

I want to start with the off-grid world because it is the reason why I undertook this challenge of completing an integrated master's in electrical and computer engineering. I mentioned a *business model canvas* is essentially a diagram of how a company creates value for itself and its customers. This diagram also constitutes my answer to the final research question stated in the first chapter:

4. "How can *The OffGridder* integrate the services it provides (designing the system) with the purchasing of off-grid solar PV systems in order to achieve financial prosperity? In what way could information technologies perfect the experience of acquiring all the needed equipment to start harvesting energy from the sun from stand-alone energy systems?"

Here is how I plan to pursue this business venture through *The OffGridder:*



Chapter 6: Discussion and Conclusion

6.1. Discussion

With this dissertation I believe I further developed the research in the off-grid solar PV systems field. The contents listed in the references were very spread out throughout the web, books and other dissertations, but I could not find any sort of academic approach for any of the equations I presented in this thesis, so I had to create the greater part of all nomenclature presented here from scratch in order to be able to express how variables from one equation should be used in others.

Furthermore, as stated before, I believe that there isn't any platform out there dealing with off-grid PV systems with this level of interactivity. The process of automating all steps needed to design an off-grid solar PV system is, in my mind, a very interesting one which has a lot of potential for further research. In a wider context, I believe this approach could be applied to rev up the implementation of many other renewable energy technologies. The breakdown of whole procedures, the division into small, automatable steps and the manipulation of all acquired data is a very powerful approach to deal with complex problems such as the ones renewable energy technologies impose.

As for the limitations of my research, I think the whole process implemented throughout this dissertation is still somehow a simplified version of the whole design process of real-life off-grid PV systems. There are probably many more factors that have to be taken into consideration when dealing with the actual installation of any RE system, and I believe that this always establishes a limitation because academically we can only certify that our theory and calculations are correct. So in my opinion I do need a more hands-on approach in order to grasp the hidden complexities of installing an off-grid PV system. Nevertheless, I am very satisfied with the amount of information I was able to gather and squeeze into a 50-page dissertation and I believe the focus of my research was ultimately clear, well sorted out, and delivered results.

6.2. Conclusion

In this dissertation I believe there were five main things I learned:

- A great deal about how to use Microsoft Excel functions and capabilities, especially how to work with databases and how to develop a search engine within a spreadsheet document.
- A tremendous amount of both theoretical and practical information about how to design off-grid solar PV systems.
- How to write a dissertation according to the expectations and requirements of a prestigious higher education institution.

- How to perform intense academic research and deliver results – selecting information, narrowing it down to a topic of interest, deeply exploring a very specific subject, and fitting it all into 50 carefully-arranged pages in a Microsoft Word document.
- How to spend months of my life working with something I love: as stated before, off-grid renewable energy technologies were the exact reason I decided to pursue an integrated master's degree in electrical and computer engineering, with a specialization in the Energy field. It was a pleasure to see some of the knowledge and insights I gathered throughout the years come in handy when developing the platform, planning the business venture, and writing the dissertation itself.

The hardest part was, by far, narrowing down all the gathered information. It was constantly overwhelming to be surrounded by so many sources of knowledge while not knowing exactly what to do with them, and I regret having spent so many months researching and diving deep into so many different topics while producing no practical results. However, I believe I have achieved my main objectives. As it is evident in the business modelling chapter, there are many more things I still wish to learn about this topic and aspire to turn into practical solutions for people all over the world.

I also wish I had arrived to the idea of developing this interactive platform earlier on, but truly think that the final result has the potential to serve as a minimum viable product that in turn will be able to serve the scientific community – and, who knows, some business ventures. Giving that kind of contribution about a topic I love to such important and like-minded communities invokes the most satisfying feeling of my whole academic life; and I believe, in the end, that that is all one can aim for when starting the path of pursuing a higher degree.

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APPENDIX A: LIST OF EXPENSES

LIST OF EXPENSES

In order to power a total of

1783.66 Wh/day

you will have to acquire the following devices:

BATTERY BANK

BATTERY	PRICE PER ITEM	QUANTITY	TOTAL COST
Smart Battery 12V 75AH LITHIUM ION BATTERY	$999.99	8	$7,999.92

BUY IT HERE

SOLAR ARRAY

PANEL	PRICE PER ITEM	QUANTITY	TOTAL COST
GWM Sunny Poly 150 Wp 36 cells	$99.68	12	$1,196.16

BUY IT HERE

CHARGE CONTROLLER

CHARGE CONTROLLER	PRICE PER ITEM	QUANTITY	TOTAL COST
TriStar-MPPT-45	$368.65	1	$368.65

BUY IT HERE

INVERTER

CHARGE CONTROLLER	PRICE PER ITEM	QUANTITY	TOTAL COST
989	$989.00	1	$989.00

BUY IT HERE

TOTAL COST OF YOUR OFF-GRID SOLAR PV SYSTEM

$10,553.73