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Design and Implementation of a Monitoring System for Decision Support in a Micro-business Based on a Solar Energy Microgrid in Rural Colombia

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Abstract

Many regions of the world still do not have access to reliable energy sources. In recent years, there has been a push towards solving this energy problem with renewable clean energy. Introducing new energy solutions into communities with limited knowledge of technology can be a challenge. These communities need to have the tools and knowledge required to make good decisions on how to use and care for their energy source. This thesis presents the development of a monitoring system used to monitor and predict the behavior of an installed photovoltaic system in an indigenous community in Colombia. The previously installed photovoltaic system powers six refrigerators, but provides no feedback to the user. This lead the community members to make decisions without any support decision tools. The monitoring system is developed using a Human centered design process. This resulted in a local web server communicating with a photovoltaic controller and a current sensor. An electrical model created with MATLAB provides predictive abilities based on user input. Both are implemented on a Raspberry Pi with a website serving as the user interface. The implemented monitoring system has enabled the community to make informed decisions based on metrics such as battery level and predicted energy consumption and production.

Sammendrag

Store deler av verden har fortsatt ikke tilgang på elektrisitet. De siste årene har det vært fokus på å løse dette energiproblemet med fornybar energi. Det å introdusere nye energiløsninger for befolkningsgrupper med begrenset teknologikunnskap kan være utfordrende. Brukerne må ha både kunnskapen og verktøyene som er nødvendig for å ta gode avgjørelser for bruk og vedlikehold av energiløsningen. Denne oppgaven har som formål å utvikle et monitoreringssystem som gir en innfødt befolkning i Colombia muligheten til å overvåke og prediktere oppførselen til et allerede installert fotovoltaisk system. Det allerede implementerte systemet genererer strøm til seks kjøleskap, men gir ingen visuell tilbakemelding til brukeren. Det har ført til at brukerne må ta avgjørelser uten noen beslutningsverktøy å støtte seg på. Monitoreringssystemet er utviklet ved å anvende en brukersentrert design prosess. Resultatet av denne prosessen er en lokal webserver som kommuniserer med en strømsensor og den fotovoltaiske kontrolleren i systemet. En elektrisk modell utviklet i MATLAB predikterer ytelsen til det fotovoltaisk system og baserer seg på input fra brukeren. Begge er implementert på en Raspberry Pi med en webside som brukergrensesnitt. Det implementerte monitoreringssystemet har gitt den innfødte befolkningen i Colombia muligheten til å ta bedre avgjørelser basert på indikatorer som batterinivå og prediktert energiforbruk og -produksjon.

Preface

This thesis is submitted in partial fulfillment of the requirements for the Master of Science degree at the Norwegian University of Science and Technology (NTNU).

We have been given the great opportunity of using an engineering education to solve a humanitarian problem. This was made possible through a cooperation between NTNU, the La Salle University in Colombia, IUG and ren-PEACE.

By use of low cost equipment provided by NTNU and the La Salle University, we have implemented a monitoring and prediction system for a solar powered refrigeration system in rural Colombia. We have been given the necessary hardware that we have requested throughout the process. This includes a Raspberry Pi, an Aim Dynamics current sensor as well as all the necessary accessories. We have also been granted access to the 3D printing facility at our institute in addition to the electrical and metal workshop. Since the aim of this thesis is to enable others to replicate our work, the focus has been on using open software, with the exception of using MATLAB as the modeling software. This is in most cases free for students to use through .

The project is a product of two students working together within the field of cybernetics. In order to work as efficiently as possible, the work was divided based on interests and abilities. Essentially one student covered topics on web-page development and human centered design while the other focused on electrical modeling. The decisions on hardware were a joint venture so that the learning was maximized on the topics that would bind the two parts together.

Our supervisors have been Marta Molinas and Maximiliano Bueno López. Molinas has helped us keep a steady course throughout this project, making sure we were on track and moving in the right direction. López has been our source of information for everything related to the system to be monitored and has been a great help. Not only while working in Norway, but also as our guide and mentor while staying in Colombia. Without López our system would have remained a theoretical exercise for someone else to implement. Our supervisors have not helped with theory or implementation in any significant way.

The support of IUG has enabled us to travel to Colombia by supporting us with tickets, vaccinations and a safety course for our field trip to Colombia. La Salle provided accommodation in Colombia in addition to covering all travel expenses to the community and being responsible for our security while in Colombia. Ren-PEACE supported us with other living expenses while in Colombia.

We would like to thank our supervisors for their great help and guidance. A great thanks also go to all the organizations working with us to make the field trip a possibility. Thanks to the Calle Santa Rosa indigenous community for welcoming us and the technical solution we brought along. A great thanks to La Salle University students Karen López and Alejandro Muñoz Rincón for translation help during the field trip, and not at least for the friendly support.

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Nomenclature

Above the fold In computer science, this refers to what is visible on the start page of the (web page) interface before the users starts to scroll down.

ADC Analog-to-digital converter

AGM Abosrbed Glass Mat. Used in the context of battery technologies

CTC Communication technology center. In a governmental initiative called Kiosco Vive Digital, the Ministry of Information Technologies and Communications in Colombia built communication technology centers in indiginous communities to provide access to communication technology, such as computers and the Internet, in rural parts of Colombia.

DoD Depth of Discharge

HCD Human-centered design

I-V curve A standard way of visualizing the characteristics of a PV panel. Current vs. Voltage

ICT Information and communications technology

ISO The International Organization for Standardization

IUG Norway Engineer Without Borders Norway, a volunteer organization based in Norway that provides engineering expertise to non-governmental organizations involved in international development projects.

Microgrid Local power networks capable of generating power locally and supplying electricity to a relatively small number of users, often independent of the central grid, but may function in conjunction with it [1].

MPPT Maximum power point Tracker. Algorithm making sure the extracted power is at the maximum

MPP Maximum power point. The point on the I-V curve of a solar panel yielding the maximum power

NN/g Nielsen Norman Group, a leading voice in the field of interaction design who provides well-established usability heuristics to be complied with.

PV Photovoltaic

RPi Raspberry Pi, a small computer

Scripting language A programming language that does not require a compilation step beforehand, and the instructions are rather interpreted.

SoC State of Charge. Describing the battery percentage of a battery.

UI User interface

VRLA Valve Regulated Lead-Acid. Used in the context of battery technologies

Chapter 1

Introduction

Two big problems afflict the world's population with respect to energy, the vertiginous increase in the use of fossil fuels to meet energy needs and the lack of electricity in isolated areas [2]. According to the International Energy Agency (IEA), more than 1.1 billion people remain without access to electricity [3]. Ensuring universal access to affordable and clean energy is the seventh Sustainable Development Goals of the United Nations (UN), who's agenda is to end poverty, protect the planet and ensure prosperity for all [4].

Currently, 2.8 billion people rely on biomass, coal or kerosene for cooking, which pollute the household air and cause premature deaths world wide every year [3]. Universal access to clean energy is therefore essential, also because the energy sector is the greatest emission of greenhouse gases and thereby the dominant contributor to climate change [5]. IEA include renewable energy, electric vehicles, nuclear power and biofuels as clean energy technologies [6].

One of the goal targets of the UN for achieving affordable and clean energy worldwide is to expand infrastructure in developing countries so all inhabitants are supplied with energy service [7]. This involves an advance in technology, because the energy service has to be sustainable, yet affordable. The majority of the world's population without access to electricity live in rural areas [8]. Rural areas are generally characterized by low population density and geographic disparity of the population clusters, which transmission lines by their design can not optimally cover. Extending the central grid to rural areas is often prohibitively expensive due to the high cost of building transmission lines [8].

Microgrids are proposed as an excellent solution to rural electrification [8]. The United Nations Foundations published in 2014 a review of microgrids for rural electrification based on seven case studies, in which microgrids are described as local power networks "capable of generating power locally and supplying electricity to a relatively small number of users" [1]. They can function independently of the central electricity grid, and when using renewable sources of energy such as micro-hydro, photovoltaics or biomass, the microgrid is a clean and sustainable energy technology [8].

In Colombia, 52% of the country is recognized as Non-Interconnected Zones (ZNI), isolated areas that are not connected to the national electrical grid, and the country has a great opportunity to electrify these rural areas using microgrids due to its vast access to renewable energy resources [9]. In 2015, the national government in Colombia, accompanied by universities and companies, implemented solutions that sought to satisfy basic needs of communities in non-interconnected zones.

One of these solutions, the project ”Electrification for cold chains and access to Information and Communications Technology” was implemented in the Calle Santa Rosa indigenous reservation and included the installations of two microgrids based on photovoltaic panels in the reservation. The project made it possible to bring energy to one educational center and to a refrigeration center in which the community can refrigerate food and drinks [9].

The case of Colombia draws particular attention as this country is emerging from an armed conflict spanning more than 50 years. Colombia is now trying to incorporate into the society all the people who participated in this conflict, most of whom live in rural areas. A way to achieve this is to build new production systems based on energy to generate jobs.

Transfer and appropriation of social and technology knowledge is essential in order to ensure sustainability to electrification projects such as the one in Calle Santa Rosa [9]. The UN review of 2014 [1] emphasizes that the consensus best practice is to design the microgrid not on pure technological considerations, but instead "adapt to the specific social and economic characteristics of the rural community", originally identified by the Alliance of Rural Electrification in [10, p.51].

Local training is one of the critical factors for a microgrid to succeed [1]. The La Salle University in Colombia hosted a special technology transfer program for maintenance and operation of the microgrids in Calle Santa Rosa when installing the microgrids. The new refrigerator center has proven to yield new sources of income to the community members. The inhabitants sell fish, meat or agricultural products they collect and harvest during the day for a small fee from the refrigerator center.

As of today, the community in Calle Santa Rosa is limited by the fact that they do not have any decision support tools that allow them to know the status of the batteries and the autonomy in days of low solar radiation. This thesis presents a case study that includes the design and implementation of a monitoring system for one of the photovoltaic microgrids in Calle Santa Rosa to help the community with this issue.

The interface was implemented using a human-centered design process to accommodate the needs of the community the best way possible and continue the community’s appropriation process started by the electrification project of 2015. In addition to designing the interface, appropriate current sensors was selected and an electrical model of the photovoltaic system in Calle Santa Rosa was developed in MATLAB to expand the interface with prediction capabilities of energy production and use.

The resulting product of the thesis include both hardware and software, and will for this reason be referred to as a monitoring *system*. The processes of design, implementation and validation with the rural community will be presented.

1.1 Problem Description

In 2015, two off-grid solar panel systems were installed in the Calle Santa Rosa Reservation, in the municipality of Timbiquí, department of Cauca. One solar panel system provides electricity to the school, and the second provides electricity to six refrigerators for preservation of food and drinks that can be sold and yield additional income for the community. However, as of today, the monitoring of the solar panel systems is close to non-existing. The community has few opportunities to know the state of the system due to the lack of installed sensors. This jeopardizes the community's use of the solar panel systems. The task of the students is to provide the community with a better system for monitoring the system in order to enable the community to take better decisions with respect to the use of the energy in the solar panel system. The students will carry out a study and model the existing production process system based on solar energy in the Calle Santa Rosa indigenous reservation in Colombia, and research the possibility of implementing different sensors in the system.

1.2 Thesis outline

The following chapter, Chapter 2, describes the site for installation, the Calle Santa Rosa Indigenous Reservation in Colombia. Chapter 3 explains the theoretical framework that guided the work of this thesis, a human-centered design approach, and how it was applied to make sure that the system would meet the users' needs. The developed monitoring system that the design approach lead to is presented in Chapter 4, which includes a presentation of the hardware and software setup and the implementations costs. Chapter 5 entails the details about the modelling process of the electrical system in Calle Santa Rosa. The experiences of the field trip and the installation process is devoted to Chapter 6. Finally, the thesis ends with one chapter of discussions and a chapter with conclusions and references to future work.

Chapter 2

Site Description

Most of the information in this section stem from an article by postdoctoral Maximiliano Bueno-López and thesis from the La Salle University, Colombia, related to the installment of microgrids in Calle Sante Rosa, Colombia, in 2015. Some of the facts rely on a survey that was conducted in the community by a research team from the La Salle University to map the living conditions and the community's attitudes towards technology.

The survey involved interviews with 42 of the community's male family overheads, who answered 51 questions about economics and social, technical and environmental aspects on behalf of their families. The results of the survey has not been published, but will be referred to in the following. It was considered not expedient to reproduce the survey in an appendix due to its comprehensiveness.

2.1 The Calle Santa Rosa Indigenous Reservation

Calle Santa Rosa Indigenous Reservation is a rural area in the municipality of Timbiquí, department of Cauca, in Colombia. It is located at 2.8348 latitude, -77.595 longitude (2 ° 49'65.4"N, 77.2 ° 35'43.5W).

The inhabitants belong to the indigenous ethnic group "Eperara Siapidaara" and is made up of about 71 families and 386 people, according to [11]. The village consists of approximately 55 wooden houses, some of them are two-story houses, a school and a church. An illustration of the village drawn by the community themselves is given in Figure 2.1.

Figure 2.1: A drawing of the Reservation made by the community themselves. The village stretches out about 1 kilometer.

2.1.1 The Ethnic Group Eperara Siapidaara

The community that lives in Calle Santa Rosa is of the ethnic group "Eperara Siapidaara". According to [12], the group has a cosmological belief including different worlds guided by spiritual forces and sacred areas that are linked to their food. The governmental electrification project in Calle Santa Rosa in 2015 built a new building for the refrigerator center to install the photovoltaic panels on in order not to affect the community's sacred areas, which is one example on how the electrification project of 2015 adapted to the characteristics of the community.

The community's economy is oriented towards agriculture, handicrafts, hunting and forestry [9]. The farmers' work is seasonally based, and they grow banana, sugar cane and oranges in the rainforest, among other things. The women are responsible for making handicraft arts that are jewelries.

2.1.2 Environmental Characteristics

The community experience little seasonal variations as they are close to the Equator, and are rather affected by the El Niño phenomenon, causing changes in temperature on a multiple year interval. The survey of 2014 [13] reveals a relative humidity of 71% and an average temperature of 28° C, with the temperature ranging from 27°C to 32°C [12].

The village life is influenced by the daily tidal waves of the nearby river [12]. Houses are built on 1.2 m wooden stilts for this reason, as shown in Figure 2.2. The flooding of the river scatters the garbage accumulated in the community and neighbouring towns all over the town center in a mix of sewage and river water, which is yet another problem in the community.

Figure 2.2: A picture from the village. The community is affected by daily tidal flooding of the nearby river.

2.1.3 Communication with the Community

Maximiliano Bueno-López is a postdoctoral researcher at NTNU working together with professor Marta Molinas from NTNU. Through his position as a Research Professor at the La Salle University, he was part of the rural electrification projects in the Calle Santa Rosa Reservation in 2015, and he is the writer of the article [9] that presents the methodology for rural electrification that was applied to the Calle Santa Rosa Reservation.

Bueno-López has had the communication with the community and other contributors throughout this project, in order to confirm any technical aspects of the installations whenever necessary. Bueno-López also provided access to the community survey of 2014.

2.2 The Electrification Project of 2015

A project called "Electrification for cold chains and access to Information and communication technology (ICT)" was funded by the Inter-American Development Bank-BID, the Department of Science, Technology and Innovation in Colombia (Colciencias), The Institute of Planning and Promotion of Energy Solutions for Non-Interconnected Zones

(IPSE) and the Colombian energy-generation company ISAGEN [9]. It provided Calle Santa Rosa with two microgrids based on photovoltaic systems in 2015. This was used to power the school and a new refrigerator center.

In the article [9], Maximiliano Bueno-López presents a methodology used to bring technology for electricity access to rural areas in a way that ensures sustainability to the project. The methodology was applied in the "Electrification for cold chains and access to Information and communication technology (ICT)" project, and the project serves as a case study in Bueno-López' article.

The La Salle University joined the other academic programs presented above to develop the electrification project in Calle Sante Rosa [9]. The La Salle University was responsible for the implementation of the photovoltaic systems. Bueno-López was one of the engineers taking part in the installation process.

The following description of the project is mostly based on the article [9] by Bueno-López. It is included here because it is believed to be important for the reader to understand the context that was the starting point for the work of this thesis. The description has been elaborated and specified through talks with Bueno-López.

The situation prior to the electrification project

Prior to the installments, the residents in Calla Santa Rosa had unsatisfied basic needs. The residents did not have adequate electricity access, lighting, water pumping or food cooling possibilities. The electrification project aimed to solve some of these.

In principal, none of the community members had continuous access to electricity in their homes before 2015. A power distribution system including 32 wooden poles for distribution was present in the community [12], powering electricity sockets in most households. However, the the distribution system does not comply with the Colombian electrical standards and the diesel generator was not functioning, leaving the electricity service in the village highly unreliable.

In addition, nine families were in possession of personal diesel generators. However, postdoctoral researcher Maximiliano Bueno-López could explain that the richest families in the village typically would buy diesel generators for personal use, but end up not using them because they could not always afford the expensive fuel.

The only place in the village powered with solar energy before 2015 was a communication technology center (CTC) that was given to the community by the government in 2014. Kiosco Vive Digital is a governmental initiative by the The Ministry of Information Technologies and Communications (MINTIC) in which communication technology centers with computers and Internet access is installed in rural parts of Colombia [14]. According to Bueno-López, MINTIC built a CTC in Calle Santa Rosa in one of the rooms of the school building, which can bee seen in Figure 2.3. In the case of Calle Santa Rosa, the CTC included computers, a printer, a TV and a telephone.

A part of the CTC installments was a photovoltaic system dedicated to the kiosk, whose panels can bee seen in Figure 2.2. The CTC's photovoltaic system is separate from the ones that were installed on rooftops of the school building and on top of the new refrigerator center in 2015.

Figure 2.3: The digital kiosk in the school to the left and the installed equipment in the refrigerator center to the right.

The survey answered by community members in 2014 showed that only two of the families owned a cell phone they could use to communicate with other people, the others would use the river. Close to everyone answered that they would like to learn about electricity and a 24 hour electricity service. Everyone asked in the survey desired new production process to yield new revenue, and close to everyone wanted new study opportunities for their children. It was clear that a desire for electricity was present in the community and that they would be willing to learn about it.

Installations

The electrification project of 2015 installed two photovoltaic systems, one in the school and one in a newly build refrigerator center. The photovoltaic system in the school enabled teachers and students to use tape recorders, television and computers in the school to improve the education. The community service was increased because the lighting at the school made it possible to host nighttime community meetings [9].

The refrigerator center was equipped with six refrigerators for food preservation in order to give the community members a new way to market their products. For a small fee, the hunters, fishermen and farmers in the community sell their catch or agricultural products that other community members and visitors from neighbouring communities buys. In addition, cold water, juice and fruits are sold from the center. The revenue of these products goes to maintenance and buying new parts. The right picture in Figure 2.3 shows the fuse box and the batteries installed in the refrigerator center.

In addition, the electrification project in 2015 provided every household with a portable solar powered lamp that the families could use to light their homes after dark and charge small devices such as cell phones.

Social appropriation of knowledge

Included in the methodology of [9] is a model to ensure social appropriation of the installed solar panel systems. The educational level of the community is low [9], so to make the electrification project a sustainable one, the community received a special technology transfer program. The "Plan of Appropriation and Sustainability" involved training of 15 people in specific activities, and more than 50 people were taught in technical, environmental, economic and social aspects.

The 15 people trained for specific activities were recruited to technical and administrative committees established to make sure that the electrical service would be available to everyone and maintained properly. One technical committee was formed and given the responsibility of maintenance tasks. A second committee, called the Energy Cooperative, was given the responsibility of the daily operation of the refrigerator center.

The Energy Cooperative consists of five members in which two are salesmen, two handle agreements with other community members that wants to sell something from the center, and the last person is in charge of the money. They were taught basic knowledge on how to handle and market chilled and frozen products.

The whole community was included in the installation process. They helped move and unpack the installation equipment [9]. With the Plan of Appropriation and Sustainability, the project made sure to implement one of the crucial factors for a microgrid to succeed, according to the UN review of 2014 [1], which is local training, and also to adapt to the characteristics of the community. This is considered best practice by [1], [10]. Its succeess can be seen in the today's situation in Calle Sante Rosa.

Today's electric situation

The adoption of technology has continued to grow. As of today, Bueno-López estimates that every family in the community owns about two smart phones, as opposed to only two families in total having access to such a device in 2014. The computers in the digital kiosk are roughly in use all of the time in the opening hours of the kiosk. The refrigerator center generates about $330 U.S dollars monthly, which goes directly to savings for system expansion, as the photovoltaic systems has been close to maintenance free so far [9].

The Energy Cooperative continue to report the state of the generation system and the profits generated by the sale of products from the refrigeration center to the rest of the community. So far, none of the community members have been in conflict with the Energy Cooperatives about the way they handle their commodities.

The project has given the children more study hours and the women more working hours after dark due to the portable solar powered lamps each household were given. This is an example of one of the many benefits by rural electrification listed by the UN review of 2014 [1]. It is inarguable that benefits such as these are of such basic character that it makes the importance of rural electrification immense. To stress the point even further, yet another example of an observed benefit of rural electrification will be given. In a village in India, the introduction of electric light enabled the inhabitants to avoid snake bites, simply because they were able to see the snakes in their bed rooms after dark [1].

The electrification project in Calle Santa Rosa serves as a case study on how rural electrification can help improve the living conditions for people in isolated areas [9]. To conclude, the electrification project in Calle Santa Rosa facilitated technology transfer and community involvement in a way that guaranteed the sustainability of the solar power systems. The community involvement enhanced the appropriation and the feeling of ownership towards the new energy solution, which made it possible for social benefits to thrive.

2.3 Technical Specifications

This section will introduce and explain the technical specifications of the photovoltaic systems already installed in Calle Santa Rosa Indigenous Reservation. The focus lies on the system in the refrigerator center and the system in the school building. The CTC will be ignored as that system is not used in this paper and is under governmental control. The information gained from this section will be useful as a reference point for the subsequent chapters, especially in Chapter 5 in which the electrical model will be explained.

2.3.1 Refrigerator Center

The refrigerator center has its own standalone solar panel system. This system is comprised of four solar panels, one controller performing maximum power point tracking (MPPT) battery charging and DC/DC conversion, 12 batteries and six refrigerators.

PV panels

The solar panels that are used in this project are YL250P-29b units produced by Yingli. The white paper for these panels can be seen in Appendix A.2. Each of the panels are made up of 60 cells and has the dimensions (L / W / H) 1650mm / 990mm / 40mm. At standard test conditions (STC) defined by cell temperature of $25\,°C$ and incoming irradiance of

$1000\,W/m^2$, the power produced at the maximum power point (MPP) is given as $P_{max} = 250\,W$ with $V_{mpp} = 30.4\,V$ and $I_{mpp} = 8.24\,A$.

In the cooling center there are four such panels making up what will henceforth be called the PV field. Two panels are connected in series parallel to each other. This means that the voltage and current available from the PV field is twice that of one panel. The power from one panel is as stated above 250w. Thus, the maximum power that the four panels can produce all together is 1000w.

Batteries

There are twelve batteries of the type MT25000S installed in the refrigerator center. Each of the batteries are one lead-acid battery cell yielding 2VDC. All the batteries are connected in series, which creates a total battery voltage of 24VDC. The individual batteries have a stated capacity of 500Ah, which of course also holds true for the combined capacity at the higher voltage. The battery technology used is Valve Regulated Lead-Acid (VRLA) of the type Absorbed Glass Mat (AGM). This means that the batteries are using a standard technology in a solar power generation setting. The advantages of this type of batteries are discussed in [15]. One of the major advantages is their fair deep cycle performance as well as their low maintenance requirements. The batteries are depicted in Figure 2.3 and more information can be found by inspecting the white paper in Appendix A.4.

Solar Charge Controller

The controller used in the refrigerator center is a BlueSolar Charge Controller MPPT 100/50 produced by Victron Energy. This unit is in charge of tracking the MPP using a MPPT algorithm as well as stepping down the voltage from the PV field. In order to keep the batteries in an optimum working condition, the controller uses charging algorithms specific for the battery technology used. In addition to this the BlueSolar has the capability of providing information through a serial communication port.

The manufacturer does not specify which MPPT algorithm is used, but clearly states that it is superior to simply connecting a battery to the PV panels. This is quite obvious and at the very least it can be assumed that they are employing a Perturb and Observe (P&O) MPPT algorithm in order to "maximize the energy harvest" as they say on their website. The manual does mention the MPPT having advanced features enabling a better MPP choice in the presence of partial shading of the PV panels.

The charge algorithms used for the connected batteries can be programmed manually in addition to a number of pre-programmed charge algorithms available. This might be useful if the manufacturer of the batteries being used is providing detailed charge and discharge instructions. The BlueSolar is capable of charging a lower voltage battery from a higher voltage PV panel. This indicates the the DC/DC converter being used is a step-down buck converter.

Refrigerators

The refrigerator center has one main purpose, which is to cool food and drinks. In order to achieve this, six refrigerator have been installed. These refrigerators are responsible for the bulk of the power consumption related to the refrigerator center. The refrigerators in use are SunDanzer DCR165 refrigerators. The documentation for these are appended in Appendix A.5. The particular model being used is capable of operating on either 12 or 24 volts. In this case they are used with 24 volts by connecting them to the BlueSolar charger and the batteries. One of key advantages of these units is their extremely low power consumption as rated by the manufacturer. This is achieved by having thick insulation and motors designed for running on DC power. The motor is also stated to be brushless which essentially means zero motor maintenance.

By looking at Figure 2.4, it is possible to see how much power these refrigerators potentially use under a typical residential usage pattern given varying temperatures. The test conditions imposed by the manufacturer is defined for residential applications with average door openings and change of contents. With a 29 °C average temperature the power consumption per day seems to be approximately $200\,Wh/day$. In order to get an approximation of what the consumption could be in what hours, it would be necessary to divide by 24. This yields a power consumption of around $200/24 = 8.33\,Wh$. Clearly this is not much.

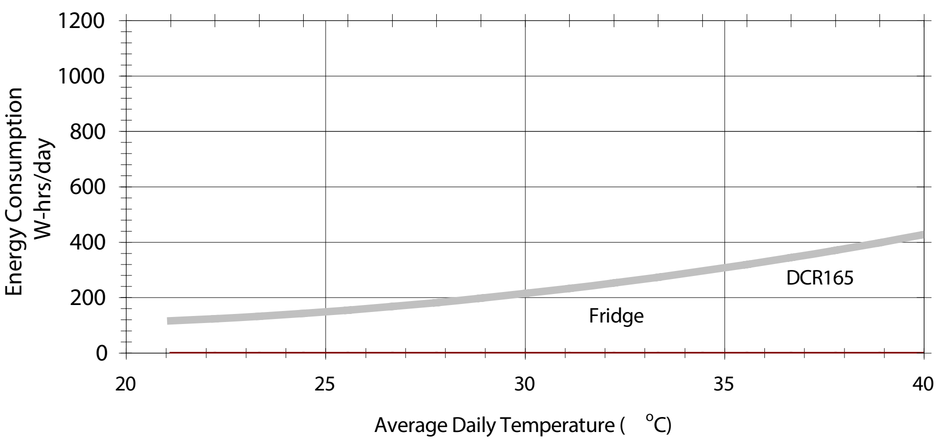


Figure 2.4: Showing the daily power consumption graph of the DCR165 refrigerator. Edited for readability from the graph included in the documentation, Appendix A.5.

2.3.2 School

Less focus has been put on the system used in the school as the monitoring system is mainly concerned with keeping track of the refrigerator center. However, the two systems are quite similar. The main difference lies in the larger variability of loads. Some of the loads require AC power and there is therefore an inverter present in the system. This AC power is also made available in the refrigerator center through a dedicated power cable connecting the two houses. This power is being used in the refrigerator center for tasks such as lighting and food processing using a blender.

PV panels

The PV panels used in the school are also YL250P-29b units. In the school however, six such panels were installed. The panels are connected with two sets of panels in parallel, where each set consists of three panels in series. Thus, the total voltage is three times that of one panel, and the total current is twice that of one panel. The maximal power that can be harvested is $250 \cdot 6 = 1500\,W$.

Batteries

The batteries used in the school system are of type MT122550 produced by MTEK. These batteries are rated at a voltage of 12V. This means that each battery consists of six 2V cells. The capacity of each battery is stated to be $255\,Ah$. There are eight batteries that are connected with two sets of batteries connected in parallel, and each set consists of four batteries in series. This yields a total battery voltage of $12 \cdot 4 = 48V$. The total available ampere hours is similarly calculated as $255 \cdot 2 = 510\,Ah$.

The batteries use the same type of technology as those in the refrigerator center. By comparing the datasheet found in Appendix A.3, with the datasheet for the batteries in the refrigerator center, it is clear that the cycle life graph is identical. The graph is reproduced in Figure 2.5. It is evident that it is advantageous to keep the depth of discharge to a minimum.

Solar charge controller

The controller used in the school system is an OutBack FM60. This controller is capable of handling higher voltages from the connected PV panels than the BlueSolar controller. It is also capable of handling 60A compared to the 50A of the blue solar. As with the BlueSolar, the power is stepped down from a higher input voltage to a lower battery voltage. This battery voltage is specified to be approximately 48V. Also in this case the manufacturer is advertising the use of an MPPT algorithm without going into specifics on how it works. In general, the OutBack system is less open source and uses an propriety communication protocol requiring extra hardware in order to leverage the data it generates. It does however have a display that allows viewing historical and live data. The technical specifications are included in Appendix A.6.

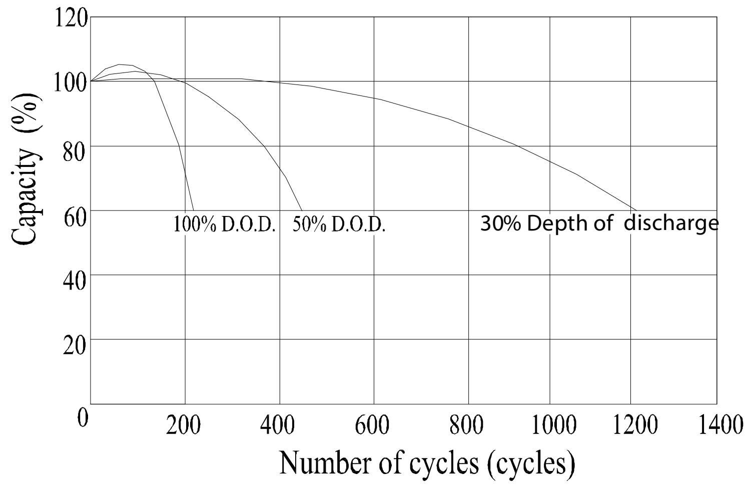


Figure 2.5: Manufacturer made graph indicating expected battery cycle life given various degrees of discharge depths. Given at an average temperature of $25°C$.

Inverter

An inverter is included in the system because AC power is required by many of the appliances in the school building. This inverter is also produced by OutBack and is of model GVFX3648. The voltage required is 120VAC. Therefore the voltage must be stepped up in addition to changed from direct current to alternating current. The input voltage requirement is 48VDC, and it can provide 3600W at its output. This is the source of the AC outlet available in the refrigerator center.

Chapter 3

A Human-centered Design Approach

The users of the monitoring system discussed in this paper is an indigenous community in Colombia, as described in the previous chapter, which implies that big cultural differences were present between the developers and the users of the system. Cultural differences can be hard to overcome and thus prevent developers from obtaining a sufficient understanding of the users' need. Principles of human-centered design was applied to overcome this issue, together with usability heuristics that are well-established in the field of user interface (UI) design [2].

Human-centered design (HCD) is an approach that asserts focus on the users' needs is of vital importance in order to create interactive systems that are effective [2], whose principles are provided by ISO 9241-210. The ISO standard 9241-210 defines an interactive system to be "combination of hardware, software and/or services that receives input from, and communicates output to users". The monitoring system includes a hardware and software setup that enables the user to view sensor data on a web page, and qualifies thus as an interactive system.

First, background theory for human-centered design and design principles will be presented. The remaining sections follow the steps of a human-centered design process and specify how they were implemented on the path towards developing the monitoring system.

3.1 Theoretical Background

Traditionally, human-computer interaction design has been concerned with usability, according to [16]. The International Organization of Standardization develops standards covering almost every industry to create consensus among their 160 country members on requirements for good quality products. ISO standard 9241-11 [17] and ISO 9241-210 [18] from the ISO 9241 series, which is concerned with the ergonomics of human-system interaction, was used to guide the development of the monitoring system.

ISO 9241-11 defines the term *usability* and specifies how to identify the information necessary to obtain or evaluate the usability of a virtual display terminal. Usability is defined as the "extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" [17]. ISO 9241-210 [18] provides a framework for implementing a Human-centered design process to ensure usability.

The ISO 9241-210 standard provides only an overview of human-centered design activities. For details on how to perform different methods and techniques to implement the activities, other references had to be turned to, such as the book "Interaction design - Beyond Human-computer interaction" [16]. The NTNU course TDT4180 "Human-Computer Interaction", which is an elective subject for cybernetics students at NTNU, was followed in parallel by one of the students for support on how to implement a human-centered design approach, and the book mentioned above is part of the syllabus in the course.

3.1.1 The Human-centered Design Process

The Human-centered design process in ISO 9241-210 define four design activities as necessary in the development of any interactive system. An illustration of the Human-centered design process is given in Figure 3.1, and the four design activities are as follows:

1. Understanding and specifying the context of use
2. Specifying user requirements
3. Producing design solutions
4. Evaluating the designs

The HCD process is iterative, which is one of the five principles of HCD put forward in ISO 9241-210. It means that each design activity should be revisited at appropriate times throughout the process. The principle of iteration is based on the fact that many of the user needs typically emerge during the design process, as users usually express their opinions better in response to a potential product.

Thus, the steps in Figure 3.1 are repeated and the output of each step is refined until the desired outcome is achieved.Figure 3.1 should be understood in the following way. After you have planned the HCD process, you start by understanding and specifying the context of use. The second step is to specify the user requirements, before producing design solutions that comply with these requirements. The fourth and last step of the cycle is to evaluate the design. The results of the evaluation decides which of the previous step you should go back to in order to do refinements.

Typical outputs from the HCD process is given in Table 3.1. The steps of the HCD process yield descriptions, specifications and prototypes that convey the results of each step. The descriptions and specifications should be considered living documents to be maintained

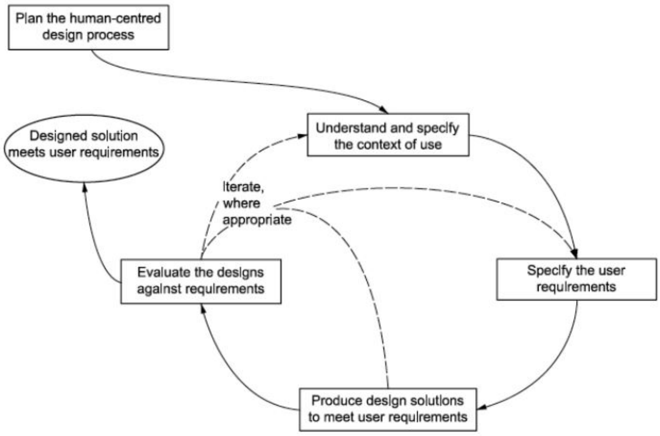


Figure 3.1: The human-centered design process by ISO 9241-210 [18].

and updated throughout the iterative process as new information is obtained, for example when users test a design solution. The risk of the system failing to meet the users' needs minimizes as the accuracy and the quality of the descriptions and specifications keeps increasing. The ISO standards provide guidelines on how the outputs should be crafted.

Table 3.1: Examples of outputs from the design activities in the Human-centered design process. Table reproduced from [18].

Human-centered design activity	**Output**
Understand and specify the context of use	Context of use description
Specify the user requirements	Context of use specification User need description User requirements specification
Produce design solutions to meet these requirements	User interaction specification User interface specification Implemented user interface
Evaluate the designs against requirements	Evaluation results Conformance test results Long-term monitoring results

Planning the HCD process involves choosing among a variety of methods and techniques to carry out the different steps in Figure 3.1 and the kind of outputs that should be produced. The methods and outputs applied to implement the HCD process relevant to the development of the monitoring system will be presented in the following as the design steps of the HCD process is elaborated.

Understanding and specifying the context of use

To understand and specify the context of use, a combination of data gathering techniques is required. A list of data gathering techniques is provided by Preece et al. in [16] and is given below.

- Interviews
- Focus groups
- Questionnaires
- Direct observation
- Indirect observation, e.g. by the use of diaries and/or logging.
- Studying documentation
- Research of similar products

A context of use description can be a description of the current context of use or a description of the context for the intended product. The scope of the context of use description should be sufficient in order to support the requirement specification and the activities to follow in the human-centered design process. According to [17], a description of context of use should should include information about the following:

- Users: Persons who interact with the product.
- Tasks: Activities to perform in order to achieve a goal.
- Equipment (hardware, software and materials).
- The physical and social environment.

As a complement to describing context of use, personas and scenarios can be used as powerful techniques to document the findings from the data gathering. They serve as a conretizations and can streamline the communication with the stakeholders. Personas and scenarios aids the designer to a user-centered focus, and are often the first step in establishing requirements [16].

Personas are a detailed descriptions of typical users of the system that the designer can focus on and cover the needs of in the design process. A persona typical includes specification about the user's goals, motivation, characteristic and behaviour. It serves a representative of one of the user groups that is realistic, but unreal, meaning it does not describe a real person. Personas are widely used in industry, according to [16].

Scenarios is used to capture the task of a user. It explains the when, where and how of a persona's interaction with a product. It too works as a powerful tool in the communication of the design process, as it provides the context, needs and requirements of a human activity in an informal narrative description resembling a storytelling, a format everyone can relate to [16].

Specifying user requirements

ISO 9241-210 [18] provides five bullet points on what a specification of user requirements should include. To keep the scope of the project at a manageable level, the user requirement specifications were narrowed down to only include a usability requirement specification.

ISO 9241-11 provides an example on how to write a usability requirement specification in Annex C. The specification is constituted by two main parts. One part specifying the product's intended context of use, and the second part specifies the usability measures and objectives [17]. Theory about the first part, the intended context of use, was given in the section above.

The second part of the usability requirement specification in ISO 9241-11 defines measures and objectives for the usability components effectiveness, efficiency and satisfaction. Measures and objectives for the usability components is given for each task put forward in the intended context of use. Effectiveness is defined as "accuracy and completeness with which users achieve specified goals", efficiency as "resources expended in relation to the accuracy and completeness with which users achieve goals", and satisfaction as "freedom from discomfort, and positive attitudes towards the use of the product" [17].

Different measures for effectiveness, efficiency and satisfaction is also provided by ISO 9241-11. For instance, the effectiveness can be measured by the the number of wrong outputs (accuracy) and the number of times the task was completed (completeness). Efficiency can be measured as effectiveness divided by some resources spent, for instance by human effort (e.g. labor hours) or by cost. Satisfaction measurement can be performed by collecting ratings from user on the level of experienced discomfort or liking of product [17].

Producing design solutions

The idea behind this step is to produce design solutions, meaning "progressively refined solutions" [18], that can be tested with users in order to obtain feedback that can be used to update the user requirements. The ISO 9241-210 standard lists the sub-activities involved when producing design solutions. First, it includes designing an user interface to meet the user requirements in order to keep the whole user experience in focus. The next activity is to make the design solution is made concrete. Lastly, the design solutions should be altered in response to user-centered evaluation and feedback.

The design solutions is made concrete by producing prototypes. A prototype is a representation of all or part of an interactive system to be used for evaluation. It can be as simple as a sketch on paper, a mock-up or close to the final product with almost all the functionality implemented, according to ISO 9241-210 [18]. Typically, the early versions of the prototypes illustrate the total system without much interactivity and functionality, for instance a paper prototype. Later in the process, the prototypes go in depth on a particular part of the system and in the end resemble the final product. The prototypes developed is what will be included in this thesis to describe the design solutions.

Evaluating the designs

Usability testing is a user-centered evaluation method for obtaining user feedback that can be used to refine the design solution.

A methodology on usability testing is provided in the NTNU course Human-Computer Interaction [19] and was used to test the prototypes and the final design solution. The procedure on how to plan a usability test by [19] (freely translated) is given below.

1. Formulate the goal of the test, an hypothesis and develop a test plan.
2. Acquire test users. The test users can be selected randomly or through a stratified selection, in order to make sure any user segment is represented.
3. Prepare the necessary material and context for the test.
4. Pilot test.
5. Choose test leader.
6. Conduct usability test (involves ten steps).
7. Transform the data to discoveries and recommendations.

The point in which the user interacts with the design solution, the sixth step, involves the following ten additional steps (freely translated from [19]):

1. Introduce yourself.
2. Explain the purpose of the test.
3. Tell the participant that he or she can end the test whenever they want, in case they feel uncomfortable at any point.
4. Describe the test equipment and the restrictions of the prototype.
5. Teach the participant how to "think out loud": This is important because this is the only way to get access to the mental model the users has of the system, which might deviate from the design model that the the implemented design is intended to convey.
6. Explain that you can not help during the test.
7. Ask if the participant has any questions. Else, start the test.
8. End the test by first giving the participant the chance to state any opinions. Then ask questions to collect any loose ends.

The methodology also includes an observation form to report findings during usability tests. This observation form was adapted and translated, and it is illustrated in Figure 3.2.

According to Jakob Nielsen from the Nielsen Norman Group (NN/g) [20] in [21], the number of test users in a usability test should be five. A higher number of test users is a waste of resources. This was the guiding number used in the usability tests in which the design was evaluated against user requirements. Also recommendation on design principles was retrieved from NN/g research.

Observation form - usability test

Sheet ____ of ____

Observer: Date: Time:

Product tested: Test leader:

Test person: Age: Gender: Other:

Time	Problem	Cause	Solution

Figure 3.2: Observation form used to report results during a usability tests from [19].

3.1.2 Design Principles

In addition to the principles of human-centered design provided by ISO, well-established usability heuristics for user interface design were used to guide the design process. Jakob Nielsen and Don Norman started NN/g in 1998, and has ever since been one of the leading voices in the field of user experience. Norman states in [22] that design principles based on psychology will remain the same since the principles of human psychology will remain the same. Thus, the idea was that despite cultural differences between developers and users, it is possible for developers to follow design principles of universal character to increase the probability of developing a product with high usability. The following ten usability heuristics for user interface design by Jakob Nielsen were used for this purpose and will be described in more detail in the next paragraphs [2].

1. Visibility of system status
2. Match between system and the real world
3. User control and freedom
4. Consistency and standards
5. Error prevention
6. Recognition rather than recall
7. Flexibility and efficiency of use
8. Aesthetic and minimalist design
9. Help users recognize, diagnose and recover from errors
10. Help and documentation

Visibility of system status: Feedback should always be presented within reasonable time to the user. E.g. a progress bar should appear if the user clicks something that takes a long time to upload.

Match between system and the real world: The product should speak "the user's language". This means that the phrasings and concepts used should be familiar to the user and not system-oriented. For instance, instead of giving the feedback "a user record was inserted into the database" when a user has signed up, the statement should for example be "you have been registered as a user". When it comes to concepts, the iTunes store [23] is a good example. Marketing what is in fact a software solution as a *store* gives the users an idea of what kind of services to expect and how to interact with it.

User control and freedom corresponds: The user should always be able to leave an undesirable state, and always be presented with the opportunity to undo or redo an action.

Consistency and standards: The same word should always mean the same thing, and different words should not refer to the same thing. Also, platform standards should always be complied with, which in the case of web pages concerns compatibility across different browsers and operating systems, such as Windows for computers and Android or iOS on mobile phones. However, there is good cross browser support in front-end frameworks. Also, to interfere with the standards of the operating systems is rather unlikely when designing a web page primarily displaying information, and effort should rather be put into complying with the style guidelines of a front-end framework to ensure consistency.

Error prevention: The interface should be designed to limit the possibility of users making errors in the first place. For instance, present a confirmation option before an extensive action.

Recognition rather than recall: The memory load on the user should be limited. Make important objects and options clearly visible in the interface, and the user should not have to remember information from one window to the next. One thumb of rule is that a human can remember seven, plus or minus two units of information in the short-term memory at once [16, p.75].

Flexibility and efficiency of use: In case of a more complex software tool, it should be possible to tailor the software to the user's preferences, in order to speed up the work for users who have developed from being a novice to an experienced user.

Aesthetic and minimalist design: Anything unnecessary should be removed to not lead the user's attention away from the relevant information. Dialogues in the window should not contain irrelevant information, and unnecessary options and actions should be removed.

Help users recognize, diagnose and recover from errors: Error messages should be provided in case of errors, clearly stating the problem and suggest a solution.

Help and documentation: Always provide a manual that is easy to read, not too large and that helps users with lists of concrete steps. Although the best user interface is one that can be used correctly by simply using intuition, always provide the user with documentation.

3.2 Planning a Human-centered Design Process

According to the recommendations of ISO 9241-210, it is important to consider the nature of the development environment (size and time limit on the project, etc.) when planning human-centered design [18]. The nature of development is a master thesis spanning one semester. This, as well as the available resources formed the premise when choosing appropriate methods in order to implement a human-centered design process. When the human-centered design process was planned, the data gathering sources that was known to be available were the following:

- Direct interaction with the community prior to system implementation would not be not possible.
- Postdoctoral researcher Maximiliano Bueno-López would be our only source to firsthand information about the community and its customs. Any questions that Bueno-López could not answer could be forwarded to his contact person in the community.
- There was a possibility that a field trip to Colombia could be arranged in May, at the end of the project. The realization of a field trip depended on financial support from non-profit organizations, from the La Salle University in Colombia, and whether we would be allowed to visit the indigenous community by the Colombian government. A field trip would enable interaction with the real users, and we would get our hands on the La Salle current sensors for the first time.
- Diego Perez Lara developed a monitoring system for electric energy consumption in Colombian homes in his master thesis [24] as a student at La Salle University. His work is described in cooperation with Bueno-López in [25]. It is unquestionable that Lara as a Colombian himself is closer to the real users and has a much greater prerequisite for designing such a system than the undersigned authors. Thus, his work was looked to for inspiration.

The sections ahead follow the design activities of the human-centered design process and specify how they were implemented: understanding and specifying the context of use, specifying user requirements, and producing and evaluating design solutions.

3.3 Understanding and Specifying the Context of Use

The current context in the community should be researched and described in order to be able specify the context of use for the future system. The example on how to specify the context of use in ISO 9241-11 [17], Annex A, was applied. The example includes a variety of attributes, from which the appropriate ones was selected, and adaptions were made to make the framework fit a user group of indigenous people. Documentation on the current context in the community is given in Appendix C, and includes tables specifying the users, tasks, equipment and the environment.

The current context of use in Appendix C should be considered a working document that was reviewed, maintained and updated throughout the project, in line with ISO standard 9241-210. The example given in the Appendix is the latest version.

To specify the current contact of use, appropriate data gathering techniques from the ones listed in Section 3.1.1. The biggest restriction was naturally that direct interaction with the community was not possible. The data gathering techniques that was applied were as follows:

- *Interviews*: Interviews were performed by a La Salle research team in 2014 prior to the installations in the community in 2015, as mention in the introduction of Chapter 2. The interviews were documented in a spreadsheet and handed to us, which entailed 42 males answering general questions about themselves, economics and the social, technical and environmental aspects of the community on behalf of their family [13].
- *Researching similar products*: The home monitoring platform by Lara in [24] was researched.
- *Conversations with postdoctoral researcher Maximiliano Bueno-López*: The knowledge Bueno-López had obtained while engaged in the installation process of the solar panel systems in 2015 was invaluable, and this document aims to document this knowledge. In addition, Bueno-López had direct contact with a community member by phone, who answered questions and sent pictures if necessary.

In addition, a persona and scenario was develop as additional means to convey the current context. Only one persona was developed as there is chiefly one main user of the intended system, the salesman (the primary user in line with the current context of use specification in Appendix C). The persona in Figure 3.3 was developed using the example page 358 in [16] as template. Images are from [26]. The scenario that follows explains a typical working day for the persona. It embodies the everyday tasks of the salesman in which the monitoring system developed aims to function as a support.

Diego has the morning shift as the salesman at the refrigerator center, which lasts from 8 am to 1 pm. He is accompanied by one of his colleagues in the Energy Cooperative that is responsible for the refrigerator inventory and making agreement with the farmers, fishermen etc. that wants to sell their production in the refrigerator center, similarly to a distributor. The first thing they do when they arrive at the cooling center is investigate how many refrigerators that is running, how much inventory they have and what deliveries to expect during the day. They consider the solar irradiation of the last couple of days as low, so they decide to turn off one of the refrigerators. However, they have some technical questions related to the impact of turning on one more refrigerator on the solar system batteries, so they call the person on duty from the technical committee responsible of the solar panels using Diego's smartphone. The technician confirms that they can safely do as they intended.

The traffic is low in the morning hours, as usual. Around 9 am, the fishermen return from the sea with fish they want to store in the refrigerator center as normal. Diego handles the fee they have to pay in order to use and his colleague accepts the fish and notes who owns what so the rightful owner will get paid if the fish is sold. Some of the fishermen pay their fee with fruits - the producers can pay for storage capacity using fruit instead of cash, because the community members typically do not have much money. The income from selling fruits goes directly to the refrigerator centers earnings, but

the money they receive from selling fish and other products that producers have paid a fee to store, goes directly to the producer himself. However, the catch of the fishermen is a particularly big one, so after turning off one of the refrigerators, there is not enough room. Diego and his colleague has to call a meeting and explains to the affected fishermen that there is not enough capacity considering the electricity available, so the fish that is close to exceeding the 3-4 maximum number of storage days unfortunately has to be removed and will not be sold despite the fee they have paid.
After the meeting, Diego and his colleague use the blender to produce juice to sell from the fruit they received, while serving an occasional customer. At 1 pm the the second salesman and the second distributor person in the Energy Cooperative arrives to replace Diego and his colleague. The busiest times of the cooling center in terms of customers is in the afternoon, when people have finished work and also people from other communities come visit Calle Santa Rosa to buy goods. It is also during the second shift that the catch of the hunters is taken care of. Before closing the cooling center down, they again reevaluate the number of running refrigerators and investigate the inventory.

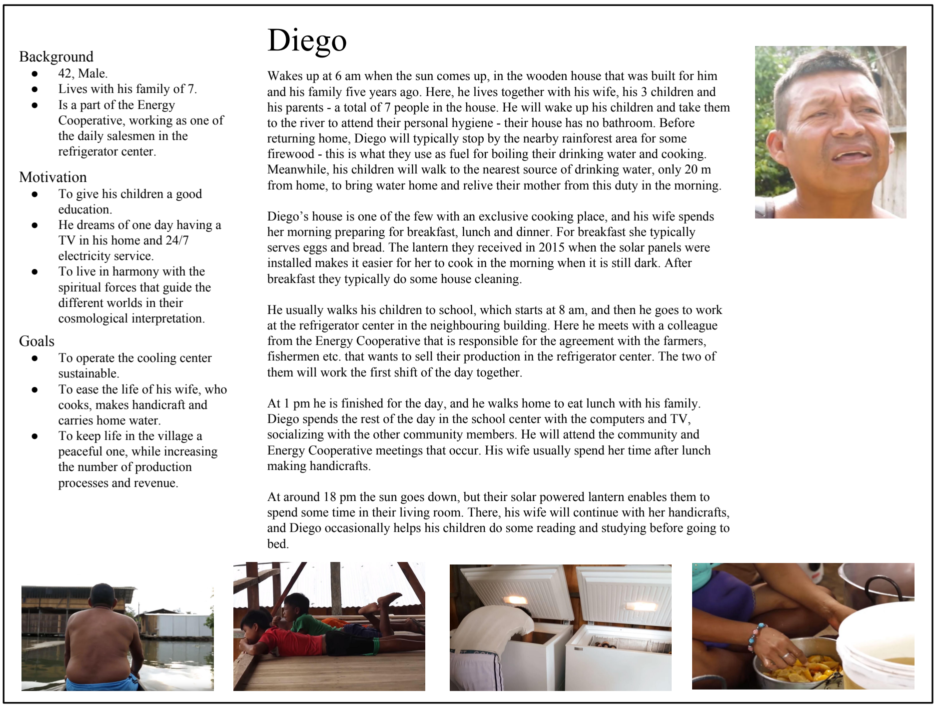


Figure 3.3: Persona used for user requirements specification. Source for information and pictures: [26].

3.4 Specifying User Requirements

This section presents a usability requirement specification that was developed by applying theory explained in Section 3.1.1 is presented. The example on how to write an usability requirement specification in Annex C in ISO ISO 9241-11 was followed in order to write the usability requirements for the monitoring system. It includes the intended context of use for the monitoring system developed and usability measures.

Name and purpose of the product

This specification defines usability requirements for the Calle Santa Rosa monitoring system. The interface of the monitoring interface is a web interface which will be referred to as *panelsolar.com*.

The purpose of the monitoring system is to provide the indigenous community in Calle Santa Rosa a tool that can support the Energy Cooperative in Calle Santa Rosa in the decisions they have to make related to the refrigerator center and substantiate their decisions in conversations about the management of the refrigerator center with the rest of the community.

Intended context of use

Specification of users

panelsolar.com is intended to be used by any person with the characteristics given in List 3.2. It is assumed that the person is a community member of the Calle Santa Rosa Reservation.

Specification of equipment

The main component of the monitoring platform is a Raspberry Pi programmed with the right software. The Raspberry Pi functions as a web server on the local network it is connected to and as a database that collects sensor measurements.

The Raspberry Pi communicates with the following devices:

- A split core 2.1 cm DC sensor mounted around the power cable that powers all the six refrigerators in the refrigerator center.
- Four current sensors communicating over Wi-Fi provided by the La Salle University that were developed by Lara in [24]. The sensors are appliance-specific, meaning they measure the current consumed by a single appliances. The selected appliances have to adhere to the maximum current constraint of the sensor - two of them measure up to 5 A, and the other two measure up to 20 A. The sensor communicate wirelessly over Wi-Fi with the Raspberry Pi. The plan was to choose specific appliances in the school, for instance the TV being one of them.
- The Raspberry Pi is connected to the BlueSolar MPPT 100/50 solar charge controller in the refrigerator center by a USB cable.

Table 3.2: The intended users of the monitoring system. A part of the context of use specification of the product.

Attribute	**User requirements**
Skills and knowledge	
Product experience	Experience with computers and web pages is expected.
System knowledge	User should be familiar with the solar panel installations and the refrigerator center in Calle Santa Rosa, and the work of the Energy Cooperative.
Task experience	None required.
Organizational experience	Person is assumed to be a community member of the Calle Santa Rosa Reservation. The primary user is intended to be one of the members of the Energy Cooperative that manage the refrigerator center in Calle Santa Rosa.
Training	None required.
Keyboard and input skills	Should be familiar with web page interaction. No keyboard inputs necessary.
Qualifications	None required.
Linguistic ability	Spanish
Physical attributes	
Vision	Vision required.
Hearing	Hearing not required.
Manual dexterity	Manual dexterity in order to handle web page interaction on a computer or a smartphone is necessary.

Specification of the environment

The following facilities needs to be in place:

- The Raspberry Pi has to be placed nearby the controller of the refrigerator center's solar panel controller, in the fuse box, so it is possible to connect the Raspberry Pi to the controller using the 1.5 m long USB cable.
- Two AC sockets in sufficient proximity to the Raspberry Pi and the DC sensor. The DC sensor is powered using a AC/DC adapter with a 3 m long power cord, and the Raspberry Pi is powered using a AC/DC adapter with with a 2 m long power cord.
- Adequate Wi-Fi signal has to be provided to the Raspberry Pi, so it is able to communicate on the local network. Internet access to the World Wide Web is not necessary. The four Wi-Fi sensors also need to be within the range of the local network.
- The current measured should not exceed the maximum current constraint of the different sensors. The maximum current constrain of the DC sensor is 50 A, and either 5 A or 20 A for the Wi-Fi sensors.

Specification of tasks

The primary intended goal is to provide the workers of the Energy Cooperative responsible for determining the number of running refrigerators in the refrigerator center with a tool that can help them make more correct decisions and substantiate their decisions in conversation with other community members.

The secondary intended goal is to give the community a tool that can enlighten all community members about how the electrical systems they got in 2015 works, and further strengthen the social appropriation and knowledge transfer started during the installment process of the photovoltaic systems in 2015. Every community member can visit the respective web page of the monitoring platform. It provides a visual display of the electrical consumption and the battery status of the refrigerator center, which is a a presentation they have not had before.

The usability requirement specification of *panelsolar.com* includes the following specific tasks:

- Web page access: Type in the correct address to view the web page on a computer or a smartphone.
- Refrigerator center's electrical status: View the electrical consumption of the refrigerators, the production of the solar panels and the battery state of the solar panel system in the refrigerator center.
- School's electrical status: View the electrical consumption measured by the four appliance-specific sensors communicating over Wi-Fi that are installed in the school.

- Prediction: Find the recommended number of running refrigerators in the refrigerator center.
- Extended use: Use the web page in the reevaluation of the number of running refrigerators during the shift at the refrigerator center, and use the web page in meetings with others related to the operation of the refrigerator center.

Specification of measures for usability for particular context

The measures below are specified for each task defined in the intended context of use above. For each task, a measure is given for each of the usability components effectiveness, efficiency and satisfaction. The definition of the usability components can be found in the theory given in Section 3.1.1.

The usability measurements should be reported separately for users that are members of the Energy Cooperative and for other community members, and separately depending whether the web interface was accessed using a computer or a smart phone.

Web page access

Task:
Type in the correct address to view the web site on a computer or a smartphone.
Specific context:
The user is placed in front of a computer or handed a smartphone connected to the local area network. The user is asked to access the monitoring web page by typing in the specified URL in the web browser.
Effectiveness:
Accuracy: The wrong URL is typed incorrectly less for first users less than 10 % of the time.
Completeness: The web site should be displayed every time the correct URL is typed.
Efficiency:
The web site should be finished loading within two minutes every time.
Satisfaction:
Less than 10% of the users report dissatisfaction with how the web page is accessed.

Refrigerator center's electrical status

Task:
View the electrical consumption of the refrigerators, the production of the solar panels and the battery state of the solar panel system in the refrigerator center.
Specific context:
The user is presented the web page on a computer or a smartphone and asked to view the electrical status of the refrigerator center.

Effectiveness:

Accuracy: Less than 10% of the users should be unable to find the correct the web page.

Completeness:

1) All users should answer correctly what the battery state is.
2) Less than 10% should answer wrongly, or be unable to answer, about what the production of the solar panels in the refrigerator center the previous hour was.
3) Less than 10% should answer wrongly, or be unable to answer, about what the consumption of refrigerators the previous hour was.

Efficiency:

Less than 10% of the users should not use more than 2 minutes to find the right page and to be sure they have found the right page.

Satisfaction:

Less than 10% of the users report dissatisfaction with how easy it was to locate the view showing the electrical status of the refrigerator center.

School's electrical status

Task:

View the electrical consumption measured by the four appliance-specific sensors communicating over Wi-Fi that are installed in the school.

Specific context:

The user is presented the start web page on a computer or a smartphone and asked to view the electrical status of the refrigerator center.

Effectiveness:

Accuracy: Less than 10% of the users should be unable to find the correct the web page.

Completeness:

1) Less than 10% of the users should be unable/answer wrongly what appliances that are measured in the school.
2) Less than 10% of the users should answer wrongly or don't find the answer to the total consumption of all appliances 1 hour ago.

Efficiency:

Less than 10% of the users should not use more than 2 minutes to find the right page and to be sure they have found the right page.

Satisfaction:

Less than 10% of the users report dissatisfaction with how easy it was to locate the view showing the electrical status of the school.

Prediction

Task:

Find the recommended number of running refrigerators in the refrigerator center.

Specific context:

The user is presented the start web page on a computer or a smartphone and asked to locate where in the view to get a recommendation by the system on how many refrigerators should be running in the refrigerator center. The user should run predictions to get a recommendation. This applies only to members of the Energy Cooperation.

Effectiveness:

Accuracy: Less than 10% of the users should be unable to find the correct web page as first-time users.

Completeness: Every user that finds the correct web page should answer correctly what the interface recommends to be the number of running refrigerators.

Efficiency:

Less than 10 % of the users should use more than five minutes to get the right recommendation.

Satisfaction:

Less than 10% of the users report dissatisfaction with how easy it was to locate the view showing the electrical status of the school.

Less than 20 % with how easy it is to get the right recommendation.

Extended use:

Task:

Use the web page in the reevaluation of the number of running refrigerators during the shift at the refrigerator center, and use the web page in meetings with others related to the operation of the refrigerator center over an extended period.

Specific context:

A salesman in cooperation with an inventory responsible, both members of the Energy Cooperative, reevaluates the number of running refrigerators during their shift, once in the morning at 8 am and once in the evening at 6 pm. During this evaluation, the web page should be used to produce a recommendation on the number of running refrigerators. Also, the Energy Cooperative meet with the technicians twice a week to make plans for the days ahead on how many refrigerator that should be expected to run. During this evaluation, the web page should also be used to produce a recommendation on the number of running refrigerators.

Effectiveness:

Accuracy: Less than 50% of of the times the web page is used to get a recommendation, the recommendation is rejected.

Completeness: The number of times the web page is used and a recommendation is produced.

Efficiency:

Average time from which the process of evaluation the number of refrigerators is started until the web page is consulted.

Average time it takes from the web page is consulted until the user believed he or she has found the correct recommendation.

Satisfaction:

During at least 80 % of the daily evaluations in the refrigerator center, the web page is consulted.
In at least 80 % of the weekly meetings of the Energy Cooperative and the technicians, the web page is consulted.

3.5 Producing Design Solutions

Three iterations of the HCD process was performed in Norway before the field trip, in which a paper prototype and a web interface was produced. The design choices made and the tools used to in the production of these will be elaborated in this section.

A variety of interfaces exists, according to [16]. The research on the current context of use had revealed that most community members had access to a smart phone, and that all community members also had access to the computers and the Internet in the CTC built in 2014. A website was thus considered to be a highly accessible interface for the community members and hence decided to be the interface of the monitoring system. First, current trends in web design was researched in order to understand how the web interface of the monitoring system should be implemented.

3.5.1 Current Trends in Web Design

When it comes to web page design, a lot of websites follow a very similar trend. In the following, this trend will be related to Nielsen's usability heuristics to illustrate why it is reasonable to opt for a similar design solution.

The trend is characterized by a navigation bar at the top of the page and and then the rest of the page is occupied by a big image and little text. The Apple web page [27] illustrates this trend as shown in Figure 3.4. Overall, the design is very clean and simple, which leads the user to click where you want them to. The website for Samsung [28] or Google products such as AdWords [29] and AdSense [30], or are other great examples of the current design trend.

The current trend in web design complies with Jakob Nielsen's eighth usability heuristic in Section 3.1.2 for user interface design, which states that the interface should be aesthetic and minimalist - everything unnecessary should be removed.

Further, the usage of digital products are expected to grow in the community, considering the increased use since the introduction of computers and Internet in the village back in 2015. Making a solution that will resemble other web pages that globally are frequently used, such as the Google web page interfaces, can only be considered an advantage. It will give the user a sense of familiarity and recognition, which corresponds to the goal of consistency across platforms in Nielsen's fourth heuristic and recognition in the sixth.

The trend in web design is based on the idea of designing "above the fold", which means to keep the most important content at the the top of the page and visible without scrolling

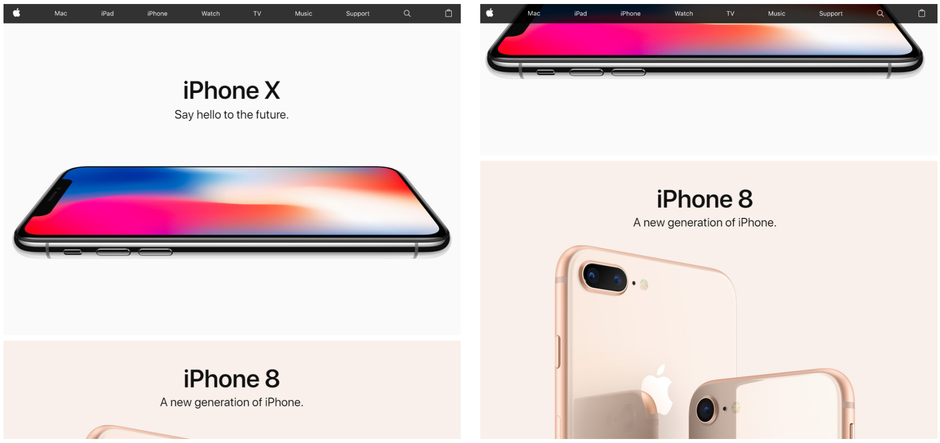


Figure 3.4: The Apple web page illustrating the current web page design trend.

([31]). This feature matches the sixth heuristic of Nielsen, which is relevant once again, but this time in the sense of supporting recognition rather than recall by making the instructions visible and evident in the starting window of the web page.

However, the space that defines the fold varies across the different kind of devices and screen resolutions. This means that the design has to be coherent across all possible screen resolutions, and this is where "responsive design" comes in.

Responsive design allows you to optimize your web page design across different devices and screen resolutions [32]. Since the use of smartphones in the Calle Santa Rosa Reservation has increased from close to zero in 2014 to about two per family (see Section 2.2), it was determined that the web page should be available both on mobile phones and on computers and thus be responsive. The next step towards producing a design solution was to research how to develop a responsive website.

3.5.2 Web Development

Web development is the process of creating and deploying a website. In this section, an introduction of the common technologies that was used in the development of a web interface for the monitoring system is presented.

Web server

A web server is essential in web development because it is where all the files associated with displaying a web page is located. According to [33], a web server is a program that use the Hypertext Transfer Protocol (HTTP) to serve web pages to clients that request them.

A Raspberry Pi (RPi) is a small and affordable computer. It was considered an excellent choice in order to host a website in a rural area and supported the decision of providing the interface of a monitoring system as a website. A RPi requires little power, yet it is powerful enough to host a website.

A web server can make websites accessible on the Internet (the World Wide Web) or only on a local area network. Generally, the term web site refers to a collection of web pages. On a local area network, only the computers connected to the private network can view the website. It was decided that a web interface accessible only on the local net would be sufficient, because the monitoring system was intended to be used first and foremost by the salesman working in the refrigerator center. Furthermore, the Raspberry Pi does not have the computational power to serve multiple HTTP web requests at the same time, so to make it available on the World Wide Web would increase the possibility of a web server overload.

When the web server has to access a database to display the necessary data on the web site, the web server is part of a server setup. One solution is to have everything located on one server, or having a separate database server. More details on the subject can be found in [34]. A common approach to simplify the server setup is to use a pre-defined infrastructure solution, such as LAMP [35]. LAMP, which is an acronym of the software components it entails, Linux operating system, Apache HTTP Server, the MySQL database and PHP as server-side scripting language, is an all-in-one server solution.

A database was needed in the setup of the monitoring system in order to store energy measurement to be displayed on the website. The LAMP server solution was considered appropriate to be installed on the RPi. The software components it contains and how they were used to produce the web interface as a part of the design solution is given in the following section. The term back-end has traditionally been used to refer to the software that runs on the web server. For instance, programs for database access run on the web server, and for this reason, a server-side scripting language is needed.

Server-side scripting language

The files on the web server that handles the request from a client are server-side scripts. A server-side scripting language is the technology that delivers the content on the web server to the user and makes it accessible on a web page. PHP is the most popular server-side programming language according to [36].

Admittedly, the terms *programming language* and *scripting language* seem to be used interchangeably. A programming language is a broad term that refers to all the computer languages that specify a set of instructions for a computer to execute. A scripting language is a programming language that does not need pre-processing (e.g. compiling) before being run [37], [38]. A PHP script is executed on the web server. The web page it generates is the response that is sent back to the user. In essence, each web page corresponds to a particular PHP file on the web server. A PHP script for web page display is usually a combination of HTML and PHP statements. The PHP script would typically include

PHP statements first to retrieve and/or process data, and HTML is what the PHP script outputs.

Thus, the server-side scripting language provides data to the software application's front-end, which is the software that runs in the client's web browser. The cornerstone front-end technologies in web development, that are used to design the look and behavior of web pages, are HTML, CSS and JavaScript.

HTML

The World Wide Web Consortium (W3C) aims to provide Web standards, and considers HTML and CSS the fundamental technologies for building web pages [39].

HTML, the Hypertext Markup Language, is a markup language intended for web page display in World Wide Web browsers. A web page is is delivered as a HTML document (file ending *.html*), which defines the web page as a tree structure, following the Document Object Model (DOM) [40]. The extent of its use can be seen in [41].

In the HTML document, HTML elements are defined by enclosing content in HTML tags, which is the annotation used in the HTML language. The documentation on HTML tags from [42] was used when developing the website. The client's web browser receives the HTML document from the web server, and interprets the HTML tags in order to display the web page.

CSS

CSS stands for Cascading Style Sheets, and while HTML defines the content for web pages, CSS defines the layout of the web page. Using the CSS language, a style can be applied to different HTML elements. A style is defined by properties such as color, size etc., and the documentation that was used on the CSS properties available can be found in [43]. The HTML elements are referenced and the styles defined in separate CSS files that are included in a link in the HTML document it belongs to.

JavaScript

Similar to PHP, JavaScript is a scripting language, but JavaScript is a client scripting language that runs in the web browser as opposed to on the web server. Whereas HTML defines the content of the web pages and CSS the layout, JavaScript defines the *behaviour* of web pages.

JavaScript makes the web page more dynamic. It makes it possible to add and modify content on the page without reloading (Dynamic HTML), respond to action events (such as a mouse click) triggered by the user, and add interactivity to the web page. *AJAX* (Asynchronous JavaScript And XML) is the technology that makes it possible to make requests to a server without reloading the page or having to wait for the response.

A JavaScript library is a collection of pre-written JavaScript functions in a file that serves as an interface and an easy way to include JavaScript on your web page to accomplish some useful task. JavaScript is supported by a vast community of developers that develop open-source JavaScript libraries. The JavaScript library jQuery [44] was used to simplify HTML document traversal and to get access to jQuer's AJAX [45] interface to create asynchronously HTTP requests. Asynchronously HTTP requests allows for the web page to update only the necessary parts, without having to the reload the whole page. This leaves the user to a greater extent more aware what is going on, because feedback can be giving withing a shorter amount of time, in line with Nielsen's tenth usability heuristic in Section 3.1.2.

The JavaScript library Highcharts [46] was used to include plots of energy measurements on the monitoring system's website. Highcharts makes it simple to add interactive charts to a web page, offering a wide range of chart types.

Different frameworks for web development exists that include JavaScript libraries. However, when searching the Web, the distinction between JavaScript frameworks and JavaScript libraries is seemingly vague. JavaScript frameworks impose a structure on the code in order to simplify the logic for information flow in the UI and make sure the web page is always up-to-date, for reasons elaborated in [47]. React [48] was developed for similar purposes and is one of the most popular JavaScript libraries [49], but it was believed that the information flow in the monitoring system's website would not be of such complexity that React would be required. A front-end framework is a bundle of JavaScript and CSS files that provides a template for web page design that can be build upon. Typically, the front-end framework includes predesigned HTML components and a grid for the HTML components to be placed in that makes it easy to develop a responsive design, as discussed in Section 3.5.1 [50]. It was decided to include a front-end framework to simplify the web page design process.

Material Design Lite

Material Design Lite is a front-end framework that aims to be an easy way to add the look and feel of Material Design [51], a "visual language that synthesizes the classical principles of good design" developed by Google [52]. Material Design aims to bring the design experience Google has built over decades into one place, and it attempts to simplify the process of designing responsive user interfaces so the web designer can ensure the same experience across platforms and device sizes.

Other front-end frameworks such as SASS/SCSS and Bootstrap are proved to be more popular [53], but they do not provide the same assurance of complying to the classical principles of design as Material Design Lite does. For this reason, Material Design Lite was considered a great starting point for including the design principles in Section 3.1.2. It was the front-end framework opted for in the web development of the monitoring system's web interface.

3.5.3 Producing a Paper Prototype

The first prototype produced to test the initial ideas of how a interface for the monitoring system should look like was a paper prototype. Based on the current context of use and user requirements specified in the previous steps of the HCD process, the goal of the prototype was set out to be the following:

- To provide an interface in which the current battery level is displayed.
- To provide an option to predict how many refrigerators can safely be run in the next 24 hours without getting to a dangerously low battery level.
- To provide an interface with a visualization of the energy consumption of specific appliances in the school.

The last goal was based on the idea that it would be very enlightening for the community to be able to see the consumption of specific appliances they often used. For instance, it was known that they had a TV in the school building they occasionally used in the education in the school, or at night to watch TV. The idea was that it could serve as a great educational tool to e.g. show the kids the current consumption after watching TV for an hour. This would only help them increase their understanding of the solar panel systems and the concepts of power and energy. A web page for each of the goals listed above was included in the prototype of the website.

The paper prototype is showed in Figure 3.5, and the design implications of the front-end technologies explained in the previous section decided the look and feel of the paper prototype. The front page of the website is illustrated to the left, with a battery icon to denote the current battery level and a Highcharts bar chart to display the energy production and consumption in the refrigerator center the last 24 hours. The image to the right in Figure 3.5 shows what the result of running a prediction for a selected number of refrigerators was intended to look like. The idea was to display the prediction result using two different charts from Highcharts. One bar chart to plot the energy production and consumption in the refrigerator center the last 24 hours (top chart), and a line chart to plot the predicted progress of the battery level for the 24 hours against the minimum recommended battery level (bottom chart).

Lara's interface served as an assurance of what kind of a user interface Colombians might find appealing. Parts of the interface is showed in Figure 3.6. The colors of red and yellow was decided based upon the interface of Lara's monitoring platform.

Admittedly, the design of the monitoring platform in [24] was not specifically aimed at the indigenous people of Calle Santa Rosa. It is unknown to what extent the requirements and interface design of the respective interface of [24] was based on user-centered design research prior to the development. However, it was directed at the average Colombian, and those in need of monitoring their electricity bill, hence rather poor people who also has experienced limited exposure to electricity and the Internet.

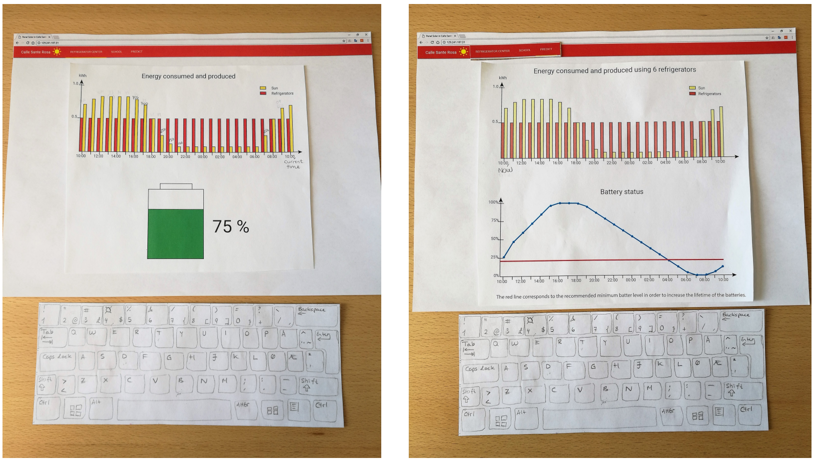


Figure 3.5: The paper prototype developed to test the first initial ideas about how the monitoring system's interface should look like. The front page of the website illustrated to the left, and the page providing prediction results for the refrigerator centers capabilities to the right.

3.5.4 Producing a Web Interface

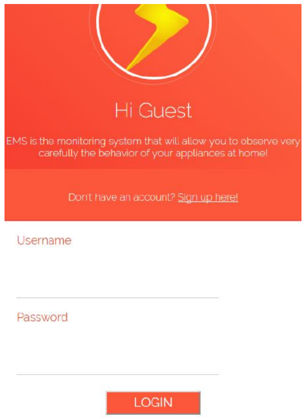
A web interface was implemented based on the feedback received on the paper prototype using the web development technologies in Section 3.5.2.

Relevant for all the front-end technologies, HTML, CSS and JavaScript, is that the web browser has to support the specific features of the language that you plan to use, in order for the web page to load properly. In a rural area, the most common web browser might be different from the preferred choice of the web page developer. The web page `https://caniuse.com/` was used to check the web browser support for the specific features for the different front-end technologies.

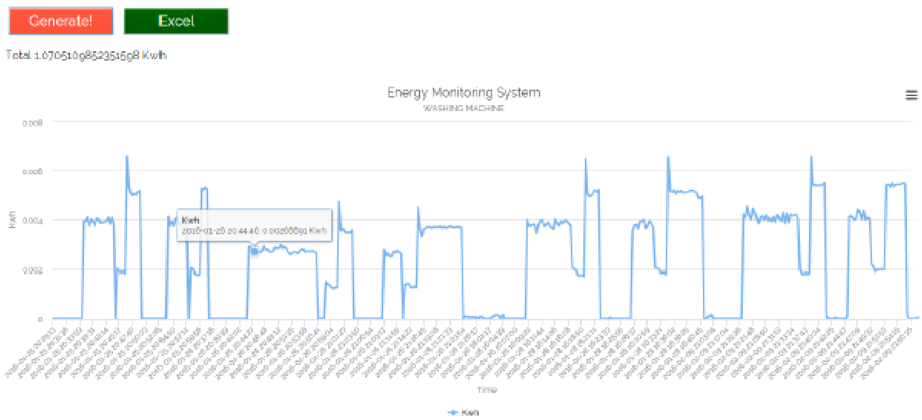
The color scheme used in the paper prototype was carried forward into the web interface. Material Design recommends using two colors throughout the design, a primary and a secondary color, in line with the design Material Design color system that can be read about in [54]. Material Design Color Tool [55] was used to visualize different color schemes beforehand, and the Material Design Lite Custom CSS theme builder [56] was used to download a CSS file with the color scheme selected.

In order for the website to meet the goals put forward in Section 3.5.3, it was concluded that the following data had to be available in the database:

- Current measurements of the refrigerators
- Current measurements of the energy produced by the solar panels, so that the current fed to the battery could be calculated by subtracting the current used to power the refrigerators from the total current produced by the solar panels.
- Current measurements of specific appliances in the school.



(a) The login page



(b) Graph of energy consumption

Figure 3.6: The desktop interface (PC) of the implemented home monitoring system by Lara in [24].

The next step was to determine what sensors to include in the system to obtain the above listed measurements. A great effort was put into researching various types of sensors, which lead to the hardware setup and current sensors that will be presented in Chapter 4. In reality, the task of selecting sensors and the tasks of designing the interface was a joint process in which each task influenced the other. What was desired to be displayed on the website influenced the type of sensors that was needed, and the research on sensors revealed what information that would be possible to obtain in the refrigerator center. This was how the monitoring scope of the system was decided.

The last version of the web interface that was produced in Norway before leaving for the field trip, which was the result after several iteration of the Human-centered design process, is presented in the following.

3.5.5 Website Design

In this section, the web interface that was continuously updated through iterations of the human-centered design process is presented. The interface has been translated to English for the purpose of this text. The interface was originally installed in Spanish, since the community members of Calle Santa Rosa speak Spanish and have no English speaking capabilities, but speak Spanish as their second language next to their native mother tongue. The website is responsive, and what it looks on a computer is showed to the left in the figures, and what it looks on a smartphone (Iphone 5) to to the right. How the usability heuristics from Section 3.1.2 influenced the design of the web interface will also be presented in this section.

The index page (front page) of the web site is shown in Figure 3.7. It displays the current status of the refrigerator center. The graph shows energy consumption and production in the last 24 hours, and the icon to the right in the computer version shows the current battery level. The icon wraps underneath the graph in the smartphone version. At the bottom of each page on the website, the user is provided with a small explanation of what is displayed.

Pushing the menu button "School" displays the page in Figure 3.8. The menu is the top red bar on the computer version, and on a smartphone the menu is a drawer, shown in Figure 3.13, that is made visible by clicking the hamburger icon in the top left corner. The school page shows the production and consumption for the appliances in the school connected to a sensor as a bar plot, as well as the total consumption of these appliances, for the last 24 hours.

The page for prediction is given in Figure 3.9. The predict page allows the user to select the number of refrigerators he or she wants to see a prediction on for the next 24 hours, by clicking one of the red numbered buttons. After clicking one of the buttons, the user is provided with a loading bar and an explanatory text similar to "You selected 6 refrigerators, and now the request is being processed...", as showed in Figure 3.12. The user is provided with a loading bar and a suited text every time it is necessary to retrieve the data from the database first, which is the case for both the index page and the school page

Pushing a button to select the number of refrigerators, provides the result shown in Figure 3.10. A pop-up box informs the user if the selected number of refrigerators is recommended or not, stating "Be careful!!", and the time at which the battery level will go beyond the minimum recommended battery level one, or "Very good!" if no problem is expected. The user has to close the pop-up box away in order to investigate the graphs that are in the background and advance to the view showed Figure 3.11. The first graph show the predicted progress of the battery level for the next 24 hours, including a red line that denotes the recommended minimum battery level. The second graph displays the predicted energy production and consumption for the next 24 hours.

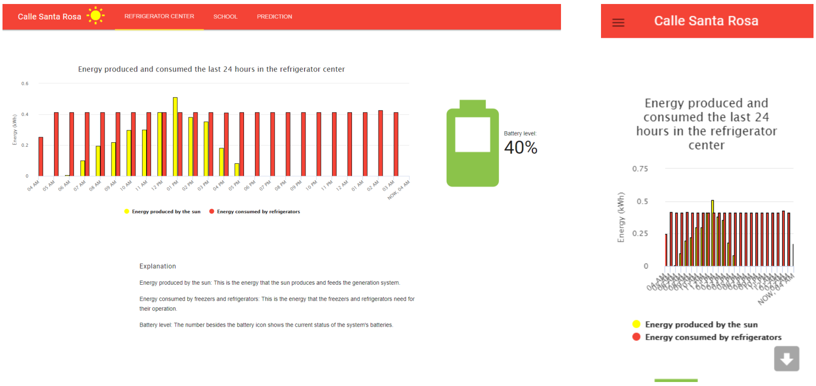


Figure 3.7: The index page (the front page) of the monitoring system's web site.

Figure 3.8: The school page to the left and how the menu look on a smartphone to the right. The drawer

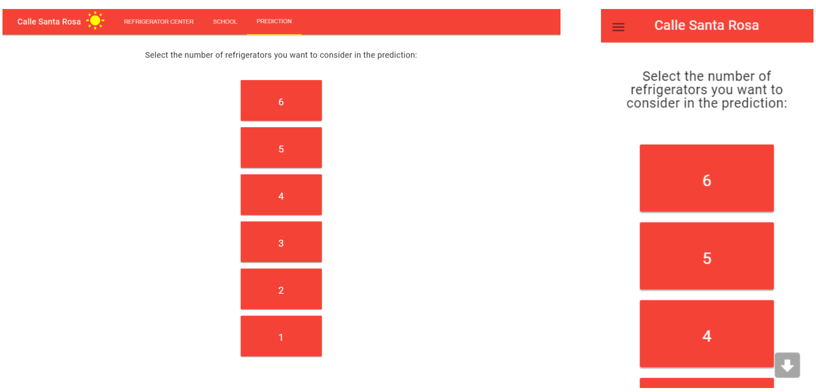


Figure 3.9: The prediction page.

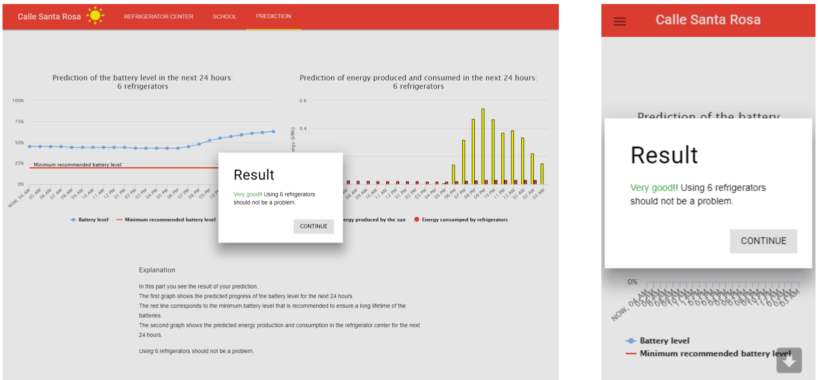


Figure 3.10: After running a prediction, the user is presented with a pop-up box that informs the user about the result. The pop-up box states "Be careful!!", and the time at which the battery level will go beyond the minimum recommended battery level one, or "Very good!" depending on the selected number of refrigerators.

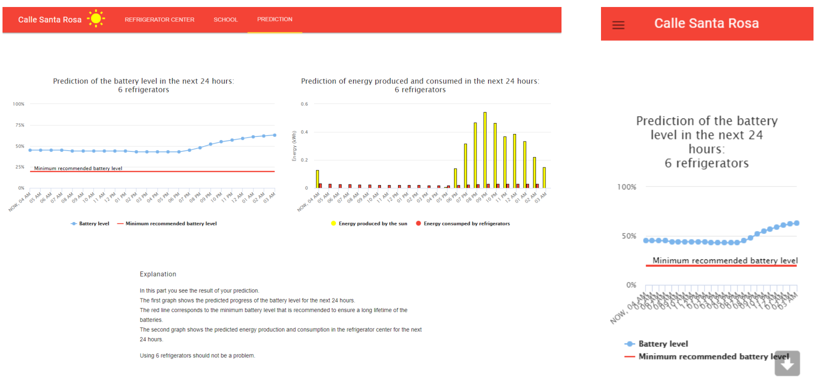


Figure 3.11: After closing the pop-up window away, the user can investigate the graphs in the background. The graphs show the predicted progress of the battery level (including a red line that denoted the recommended minimum battery level) and the predicted energy production and consumption for the next 24 hours, respectively. On a smartphone, the graphs are stacked one over the other.

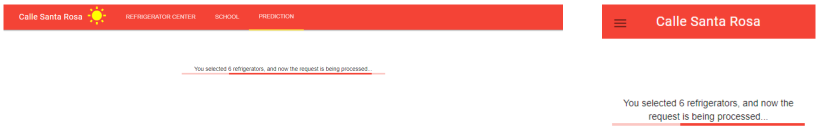


Figure 3.12: The user is provided with a loading bar and an explanatory text whenever it is necessary to retrieve the data to be displayed from the database first. In this case, the explanatory text above the loading bar is "You selected 6 refrigerators, and now the request is being processed...".

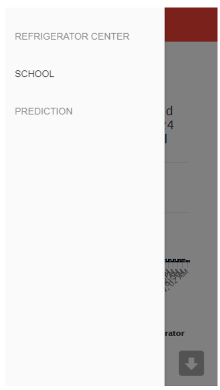


Figure 3.13: The website menu on a smartphone is a drawer that is accessed by clicking a hamburger icon in the top left corner. This is a navigation layout provided by the Material Design Lite front-end framework [51].

Aesthetic and minimalist design, the eight usability heuristic in Section 3.1.2, was the main guideline when designing the website. The focus was to design "above the fold" and keep the interface clean and simple in line with the current design trend discussed in Section 3.5.1. This is based on the idea that by limiting the functionality on a web page, it is easier for the user to make the correct actions in the interface as intended by the designer.

It was believed that an aesthetic and minimalist design would serve as a mean for other design principles. A design that is minimal, in the sense of a limited number of functionality, prevents errors because it automatically also number of unwanted states in the interface (the fifth usability heuristic).

The first usability heuristic, visibility of system status, was the reason for including the loading bars, as illustrated in Figure 3.12, and the pop-up box in Figure 3.10. The loading bars give feedback to the user that the request he made is being processed when it takes time to retrieve data from the database, and the pop-up box highlights the most important information to the user.

Related to the fourth usability heuristic, consistency and standards, Material Design can be argued to be the brand of Google. To opt for a solution with similarities to the number two most popular websites online, Google.com and YouTube.com (owned by Google) [57], [58], only supports what can be considered platform conventions on the Internet.

A user manual was written in order to abide with the tenth usability heuristic, and it is also why the user manual was written as a list of steps on how to carry out the typical user tasks. The user manual can be viewed in Appendix F.

3.6 Evaluating the Designs

Three usability tests were performed in Norway leading to the development of the web interface presented in the previous section. The usability tests conducted in Norway included one usability test with a paper prototype and two usability test with the web interface that was implemented.

For all usability tests, the framework presented in Section 3.1.1 was applied. A test plan with a goal and a hypothesis was formulated for each usability test, and observations forms was used to take notes.

User interaction with the community was possible only once during this project. This opportunity was used to evaluate the design against user requirements. The usability tests conducted prior to the field trip is described in this section.

3.6.1 Evaluating the Paper Prototype

To test the paper prototype, two test users were engaged, our supervisor professor Marta Molinas and postdoctoral researcher Maximiliano Bueno-López. The paper prototype that was tested is showed in Figure 3.5. The goal and hypothesis of the usability test were as follows:

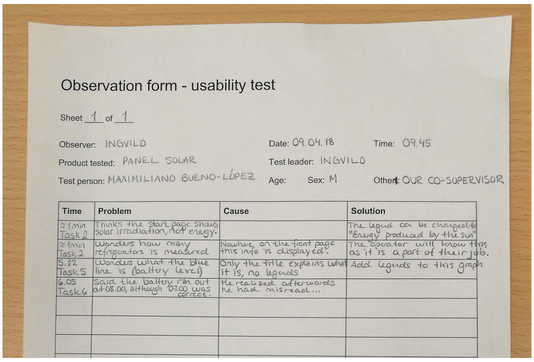
Goal: To get user feedback on how the web interface of the monitoring system should be implemented.

Hypothesis: The test users will only give suggestions of minor changes.

The tasks that the test users were given in all usability tests were similar. The tasks of the first usability test is given below. This serves as an example for the tasks given in the usability tests. The tasks of the other usability tests will not be specified further. The use of the observation form is illustrated in Figure 3.14.

1. Visit 129.241.187.31 in the web browser.

2. Find the battery level in the refrigerator center.
3. Find the energy consumed by the refrigerators at 10 o'clock yesterday.
4. Find the page where you can get a recommendation on how many refrigerators you should have running.
5. Run a prediction for 6 refrigerators.
6. Find out when the battery is emptied when using 6 refrigerators.
7. Visit the web page displaying energy status of the school.



Observation form - usability test

Sheet 1 of 1

Observer: INGVILD Date: 09.04.18 Time: 09.45

Product tested: PANEL SOLAR Test leader: INGVILD

Test person: MAXIMILIANO BUENO-LÓPEZ Age: Sex: M Others: OUR CO-SUPERVISOR

Time	Problem	Cause	Solution
≈1min Task 2	Thinks the start page shows solar irradiation, not energy.		The legend can be changed to "Energy produced by the sun"
≈1min Task 2	Wonders how many refrigerators is measured	Nowhere on the front page this info is displayed.	The operator will know this as it is a part of their job.
5.32 Task 5	Wonders what the blue line is (battery level)	Only the title explains what it is, no legends	Add legends to this graph
6.05 Task 6	Said the battery ran out at 08.00, although 07.00 was correct.	He realized afterwards he had misread...	

Figure 3.14: Filled out observation form from the second usability test

The feedback from the test users on the paper prototype in the usability test is given below:

- Both test users preferred that the result of a prediction was showed in two separate graphs, meaning that the predicted progress of the battery level for the next 24 hours was presented in one graph, and the predicted energy production and consumption in the refrigerator center in another. The second option of presenting the result using only one graph was voted down because the test users found the graph too crowded and difficult to read.
- The test users found the name of the three menu items, "Refrigerator center", "School" and "Predict", explanatory and liked them.
- Functionality to change the name of the appliances measured in the school in the interface, in case the community members wanted to change what appliances in the school that was monitored, was included in the paper prototype. However, the idea was discarded because both test users believed it would be better to keep the interface as simple as possible and drop this functionality.

3.6.2 Evaluating the First Version of the Web Interface

The web interface was implemented using the tools described in 3.5, and by taking into account the feedback obtained on the paper prototype. After that, supervisor professor Marta Molinas and postdoctoral researcher Maximiliano Bueno-López was once again engaged in a usability test, but this time they would interact with a prototype using a computer.

The web interface that was tested in the usability test was similar to the one presented in Section 3.5.5, but without the features related to feedback obtained in the second and third usability tests that led to this final version. The web interfaces that was tested in the second and third usability test were simply earlier version of the one presented in Section 3.5.5, and will not be specified further than this. The goal and hypothesis of the second usability test were the following:

Goal: To get user feedback on how the web interface of the monitoring system should be implemented.

Hypothesis: The test users would express stronger opinions in response to a prototype that resembles the real product, as opposed to a paper prototype whose limitations can make it hard for the test user to envision how it would be to use the product in real life.

This was the user feedback obtained from the second usability test:

- Both test users liked the solution they had voted for in the last usability test, in which the result of a prediction was shown in two separate graphs.
- In all graphs the 24 hour interval of the measurements displayed should be made clear in the title, i.e. "Energy produced and consumed *the last 24 hours*".
- The unit kWh should be added to the data points to make it clearer that the interface displays energy and not solar irradiation, as illustrated in Figure 3.15.

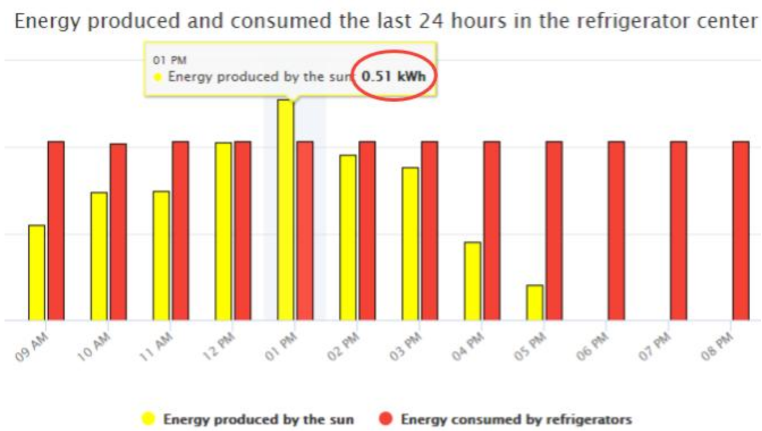


Figure 3.15: Filled out observation form from the second usability test

- The battery level graph should have a legend also for the red line denoting that it is the recommended minimum battery level.
- The *total* consumption of the school should also be displayed.
- The x-axis labels showing timestamps should to be in the 12 hour clock format.
- Both test users liked the message in the pop-up box in Figure 3.10, but wanted the message to be clearly visible also in the window after clicking the message away.
- After the batteries has reached zero battery level, the graph will be ended, since the community then will experience a power shortage and in fact turn off the equipment.

- The interface had to be translated to Spanish so the indigenous community would understand it.
- The web page for the current status of the refrigerator center should state the number of refrigerators running at the moment.

Changes were made to the interface related to the feedback in all the bullet points except the last one. Information in the interface about the current number of running refrigerators was considered unnecessary because the primary user of the monitoring system, the salesman, would be aware of number of refrigerators that is powered at all times.

3.6.3 Evaluating the Second Version of the Web Interface

In the third usability tests, efforts were made to simulate to a great extent the real use of the interface in the next usability test. Test users ere asked to envision themselves being the salesman in the refrigerator center. The refrigerator center was described in detail, including the dimensions of the room and how the customers are served. White sheets of paper was used to symbolize the 6 refrigerators, as showed in Figure 3.16. Also, the current sensor intended to be installed at the site and the Raspberry was brought along and showed to the test users, all means to help the test users envision themselves being at the site. Each test user performed a number of tasks on a smartphone or a computer first, then the same task on the remaining device.

Two test users were engaged also in the third usability test, a Colombian PhD student in electrical engineering doing an exchange year in Norway and a fellow Spanish-speaking student who were both new to the interface. The interface was tested both on a computer and on a smartphone. The order of which device the test users interacted with first was changed, to remove any bias. The following goal and hypothesis was formulated:

Goal: To perform a usability test in Norway that simulates as close as possible the real usage of the interface, using Spanish-speaking test users in the attempt.

Hypothesis: That the test users will complete the tasks they are given without any problems, considering the fact that the test users are highly educated (one PhD student and one Cybernetics master's student).

The feedback that was received in the third usability test is given below, and the changes that were made based on the feedback received will be presented in the next paragraphs.

- The test users failed to complete several tasks because they did not scroll down the page to where necessary information to answer questions correctly could be found. Admittedly, one of the test users said in hindsight that he did not explore the interface enough because he felt some kind of restrictions due to the fact that he was observed by someone else. However, the tendency was that the test users would digest the information that was above the fold and not scroll to find the information located below it.
- The same test user was unhappy with the location of the explanations that was provided for each web page at the bottom of the page. As described as the first problem,

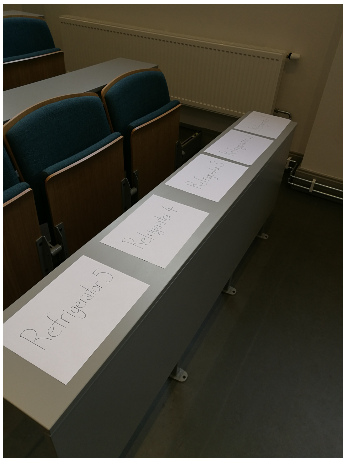


Figure 3.16: Efforts were made in the third usability test to simulate the real use of the interface. Paper sheets were used to help the test users envision the refrigerators.

the user did not scroll sufficiently to find the explanation, which possibly could have helped him solve the tasks he was not able to answer. After showing him the explanations afterwards, he desired that they should be made visible on the front of each page, either on the top or closer to the graph at the bottom (meaning less space between the graph and the explanation).
- When performing usability tests in Norway, the test user needs to be informed of the current time in Colombia since the interface is in Colombian time.
- In the case of users with Spanish as their mother tongue, the tasks in the tests has to be translated to Spanish. Else, the tasks (written in English) will disrupt the user's interaction with the interface.
- Some of the tasks were misunderstood. The usability tests gave pinpoints on wordings that should be avoided in order to avoid misunderstandings. For instance, the question "find out how much energy the 6 refrigerators need in two hours", was interpreted by one of the test users that measurements from two consecutive hours had to be added, instead of simple reading the measurement of a single data point, which was the intended task. Also, the tasks should be formulated in the mother tongue of the test user if possible.
- Both test users found the interface on smartphone illegible, but when they flipped the smartphone horizontally, the space between the labels on the graphs was sufficient to make the graph legible and the test users were satisfied.

The interface was changed such that more of the information was above the fold in response to the feedback in the first bullet point. The battery icon on the front page was put beside the graph instead of underneath it, which is showed in Figure 3.7, and the two graphs on the result page were put on the same row instead of underneath each other as showed in Figure 3.11.

Still, the changes discussed in the previous paragraph would leave the explanations about what each web page displays below the fold. However, changes with respect to this was considered to be related to Jakob Nielsen's seventh usability heuristic - flexibility and efficiency of use in Section 3.1.2. An interface should cater to both experienced and inexperienced users. The thought was that putting the explanation on top of the page would be cumbersome for experienced users. Experienced users know the interface and are solely interested in viewing the data, so the need to scroll past some unnecessary explanations was believed to be experienced as irritating. An arrow was added in the bottom right corner of the interface, which can be seen in Figure 3.7, to signify that the user should scroll and hopefully help the user find the explanations when necessary.

Lessons were also learned in respect to how usability tests should be conducted. The test user was confused by the time difference as the interface followed Colombian time (Colombia is seven hours behind Norway). This showed that it is important to make sure that the user has all the information needed in order to envision the proper use of the product in a usability test. It also made the undersigned aware that also the tasks needs to be translated to Spanish if a usability test was to be performed in Calle Santa Rosa.

In general, the third usability test was thought to be a great preparation before any usability tests could be performed in the field. The Colombian PhD student's interaction with the interface was surprising as the hypothesis of the test was that the tasks would be completed without any big problems, but he failed to complete four of the ten tasks. This experience was important because it helped adjust the expectations towards the level of experience with web page interaction among the community members in Calle Santa Rosa.

After the last usability test, the web interface had finally developed into the one presented in Section 3.5.5.

Chapter 4

The Monitoring System

In the following, a description of the monitoring system is given. The monitoring system was developed by applying the Human-centered design process as described in Chapter 3. Research on the community, which was facilitated by the process, allowed for an an appropriate monitoring scope to be selected. The monitoring scope will first be described. The hardware setup and the respective software setup will be explained thereafter, before the implementation costs of the monitoring system is provided at the end of the chapter.

4.1 Choice of Monitoring Scope

As described in Section 2, Calle Santa Rosa has three solar panel systems installed. The system in the refrigerator center has the most vital need for improved monitoring capabilities as the community has no way of knowing the status of the system.

In the school, however, they have a controller with an LCD screen that displays the current panel voltage, battery voltage, and power and energy generated, as can be seen in Figure 4.1. The community was left with the task of filling out the form on the right in Figure 4.1 on a regular interval, using the controller's LCD screen, in order to be able to detect irregularities and take action whenever needed.

The community has no opportunity to implement a similar procedure in the refrigerator center due to the lack of an LCD screen on the controller installed there, therefore, the development of a monitoring system for the refrigerator center was considered most beneficial to the community.

The refrigerator center also serves as a new source of revenue, and it is the first step towards building the new production processes that the Colombian state aims to implement in such areas, with the goal of accelerating economical growth [9]. Thus, to improve the conditions for operating a system of value to the community and with an adherence to the local politics is the foundation for selecting the refrigerator center as the scope of the monitoring system.

Battery Status / Estado		Controlador			
Fecha	Hora	Voltaje Paneles(V)	Voltaje salida (V)	Potencia (KW)	Energía generada (kWh)

Figure 4.1: The controller display in the school to the left, and the form they use to collect data from the controller

4.2 Hardware Setup

An illustration of the setup is given in Figure 4.2. The main components of the hardware setup is a Raspberry Pi, analog-to-digital converter (ADC) Raspio Analog Zero, a DC current sensor, a burden resistor, Wi-Fi current sensors from the La Salle University and the BlueSolar charge controller. Each of the components will be explained in the following.

An installation manual for the monitoring system was developed. The installation manual is given in Appendix G.

4.2.1 Raspberry Pi

Raspberry Pi [59] is a small and affordable computer based on a single circuit board common in do-it-yourself programming projects and used to learn programming and to promote computer science to children in school.

The Raspberry Pi 3 Model B was used to implement the system. It costs less than $40 U.S dollars. Specifications can be read in [59]. It can connect to Wi-Fi, has a 1.2 GHz 64-bit CPU, 1 GB RAM, 4 USB ports and 40 GPIO pins. GPIO stands for general-prupose input/output. More about the GPIO pins can be found in [60].

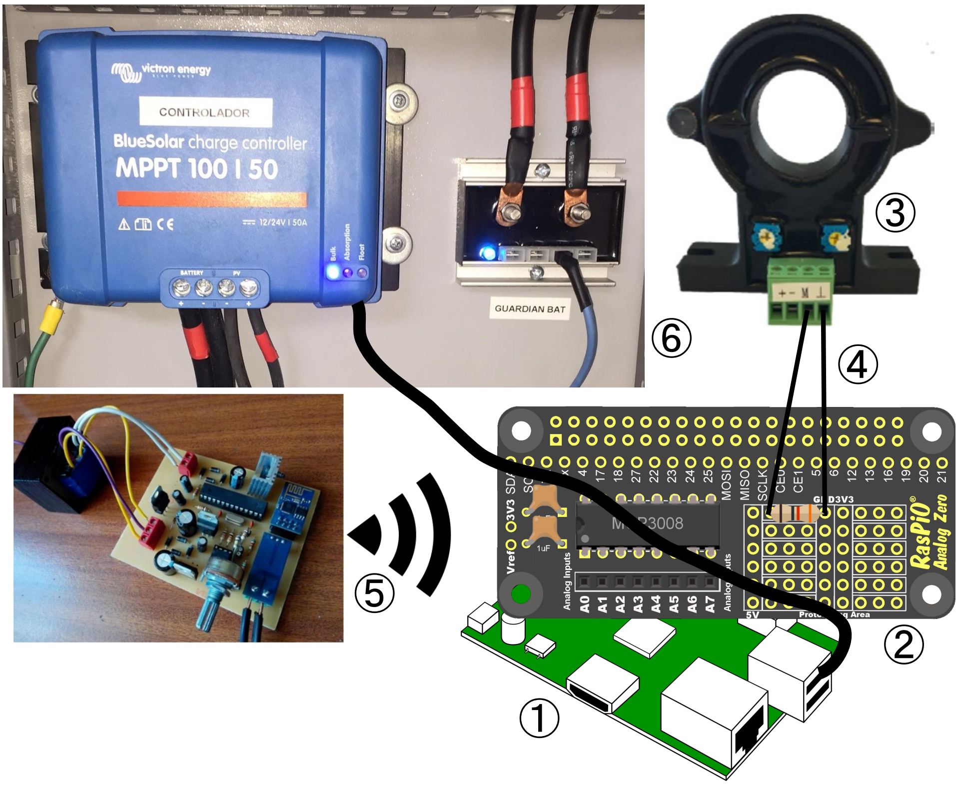


Figure 4.2: Illustration of the Hardware Setup: 1. Raspberry Pi 2. ADC Raspio Analog Zero 3. DC current sensor 4. Burden resistor 5. La Salle current sensor 6. BlueSolar charge controller connected to the RPi via an USB interface

4.2.2 ADC Raspio Analog Zero

The Raspio Analog Zero [61] is an ADC for Raspberry Pi, which is a HAT (Hardware Attached on Top). This means that it can be mounted on the GPIO pins of the Raspberry Pi as an expansion board. This makes it possible to easily read analog signals onto the Raspberry Pi, which otherwise can only read on or off signals using the GPIO pins. The Raspio is based on the MCP3008 ADC chip. The main reasoning for choosing the Raspi over just buying the MPC3008 chip is that the Raspio provides a nice prototyping area that can be used for adding additional components.

4.2.3 DC Current Sensor

The DC current sensor is the AIMH021 DC current sensor provided by Aim Dynamics [62]. The specification can be found in [62]. The sensor is made with a split core design, which makes the sensor easy to install because one can unhinge one of the sides and clip it around the wire to be measured. The sensor is clipped around *either* the hot or neutral wire.

Aim Dynamics provides many different versions of the sensor, depending on the amplitude range of the input signal and the type of signal the input signal is transformed to and the sensor outputs. A sensor that has 50 A as the amplitude range and 4-20 mA as the output signal was chosen.

A sensor amplitude range of 50 A was considered appropriate since the technical specifications of the refrigerators revealed that the fuse size should be 7.5 A at 24 V for one refrigerator. This implies a maximum current powering all six refrigerators of 45 A.

The sensor output was chosen to be the 4-20 mA current loop because it considered a robust sensor output signal [63]. Current loops are inherently insensitive to electrical noise, which are unwanted disturbances in the electrical signal, as opposed to a voltage output signal. When the output has to travel more than a medium length cable (e.g. 2 meters), the electrical noise can be of significance, especially in an environment with a lot of electromagnetic noise, which is believed to be the case in the refrigerator center with the refrigerator generators turning on and off.

A range of current sensors were researched in order to find the appropriate one. A split-core current sensor was considered to be the least invasive, as opposed to for instance the integrated circuit current sensor ACS712. It is cheap, but it requires the current to run through the copper wires of the chip [64], which would entail that the electrical circuit of the refrigerator center had to be broken. The Aim Dynamics AIMH021 DC current sensor make use of the Hall Effect principle. The sensor concentrates the magnetic field generated by the conductor being measured in the gap where the jaws of the sensor meet. The magnetic field is proportional to the current in the conductor [65].

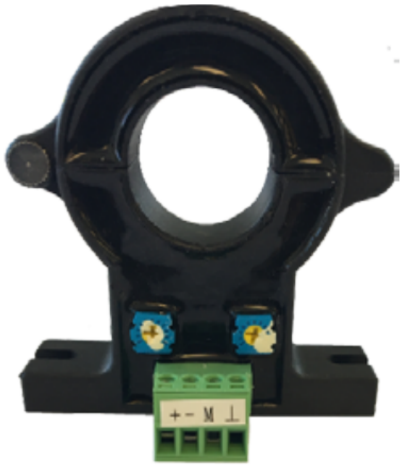


Figure 4.3: 50 A to 4-20 mA DC current sensor by Aim Dynamics in [62]. The sensor is powered using the two leftmost input with $\pm$ 15 V power supply, the M denotes wiring for the output signal and $\perp$ for ground.

4.2.4 Burden Resistor

To be able to measure the 4-20 mA current loop that the DC sensor outputs, the signal has to be converted to voltage over a burden resistor [66].

The burden resistor has to be properly sized in order to measure the current correctly. According to the Raspio Analog Zero's user guide [61], the reference voltage is 3.3 V. With the 4-20 mA current loop, this means that 3.3V should represent 20 mA. Thus, the burden resistor was dimensioned to be $\frac{3.3V}{0.020A} = 165\Omega$.

4.2.5 BlueSolar Charge Controller

Victron Energy, the producer of the BlueSolar MPPT charge controller, has created the *VE.Direct protocol* to simplify communication with their products and support customers in open source project that want to integrate Victron Energy products into their own systems [67], [68].

The VE.Direct protocol is a serial communication interface, and the format of the protocol depend of the selected mode, which can be text-mode or HEX-mode. Text-mode is the default mode and it's purpose is to make information retrieval from Victron Energy products extremely simple. In text-mode, the device transmits blocks of data every second. HEX-mode makes it possible to also write data, in order to change settings, and the device switches to HEX-mode once it receives a valid HEX-message.

Specification on the VE.Direct Protocol is given in its white paper, which has to be requested from the Victron Energy download web page [69] in order to get access. The white paper [70] also describes the physical interface, the VE.Direct communication port, that Victron Energy provide most of their products with.

The BlueSolar MPPT 100/50 charge controller installed at the site is provided with a VE.Direct communication port. Victron Energy produces two types of cables that connect to the VE.Direct port and give access to the VE.Direct protocol, a VE.Direct to USB interface cable or a VE.Direct to RS232 interface cable. The VE.Direct to USB interface cable was chosen because the RPi has four USB input ports and no RS323 input port.

4.2.6 Wi-Fi Adapter

A Wi-Fi adapter is used in order to connect to a wireless network or to let a wireless device connect to a network hosted by the adapter. This particular adapter is a USB Wi-Fi dongle manufactured by TP-Link. The model number is TL-WN725N. This adapter is compliant with the IEEE 802.11b,g and n standards. Drivers are readily available for both Windows and Linux. The device will be plug-and-play as a Wi-Fi client on most operative systems. The Adapter will be used for connecting to a router, while the internal Wi-Fi module will act as an access point and thereby be accessible like it was a Wi-Fi router. This will provide a backup solution for connecting to the RPi. The reason for choosing such a small device is that it does not require an external power source and can therefore be powered directly from the RPis USB port.

Figure 4.4: TP-Link TL-WN725N. A small low powered Wi-Fi USB adapter

4.2.7 La Salle Current Sensors

In his master thesis [24] from 2015, the Colombian student Diego Andrés Pérez Lara from the La Salle University explains the construction of a prototype current sensor for his home monitoring platform. The current sensor has to be wired into the current loop of the appliance it is designed to measure, and it transmits the measured output signal over Wi-Fi. In order to continue the work of Lara and to increase the collaboration between NTNU and the La Salle University even further, it was decided to include his current sensor into this project. It is referred to as the "La Salle current sensor" in order to distinguish it from the

DC current sensor that was bought specifically for the monitoring system in Calle Santa Rosa.

The current sensor developed at La Salle is built on an Arduino. The ESP8266 Wi-Fi module provides the Arduino with Wi-Fi, and the Hall effect-based ACS712 current sensor converts the current that flows through it to a proportional voltage. The schematic diagram of the current sensor's electronic circuit is given in [24].

The Arduino communicates with the ESP8266 Wi-Fi module using TCP, and the ESP8266 sends the HTTP requests that allows the current measurements to be saved in a database. The HTTP requests is sent to a web server running PHP as the server side language to handle the requests. The thesis [24] also provides the code for the communication protocol. The necessary PHP scripts provided were adapted and used with the web server of this project.

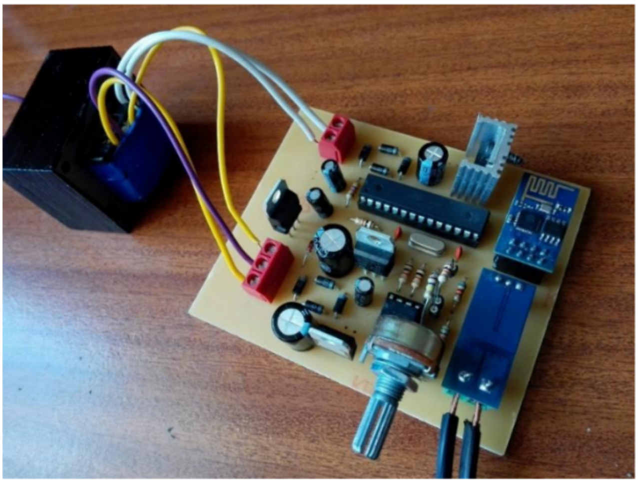


Figure 4.5: Wi-Fi current sensor developed at the La Salle University. Soruce: [24].

4.2.8 Hardware Enclosures

Both the RPi and the current sensor require some sort of protection against the environment they will installed in. The most exposed of the two is the RPi as it is only a circuit board in its base form. As a part of the preparation towards installing the system, two tailored enclosures were produced.

Current sensor enclosure

Technically the current sensor could be used without an enclosure if it were to be mounted in a safe and undisturbed space. In this project however, it was not possible to know were the sensor would need to be placed beforehand. Therefore, an enclosure was built as an insurance, such that it would be possible to place it safely in a greater variety of locations.

The box used was a suitable sized enclosure found in NTNUs workshop. Holes were made in order to facilitate the sensor and connectors to be mounted. The signal carrying cable was decided to be an Ethernet cable. An Ethernet cable is both inexpensive and robust in addition to being widely available world wide in case it should break or a longer one is needed. It is also available in both shielded and unshielded versions, which could be important with very long cable stretches or noisy environments. Using an Ethernet cable means that a RJ45 female connector also had to be installed in the sensor enclosure.

The power adapter used with the sensor is a dual output 240/110VAC to ± 15VDC converter. This means that it has three wires that need to be connected to the sensor. Ground, +15 and -15. This is quite uncommon so once again the best available connector that was mountable in a box from the NTNU workshop was selected. The green connector shown in Figure 4.6 is only intended as a backup connector in case the sensor is to be powered from a 24v DC-DC converter instead of the AC adapter.

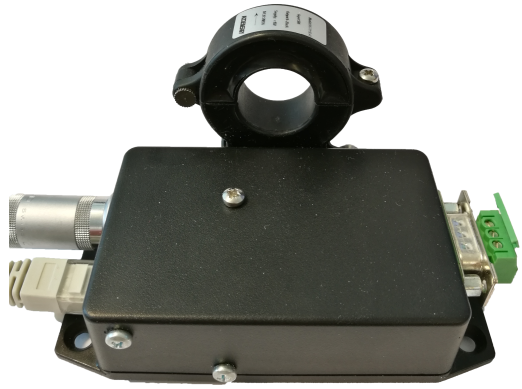


Figure 4.6: Current sensor mounted in enclosure

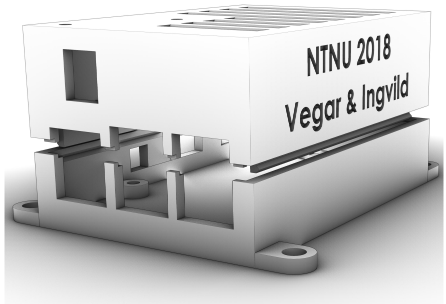
Raspberry Pi enclosure

There are a plethora of available enclosures for a RPi from online stores. These differ in design and intend function based on what additional hardware is used with the RPi. In the context of this project the enclosure needs to contain the RPi, with the Raspio ADC shield attached, in addition to the RJ45 connector needed to interconnect the sensor and the RPi. There did not seem to be an easily available enclosure that would suit this need. The solution was to create a 3D model and use 3D printing technology to produce a case to our specific needs.

The 3D model was created using Sketchup and Rhino based on a design found online [71]. This design was edited in order to better accommodate the Raspio ADC and the necessary RJ45 connector. The wall construction was fortified by doubling the model thickness from

1.5mm to 3mm and four mounting holes were added in case it could be mounted directly to the wall. The 3D printer facility at the Engineering Cybernetics department at NTNU was utilized for the actual printing of the model.

(a) 3D printed result



(b) 3D model render. The area for the RJ45 connector can be seen in the top left corner

Figure 4.7: Raspberry Pi enclosure

4.3 Software Setup

The hardware setup facilitates the software setup that in essence handles the sensor measurements and displays the data on a website. An illustration of the software setup, or software architecture, is given in Figure 4.8 and will be elaborated in the following.

The authors can be contacted if access to the entire code base is desirable. The focus of this section is the purpose of the scripts included in the monitoring system, how the content is structured on the web servers, and not the details of the code written. Lessons learned along the way are included to give some advice for the implementation process.

The source to relevant internet tutorials are provided for reproducibility, but the emphasis should rather be on the purpose of the source's content, not on the exact lines of code. This is because the rapid evolution of computer programming languages results in fast deprecation of the software tutorials. A solution that worked one year, may not work the next, due to deployment of new software versions.

4.3.1 The LAMP Stack

LAMP is an open source software web development platform with the components necessary to get a web server up and running. It is referred to as a LAMP stack, because of the four software components it includes that will be described in the following [35]: The Linux operating system, Apache HTTP server, MySQL or MariaDB as database and PHP as server side scripting language.

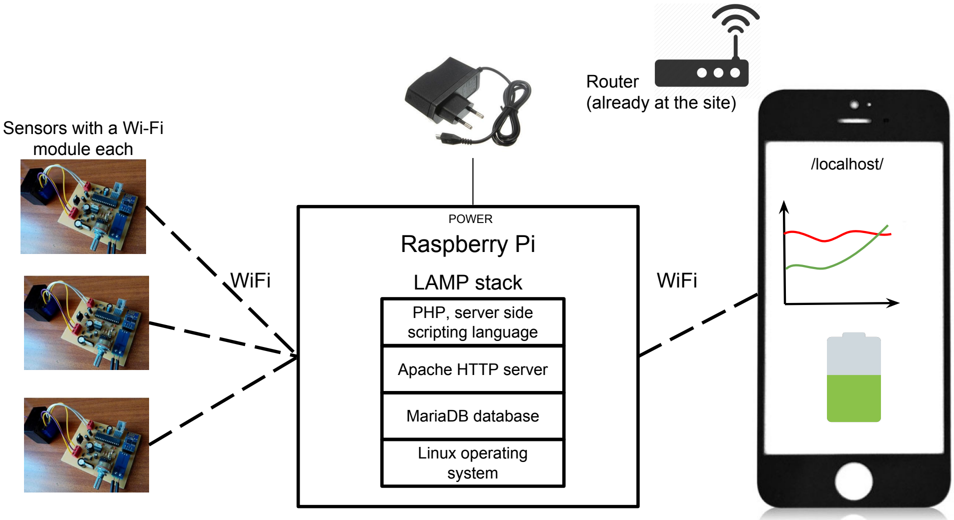


Figure 4.8: The software architecture. The Raspberry Pi runs a LAMP stack, which includes the Linux-based operating system Raspbian, Apache HTTP web server, MariaDB database and PHP as server-side scripting language. Current sensors send HTTP requests using Wi-Fi to the Raspberry Pi, that displays the measurements on a web page it hosts on the local area network.

Linux operating system

Linux is the most dominant operating system and the largest open source software project in the world [72]. The operating system installed on the Raspberry Pi micro SD card is the Raspberry Pi Foundation's own officially supported operating system (OS), Raspbian. It is based on Debian, which is an operating system with Linux at the kernel.

Raspbian can be installed by downloading the free operating system image at the the Raspberry Pi Foundation's web page [73], or by using the foundation's easy to install operating system manager, NOOBS.

The rest of the LAMP stack was installed on the RPi using the command-line tool for to handle packages in Linux, `apt-get`. The tutorial in [74] was used to install the packages *apache2, php, libapache2-mod-php, mysql-client, mysql-server* and *phpmyadmin* correctly on the RPi. The tutorial explains how to get a PHP7 LAMP server up and running on Debian 9, the version that the Raspbian OS installed at the Pi was based on.

The LAMP installation on a Raspberry Pi depend on the current stable version of each software component. Thus, it can be a troublesome process because of the fast deprecation of tutorials on the Internet due to the deployment of new software versions. For instance, difficulties were encountered related to the fact that Debian has recently changed to using MariaDB as the default database instead of MySQL.

However, the Raspberry Pi Foundation is supported by a great community of developers that continuously helps improve the open source solutions. The Raspberry Pi Forum

[75] was of great help when configuring the RPi, and it helped find the above mentioned tutorial that included the solution. The `mysql_secure_installation` shell script had to be run from the command line to set the password for the MariaDB installation correctly. Also, it is worth mentioning that the RPi provides an easy way to reinstall the system at reboot, an useful feature that was used whenever wrongs steps were taken in the installation process.

An important concept to be aware of when working with Linux-based systems is file permissions. A guide to access control on a RPI can be found in [76]. To control access, the properties of every file in Linux is specified with an owner and a file group with respective permissions. The permissions can be read, write and/or execute. It is also possible to grant permissions to everyone who is not the owner or in the file group. On the RPi, the correct user has to have the right permissions in order for the software to run correctly. When creating executable files or configuring the Apache web server, one has to make sure that is the case.

Apache HTTP server

Apache HTTP server is the most popular web server used on the Web today [77]. Apache solves the issue of multiple websites residing on one server through *virtual hosts* [78]. A virtual host was configured to hold the content of the monitoring system's website. The tutorial followed for this purpose was [79], and an outline of the procedure is provided in the next sections.

In the configuration of the virtual host, the directory structure shown in Figure 4.9 was used. The top level directory that the Apache web server on the Raspberry Pi looks to find content to serve is the `/var/www/` directory. The domain called *panelsolar.com* was created within this to hold the content of the monitoring system's web page.

The configuration of a virtual host involves creating a new virtual host file to specify the location of the document root for the new domain. In the `/etc/apache2/sites-available`-folder, the virtual host file *panelsolar.com.conf* was created, specifying `/var/www/panelsolar.com/public_html` as the document root. Then, the virtual host file was enabled using the `sudo a2ensite panelsolar.com.conf` command.

In order to make the panelsolar.com domain that hosts the monitoring system's web page the default one, any other virtual host files was disabled using the `a2dissite` command. After that, the newly created domain could be visited by any computer connected to the same local area network as the RPi, by simply typing in the IP address of the RPi in the web browser. The Apache web server would then serve the contents of the *index.php* page in the domain, as this is the file the server searches for within a domain, by default. With more enabled domains, the server treats the config-files in the *sites-available*-folder in a top-down approach [80].

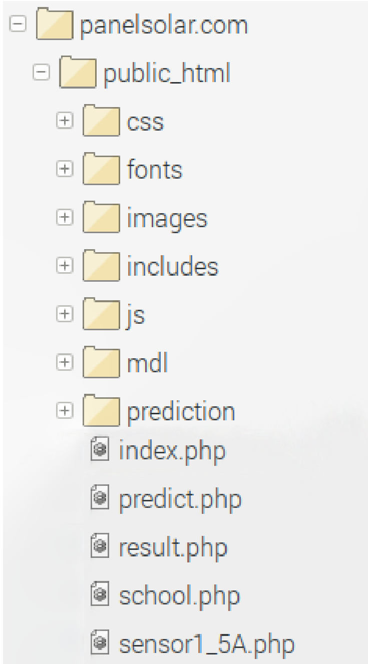


Figure 4.9: Web server directory structure for the domain of the monitoring system.

The MariaDB database

MariaDB is the fastest growing open source database [81]. It was created by the same people behind MySQL after Oracle acquired MySQL and they feared Oracle would completely commercialize the product. In 2017, Debian Stretch, the newest stable version of Debian at the current time and the version the OS on the RPi is based on, was released with MariaDB as the default MySQL variant [82].

MariaDB functions as a "binary drop in replacement" for the MySQL database, which means that all APIs and connectors are identical [83]. For this reason, the MySQL documentation [84] could be used during development. When writing code to connect to the database, it was performed as if the database was a MySQL database.

The database was managed using the *phpMyAdmin* [85] free software tool. It yields a graphic interface that supports the wide range of operations a MariaDB or MySQL database allows, such as creating tables and viewing the contents of a database table. phpMyAdmin is an alternative to the more traditional command-line interface.

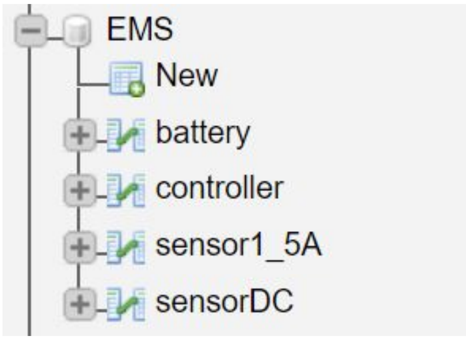


Figure 4.10: Tables in the MariaDB database used to save sensor measurements in the monitoring system.

A database called *EMS* (an acronym for Energy Monitoring System) was created in phpMyAdmin, containing the tables showed in Figure 4.10. The database model showing each table's fields is showed in Figure 4.11, and how the table implementations look like in phpMyAdmin (using the sensorDC table as the example) is illustrated in 4.12. The tables are updated with a new record to save sensor measurements on a regular interval. The *time* field that all tables have in common is set by default by the database to the current time. This time follows the time of the operating system, which is set to 'America/Bogota' in order to comply with the timezone where the system will be installed.

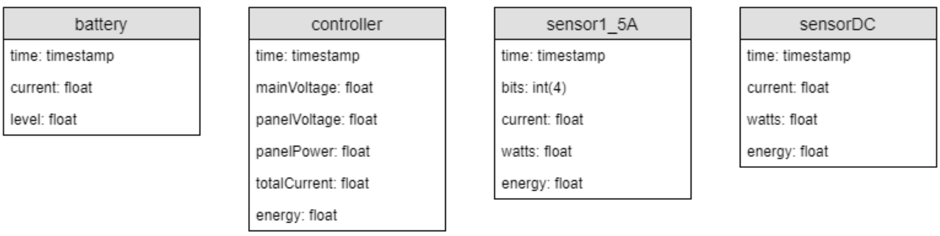


Figure 4.11: Model of the EMS database. The *battery* table saves updates on the battery, the *controller* table readings from the BlueSolar charge controller and the *sensorDC* table measurements of the refrigerator current by the DC current sensor. The *sensor1_5A* table corresponds to measurements from a La Salle current sensor, and can be replicated, following the naming convention, to include more of the appliance-specific sensors.

How the rest of the table fields are filled in is determined by the PHP and Python scripts that handle the communication with the input devices. Both PHP and Python was used as server-side scripting languages, and specifics on the usage is given in the two sections that follow.

#	Name	Type	Collation	Attributes	Null	Default	Comments
1	**time**	timestamp			No	CURRENT_TIMESTAMP	
2	**current**	float			No	*None*	Unit: A
3	**watts**	float			No	*None*	Unit: W
4	**energy**	float			No	*None*	Unit: Wh. 1 second ahead.

Figure 4.12: The database table called *sensorDC* holds the measurements from the DC sensor about the refrigerator current.

PHP as server-side scripting language

As stated in Section 3.5.2, a server-side scripting language is used to make the content on the web server accessible from a web page. The PHP scripts in the directory structure on the web server in Figure 4.9 serves the following purposes:

- *index.php*: Each page on the website corresponds to a specific PHP script. index.php displays the front page that can be seen in Figure 3.7.
- *school.php*: Determines the web page content when the "Centro Educativio" menu item in the menu bar (the top red bar in Figure 3.7) is clicked. The web page is showed in Figure 3.8.
- *predict.php*: Displays the web page in Figure 3.9 that allows the user to choose a number of refrigerators to run a prediction for.
- *result.php*: Displays the web page with the result after a prediction for a selected number of refrigerators.
- *sensor1_5A.php*: The web server also contains PHP scripts dedicated to handle communication with the La Salle current sensors. The script sensor1_5A.php receives the HTTP requests from the LaSalle University Wi-Fi Current Sensor and saves data to the database. The script can be replicated, following the implicated naming convention, to facilitate more sensors than the present one. The code of the script is written by Lara and can be found in [24].

In general, the PHP scripts located on the web server can be divided into two types of scripts. The first type contains the web page content (*index.php, school.php, predict.php* and *result.php*). The other type handles the HTTP requests in the sensor Wi-Fi communication (*sensor1_5A.php*).

The above mentioned PHP scripts will not be described in further detail other than that the first part of the *index.php* file is included in Appendix B.5 to illustrate the general structure they all follow. The PHP scripts are a combination of HTML and PHP code, in which the PHP code is included into HTML code by simply enclosing it using the <?php > tag.

The PHP scripts follow the structure of HTML documents. The first part is the section, enclosed in HTML head tags. Within the head tags, meta data such as the character encoding (utf-8) and link to style sheets (see Figure 4.14) is included. More on the subject can be read in [86]. The second part is enclosed in `main` tags. Here, the HTML elements that contain the web page content is located. The third part includes the JavaScript libraries and the JavaScript scripts that runs in the web browser.

The head section of the web pages is included by linking to a separate PHP file. The PHP `include` statement makes it possible to separate often used PHP code in own scripts. The *includes* folder in Figure 4.9 contain PHP code that are used across pages such that it can be reused instead of rewritten. This makes the code more modular and PHP as a server-side scripting language more flexible.

4.3.2 Python as Scripting Language for Database Access

Python is, similar to PHP, a scripting language, and it can be used to connect software components of a system together as described in [87]. Python is sometimes used to replace PHP in the LAMP stack. However in this case, Python was used only to handle the communication with the devices connected directly to the input ports of the RPi and for writing to the database. Thus, Python and PHP was used in conjunction as server-side scripting languages. PHP first and foremost to serve web content, and Python to handle the peripheral devices.

The following Python scripts are included in the monitoring system:

- *DCsensor.py*: Reads the digital signal from the ADC Raspio Analog Zero, calculates the measurement it originates from, which is the refrigerator current measured by the DC current sensor, and writes the measurement to the correct database table (the *sensorDC* database table, see Figure 4.11). The calculation includes the following: The digital signal is a $0 - 1.0$ float representation (specified in [61]) of the analog voltage signal over the burden resistor. The size of the burden resistor is known, and Ohms law (current=voltage/resistance) is used to calculate the current running through it. The burden resistor corresponds to the 4-20 mA signal that the DC current sensor has transformed the current signal in the wire it is clipped around.
- *controller.py*: Reads the input from the BlueSolar charge controller on the USB interface using the VE.Direct Protocol in text-mode (introduced in Section 4.2.5). In text-mode, the charge controller transmits blocks of data every second. The scripts reads battery voltage, panel voltage, panel power and current delivered from the data block. This is written to the controller's database table.
- *battery.py*: Implements the Coulomb counter discussed in Section 5.9.5. The current delivered to the batteries has to be calculated by subtracting the current produced by the solar panels from the current consumed by the refrigerators. The script reads from the necessary tables in the database in order to calculate the battery current, and updates the battery's database table (see Figure 4.11) with the calculation.

The Python scripts that are presented above, write to the database using the Python Connector. MySQL Connectors provide a way for client programs to access a MySQL server [88], and the connector developed for Python enables the writing of MySQL queries inside the Python code. These can then be execute in a Python script. The code of the Python scrips will not be explained further into detail other than that the Python script handling of the communication with the DC current sensor is provided as an example in Appendix B.6.

The scripts are loaded when the RPi starts and runs continuously in the background to update the database tables at a regular interval. In order to run programs when the RPi boots, commands to start the programs can be added to the RPi's */etc/rc.local* file, as suggested in [89]. The Python scripts were simply located on the RPi's desktop. The rc.local file runs when the the RPi boots.

An extract of the rc.local file can be viewed in Figure 4.13. The & sign added at the end allows the program to run in a separate thread, which is important when the program is an infinite loop (for instance when a device's output has to be read on a regular interval). `sleep` commands had to be added to make sure that Python scripts accessing the database are not started before the database is up and running. The file can be easily edited using the Linux command line text editor *nano* (run `sudo nano /etc/rc.local` in the command line of the RPi).

```
# Run scripts at startup
sleep 3
sudo python /home/pi/Desktop/controller.py  &
sudo python /home/pi/Desktop/DCsensor.py &
sudo python /home/pi/Desktop/battery.py &
exit 0
```

Figure 4.13: The rc.local file on the RPi include commands that run Python scripts when the RPi boots.

4.3.3 Front-end Technologies

Front-end refers to the software that runs in the client's web browser and is responsible for the visual display of the interface to the user. The web interface of the monitoring system is presented in Section 3.5.5, and a user manual was written that explains how the interface should be used. The user manual can be viewed in Appendix F.

The web page developed in the monitoring system is displayed using HTML, CSS and JavaSCript, which is the fundamental technologies of web pages whose theoretical background was introduced in Section 3.5.2. The code base has to be consulted in order to see the details on how HTML, CSS and JavaScript was used. Instead, in this section the tools based on HTML, CSS and/or JavaScript that are used in the design of the web page will be presented.

The CSS and JavaScript files used in the project is located in the *css* and *js* folders, respectively, as can be seen in Figure 4.9. The fonts recommended by the front-end framework Material Design Lite is included in the *fonts* folder.

Material Design Lite is the front-end framework used to design the monitoring system. It can be downloaded from `getmdl.io/started/index.html`. It was added to the web page simply by including one link to the CSS file it provides (Figure 4.14), and one link to the JavaScript file it provides (Figure 4.16). This gives all the HTML elements the colors, look and behavior of Material Design.

```
<head>
    <title>Panel Solar in Calle Sante Rosa</title>

    <!-- Adding the responsive viewport meta-->
    <meta name="viewport" content="width=device-width, initial-scale=1, shrink-to-fit=no" />
    <!-- Make it unicode -->
    <meta charset="utf-8">

    <!-- Adding Google fonts -->
    <link rel="stylesheet" href="./fonts/material-icons.css">
    <link rel="stylesheet" href="./fonts/roboto.css">

    <!-- Material Design Lite included-->
    <link rel="stylesheet" type="text/css" href="./mdl/material.min.css">

    <!-- Link to custom css -->
    <link rel="stylesheet" href="./css/custom.css">
</head>
```

Figure 4.14: The Material Design Lite CSS file that enables the HTML elements to be styled in line with Google's recommendations is included in the head-section of the HTML document.

The Highcharts library used to include interactive charts on the website was easily downloaded from the Highcharts web page [46]. The js-file was included within script-tags as can be seen in Figure 4.16. A closer look on the charts Highchart offer, examplified by a bar chart, is showed in Figure 4.15

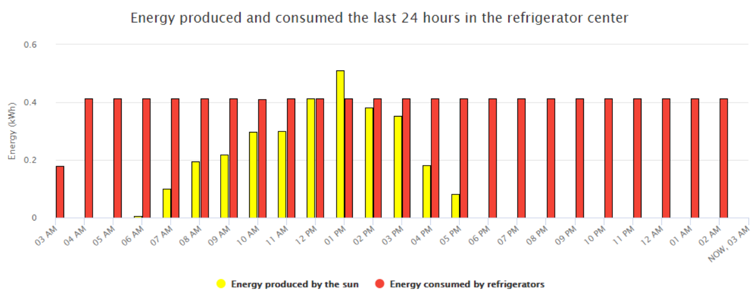


Figure 4.15: The Highcharts Javascript library provides graphs that look like this on the website.

The links to JavaScript files are included at the bottom of each PHP page, after the main section in the HTML document in which the HTML elements with the web page content is defined. This is best practice because then the web content can be displayed without having to wait for the JavaScript to finish loading, and make sure the user gets feedback as fast as possible.

After the links that include the JavaScript libraries, as shown in Figure 4.16, a section that makes use of the JavaScript libraries follows. This section is naturally also within script tags (only then the web browser is able to interpret the code as JavaScript code). An example of JavaScript code that make use the Highcharts library to draw a graph (and jQuery to perform AJAX request and select HTML elements in which the graph should be drawn) is given in Appendix B.7.

```
<!-- link to mdl js -->
<script type="text/javascript" src = "./mdl/material.min.js"></script>
<!-- link to highcharts js -->
<script type="text/javascript" src = "./js/highcharts.js"></script>
<!-- link to jquery js -->
<script src="./js/jquery-3.3.1.min.js"></script>
```

Figure 4.16: The Highcharts JavaScript library is linked to in the bottom of the HTML document, together with jQuery and the Material Design Lite JavaScript library.

4.3.4 Android Application

To increase the accessibility of the web server in case the router goes down, an additional Wi-Fi USB module was included in the setup. The internal Wi-Fi module is now used to create a standalone Wi-Fi access point handing out IP-addresses to connecting clients and thus being its own backup router. The result of this decision is that the web server now can be accessed form two different networks. If one goes down the other should be available. The drawback of this solution is that each Wi-Fi interface will have its own unique IP-address. Subsequently, the user would need to type in two different IP-addresses depending on which Wi-Fi network their device is connected to.

This is only considered to be a problem when accessing the web page from smartphones as the computers are located in the communication technology center and will only be able to connect to the main router. Therefore, the computers only need to consider one static IP-address. To facilitate easy access to the monitoring system's interface using a smartphone, an Android application was developed. A decision was made to only develop an Android application as the smartphones they use in the community are all based on the Android operative system. The application, once installed on their phone, presents a page asking which Wi-Fi network they are connected too. When the button corresponding to the correct network is pressed, the default web browser will be launched with the correct web page address loaded in the URL field. Figure 4.17 shows the Application interface in English. The interface was translated to Spanish for installment in the community.

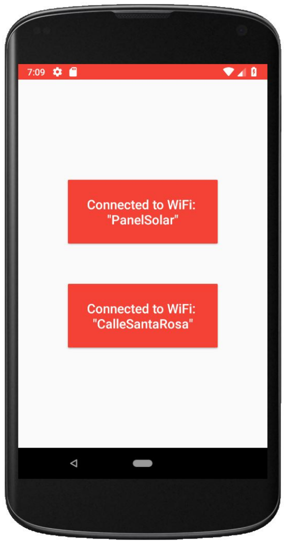


Figure 4.17: Android application interface shown in English.

The application was made available as a download directly from the web server. Thus, there will not be any need for having internet connectivity to download the application, the user would only have to connect to the local network. After connecting to one of the two available Wi-Fi networks, the user can either follow an URL that will provide a download interface (e.g. 129.241.187.20/download.php, depending on the IP address of the RPi) or a QR-code can be scanned, which will automatically load the correct URL in the user's web browser. This solution is advantageous because it makes it unnecessary to publish the application to the Google Play Store, which requires a fee. The downloading procedure of the app is described in detail in the User Manual in Appendix F. The application was developed in Android Studio which is an Integrated Development Environment (IDE) that combines Java and XML code. The IDE provides the core environment necessary to quickly develop an application.

4.4 Implementation Costs

The approximated cost of implementing the monitoring system in a similar environment to that of the refrigerator center in Calle Santa Rosa is given in Table 4.1. The table follows the structure of Table 19 in [24]. The total cost is approximately \$236. The total cost can be reduced by using a LM22596 DC-DC converter to power the RPi and a Mouser NMK2415SC DC-DC converter for the sensor. This would reduce the total by \$59.

Table 4.1: Implementation costs of installing the monitoring system

Item	**Quantity**	**Price**		Description
		Unit	Total	
Raspberry Pi 3 Model B	1	$35	$35	Small computer
MicroSD Card NOOBS 16GB	1	$15	$15	Storage unit for the RPi
TP-Link TL-WN725N Wi-Fi USB adapter	1	$10	$10	Connects to the existing router
RasPiO Analog Zero	1	14$	$14	ADC for usage with the sensor. Based on MCP3008.
Victron VE.Direct USB Cable	1	$30	$35	To connect BlueSolar to the RPi.
Aim Dynamic DC current sensor AIMH021-050A-420	1	$40	$40	To measure refrigerator current
240/110VAC to 5VDC	1	$15	$15	Powering the RPi.
240/110VAC to +-15VDC	1	$10	$10	Powering the DC current sensor
24VDC to 110VAC	1	$45	$45	Inverter required for using the AC adapters
3D printing material	-	$2	$2	Material used for RPi case.
Enclosure for sensor	1	$5	$5	Box used to protect sensor connectors
Ethernet connector	2	$1	$2	Mounted in RPi and sensor enclosure
Ethernet cable	1	$2	$2	Connecting RPi and sensor
Power connectors	2	$3	$6	Male and female connector for the sensor enclosure.
Total			$236	

Chapter 5

Modelling of the Electrical System

Modeling an electrical system can be advantageous for many reasons. The primary reason for doing so in this project is to allow a deeper understanding of the subject, as well as having the ability of using the model to perform predictions into the future, with as little computation time as possible. This chapter will go through the entire process from theory to final implementation. The first sections presents the necessary theory and tools in the implementation of the final model. Following is a step-by-step explanation of how the theory and tools were used to model the electrical system. The first step is to take a look at solar irradiance data and how such data can be obtained.

5.1 Solar Irradiance Data

In order to model the performance of a solar panel system, solar irradiance data is a prerequisite. In [90], Duus summarizes his evaluation of different databases for solar irradiance data. His finding, also found by Lockertsen in [91], is that the NASA database is the only one relatively up-to-date, which is also free and available online. Meteonorm has more recent data, but require payment. For this reason, the NASA database was used to obtain the solar irradiation data for Calle Santa Rosa.

The NASA database yields only daily and monthly insolation values, which has to be post-processed to give hourly resolution. PVSyst [92] is a software optimization tool for sizing and analyzing PV systems. PVSyst was used to generate hourly solar irradiance data for Calle Santa Rosa.

Synthetic data generation in PVSyst provides a mean of constructing meteorological hourly data from monthly known values [93]. Meteorological data was imported into

PVSyst for the geographical coordinates of Calle Santa Rosa (given in Section 2) choosing NASA-SSE 1985-2005 as the external data source. This generated a file with monthly meteorological data for Calle Santa Rosa. NASA-SSE (Surface Meteorology and Solar Energy programme) are monthly data averages of satellite measurements obtained from 1983 to 2005 [93].

The file with monthly meteorological data for Calle Santa Rosa was used to synthetically generate daily values. A screenshot of the PVSyst software interface used for this is shown in Figure 5.1. Several parameters can be adjusted to generate the hourly meteorological data. The generation is performed using the Meteonorm 7.1 algorithm, according to the PVSyst software manual [93], in which the different parameters are explained. The region typology is only used to calculate the daily temperature profiles, but it is claimed in the manual [93] that the differences among the region typologies are very low. The default "Swiss Plateau, land, important mist" was carried forward with, also because the humidity in Calle Santa Rosa was known to be more than 70 percent. The irradiation unit was chosen to be kWh/m^2.day.

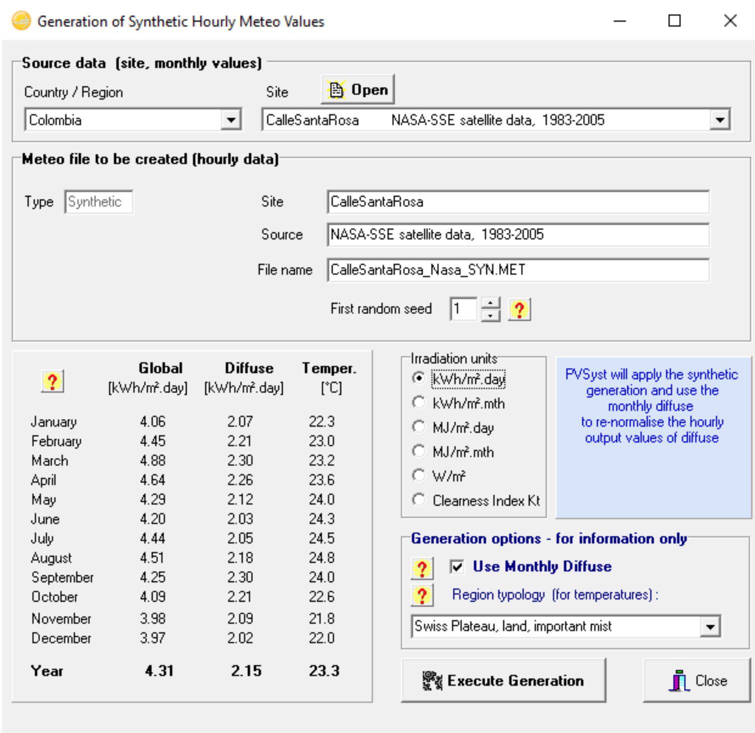


Figure 5.1: Synthetically generating irradiation and temperature data for Calle Santa Rosa using the PVSyst software tool.

The result was hourly irradiation values and ambient temperature values for each day throughout a year, as illustrated by the irradiation profile and the ambient temperature profile for January 1 displayed in Figure 5.2. The year 1990 is used as a label in PVSyst to indicate a generic year [93]. By choosing the results to be displayed as tables, the result can be exported to a CSV file. The CSV file was imported into MATLAB, which was used to transform the metorological data into an appropriate format in order to use the data as input to the electrical model.

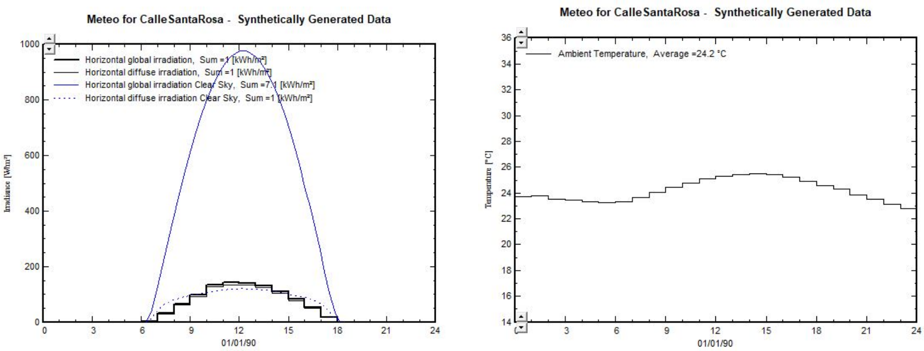


Figure 5.2: Hourly irradiation profile and the ambient temperature profile for Calle Santa Rosa for January 1, a generic year, generated by using the PVSyst software.

It was the global horizontal irradiation data that was used as input to the electrical model. PVSyst provides both the global horizontal irradiation (GHI) and the diffuse horizontal irradiation (DHI). According to Duus in [90], GHI is sum of the different solar irradiation components on the Earth's surface. DHI sums of all the weak radiation portions arriving from different directions due to the scattering of the sun rays' in the atmosphere [94]. The second component, the direct normal irradiance (DNI), is the solar irradiance that reaches the Earth's sun surface without atmospheric losses. GHI is the sum of the DNI and DHI.

5.2 Photovoltaic Fundamentals

A solar panel is usually made up of several cells in series or in parallel. Such cells are constructed using a semiconductor material, most often this is silicone. The semiconductor is doped by introducing foreign atoms in such a way as to form a p-n junction. This creates an electrical field that permits an electrical charge to move through the cell as light hits it. This charge is harvested and is the basis of any photovolatic (PV) solar panel power generation.

The approach taken towards developing the necessary understanding of how a solar cell works was to first read [94], in which a detailed introduction to semiconductors, doping and p-n junction can be found. This is also a recommended approach for the reader without a firm background in semiconductor technology, as these concepts are the basis of the content being treated throughout this chapter. The end goal is to develop a model for a solar cell, with the starting point being the diode. This leads to the photo diode which is the basic element of a solar cell.

5.2.1 Diode

The Shockley equation [95] provides the I–V (current-voltage) characteristic of an idealized diode with an applied voltage. The equation is achieved by utilizing the drift current and diffusion current at the p-n junction are the same size. This yields:

$$I = I_S \cdot \left(e^{\frac{V}{V_T}} - 1\right) \tag{5.1}$$

Where I_S is the saturation current of the diode [94]. This is the part of the reverse current in a semiconductor diode stemming from minority carriers diffusing to the depletion region from the neutral region.

$$I_S = A \cdot \left(\frac{q \cdot D_N \cdot n_i^2}{L_N \cdot N_A} + \frac{q \cdot D_P \cdot n_i^2}{L_P \cdot N_D}\right) \tag{5.2}$$

D_N and D_P are diffusion constant for the n and p-doped semiconductor, while L_N and L_P describe how far a hole or electron have to move on average before recombining. n_i is a measure of the number of electrons and holes in the semiconductor material and is known as the intrinsic carrier concentration. q is simply the elementary charge of an electron. The term V_T describes the thermal voltage.

$$V_T = \frac{k \cdot T}{q} \tag{5.3}$$

The ideal diode symbol and I-V characteristics can bee seen in Figure 5.3. No current is allowed through the diode under the threshold voltage V_{TH} that corresponds with the diffusion voltage V_D. If The voltage is sufficiently negative the diode breaks down as indicated by V_{Br} and current starts running in the reverse direction.

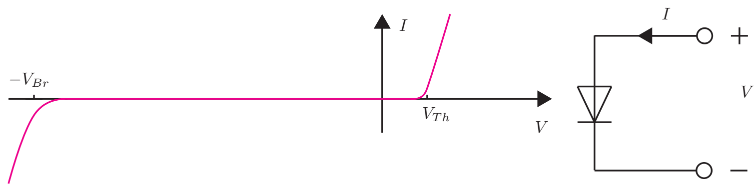


Figure 5.3: symbol and I-V characteristics of ideal diode

5.2.2 Photodiode

Continuing with development of the photovoltaic cell the next step is to look at the photodiode and not the idealized diode previously described. In this case light illuminates the photodiode and the arriving photons penetrate into the p-n junction where electron-hole pairs are generated. The electrical field in the space charge region separates the holes and the electrons such that the holes move to the p-side and the electrons move to the n-side. This separation ensures that a minimal amount of unwanted recombination occurs. The current created by the incident light is called photocurrent and is denoted by I_{Ph}. By assuming that all photons being absorbed creates an electron hole pair, the current is proportional to the irradiance E: $I_{Ph} = const \cdot E$ [94]. Without any light the photodiode behaves like a p-n junction, but with light the generated photocurrent is added to the I-V-characteristics. This generated photocurrent is also independent of voltage.

Creating an extension to how the diode was expressed by Shockley's equation, it is now possible to express the current through the photodiode by also taking the photocurrent into account. Thus the equation becomes:

$$I = I_D - I_{Ph} = I_S \cdot \left(e^{\frac{V}{V_T}} - 1\right) - I_{Ph} \tag{5.4}$$

With I_S expressed as before. As the goal is to model a solar cell, an equivalent circuit of the photo diode is necessary. For the simple equation above, Figure 5.4 shows the equivalent circuit.

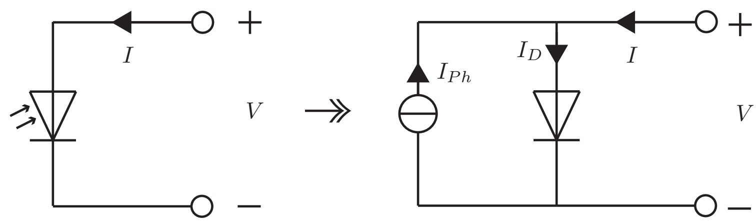


Figure 5.4: Equivalence circuit for a photodiode

5.3 Photovoltaic Cell

Up until now the focus has been on developing the tools that are needed in order to understand what photovoltaics are. From here on those tools will be used to describe two equivalent photovoltaic cell models that will prove fundamental in the later modeling of a PV array of cells.

5.3.1 Simple Solar Cell Model

A solar cell is essentially the same as a photo diode except for it being operated with a different reference system, where the current flow is regraded as positive from the energy source to the load and voltage is measured at the energy source. Thus, in comparison with Figure 5.4 the current is reversed and the equation for the current becomes:

$$I = I_{Ph} - I_D = I_{Ph} - I_S \cdot \left(e^{\frac{V}{m \cdot V_T}} - 1\right) \tag{5.5}$$

A factor of m has been added and is called the ideality or quality factor. This factor helps capture how closely a diode follows the ideal diode equation. The new equivalent circuit reflecting the change in reference system is shown in Figure 5.5. Where the new symbol used as a short for the equivalent circuit is also shown.

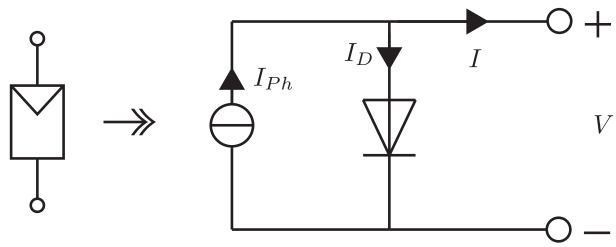


Figure 5.5: Equivalence circuit for a solar cell

This yields the characteristic curve of Figure 5.6.

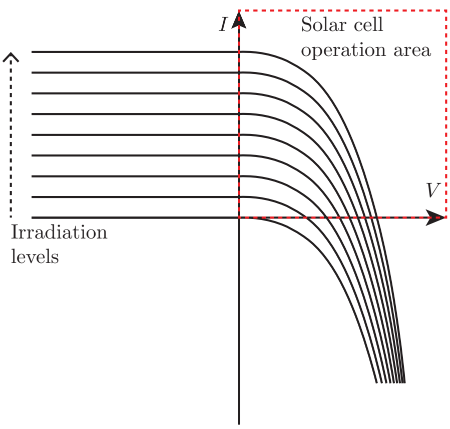


Figure 5.6: Characteristic curve of solar cell

To describe solar cells it is normal to use descriptive parameters such as the Short circuit current, I_{SC}, Open circuit Voltage, V_{OC}, Maximum power point, MPP, fill factor, FF, and efficiency η.

Short circuit current I_{SC}

The Short circuit current is the current generated by the solar cell when the terminals are short circuited, thus the voltage is zero. This parameter is given in the technical specifications of solar panels to describe how the panels behave. By using Equation 5.5 and by noting that the voltage is now zero it is possible to see that the short circuit current is equal to the photo current I_{PH} [94]:

$$I_{SC} = I(V = 0) = I_{PH} - I_S \cdot (e^0 - 1) = I_{PH} \tag{5.6}$$

As already mentioned the photo current is proportional to the irradiance and therefor it is possible to conclude that this is also the case for the short circuit current. This can also be seen by the equivalent circuit in Figure 5.5 where it is obvious that the diode is bypassed in the case of a short circuit.

Open circuit Voltage V_{OC}

The open circuit voltage is the voltage seen at the terminals when no load is connected. This results in a zero current. In a similar way as with the short circuit current, it is possible to find an expression for the open circuit voltage using Equation 5.5 together with $I = 0$ [94]:

$$V_{OC} = m \cdot V_T \cdot ln\left(\frac{I_{SC}}{I_S} + 1\right) \tag{5.7}$$

Maximum Power Point MPP

The maximum power point correspond to the operating point of the solar cell in which the most amount of power is being produced, given a certain irradiance. It s given as the maximum rectangular area under the I-V characteristic of a solar cell. In Figure 5.7 the voltage V_{MPP} and current I_{MPP} that determines the maximum power point is shown.

Fill Factor

The fill factor is determined as the percentage of the size of the area created by $V_{MPP} \cdot I_{MPP}$ compared to that of the area defined by $V_{OC} \cdot I_{SC}$. This gives a quality measure of the solar cell, where the fill factor is typically between 0.75 and 0.85 for silicon sells [94]. A simple equation for calculating the fill factor is given as:

$$FF = \frac{V_{MPP} \cdot I_{MPP}}{V_{OC} \cdot I_{SC}} \tag{5.8}$$

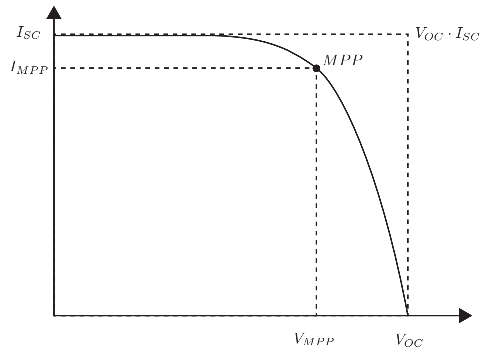


Figure 5.7: Illustration of maximum power point

5.3.2 Standard Solar Cell Model

In order to account for losses in the solar cell an extended model of the solar cell called the standard model is used. This model incorporated losses by including resistors in series and in parallel with the simple model above. The equivalent circuit for the standard model can be seen in Figure 5.8. The series resistance R_S aims to capture the ohmic losses in the contact points of the solar cell [94]. The parallel resistor, R_P, on the other hand deals with the losses stemming from point short circuits of the p-n junction and leak currents at the solar cell edges. The current I produced by the solar cell is now given as $I = I_{PH} - I_D - I_P$, where I_P is given as the voltage over the diode divided by the parallel resistor resistance:

$$I_P = \frac{V + I \cdot R_S}{R_P} \tag{5.9}$$

Thus the current I can be found according to:

$$I = I_{Ph} - I_S \cdot \left(e^{\frac{V + I \cdot R_S}{m \cdot V_T}} - 1 \right) - \frac{V + I \cdot R_S}{R_P} \tag{5.10}$$

This equation cannot be solved explicitly and must be solved with a numerical tool in order to solve for I [96].

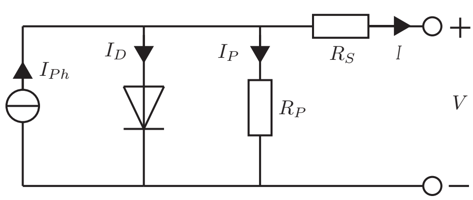


Figure 5.8: Equivalent circuit for the standard solar cell model

5.3.3 Solar Panels

The solar panel is what most people think of when discussing solar technology. This is the final product which is sold and consists of many solar cells connected together, either in series or in parallel. The choice of number of cells being in series and number of cells being parallel comes down to what voltage and currents are practical to have at the output. Each cell operates at voltages in the range of millivolts and currents up to some amperes. By connecting the cells in series the voltage can be increased to some tens of volts while the currents remain at a few amperes [96]. This is quite practical as usable voltages range from 12 volts in battery PV systems to hundreds or thousands of volts in a grid connected system. High currents carry larger losses and expenses in infrastructure. It is therefore desirable to have more of the cells in series than in parallel. An illustration of this is shown in Figure 5.9. Each of these panels are again connected in series or parallel in order to reach a predefined voltage for further use. When the desired voltage is reached by placing panels in series additional panels are placed in parallel. Multiple panels are connected together in a similar way to how the cells are connected within each panel. The characteristic (I-V) voltage - current relationship of a generator power plant can be estimated by multiplying the voltage values with the number of panels in series and multiplying the current values with the number of such parallel strings in series. This is a very ideal case and is most often not the case since it is unlikely that all the cell are operating exactly equal at all times. Temperature, irradiation and performance degradation of each individual cell play a role in how each cell operates and thus, reduces the validity of the multiplying method for finding the I-V characteristics. Such non uniform operating conditions are referred to as mismatching [96]. To mitigate problems with uneven operating conditions a bypass diode is placed between short strings of cells in series. The reason for this is that if for instance one cell is shadowed, the current of the cells in series with the shaded cell is restricted to what current the shaded cell is operating at [94]. By adding bypass diodes at intervals within the string the current has another way to be transported if shading occurs.

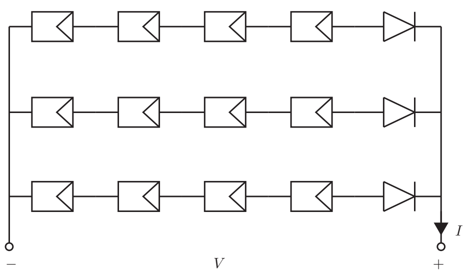


Figure 5.9: PV module with bypass diodes between the parallel strings

The characteristics of a PV panel is an important tool for visualizing how the panel operates under varying degrees of irradiation and temperatures. Normally this is shown as current vs voltage (I-V) or power vs voltage. Figure 5.10 5.13 shows two sets of such characteristic curves with either irradiation or temperature set constant while the other varies.

In these figures it is easier to see the closed-circuit condition, the open-circuit voltage condition and the MPP that was described earlier. In both Figure 5.10 and Figure 5.12 the short-circuit current I_{SC} can be found by setting the voltage to zero. The open-circuit voltage V_{OC} is defined where the current is zero. The maximum power point of the individual cases of irradiation and temperature in Figure 5.11 and Figure 5.13 can be seen as the peak of each curve. This clearly corresponds to the maximum power that can be extracted in each case. At this point (the MPP) the current value is I_{MPP} and the voltage is V_{MPP}. The definition of the power at the MPP is therefore $P_{MPP} = V_{MPP} \cdot I_{MPP}$, which is the maximum power the panel is capable of delivering under the these operating conditions [96].

Another insight that can be gleamed from these characteristic curves is that temperature has a significant effect on the open-circuit voltage, but a very small effect on the short-circuit current. The irradiation has the opposite effect, and greatly affects the short-circuit current, while not affecting the voltage in a significant way. It is worth noting that the temperature in question is the temperature of the PV cells and not the ambient temperature. The cell temperature is calculated from the ambient temperature by using the nominal operating cell temperature (NOCT) [96]:

$$T = T_a + \frac{NOCT - 20}{800} \cdot G \tag{5.11}$$

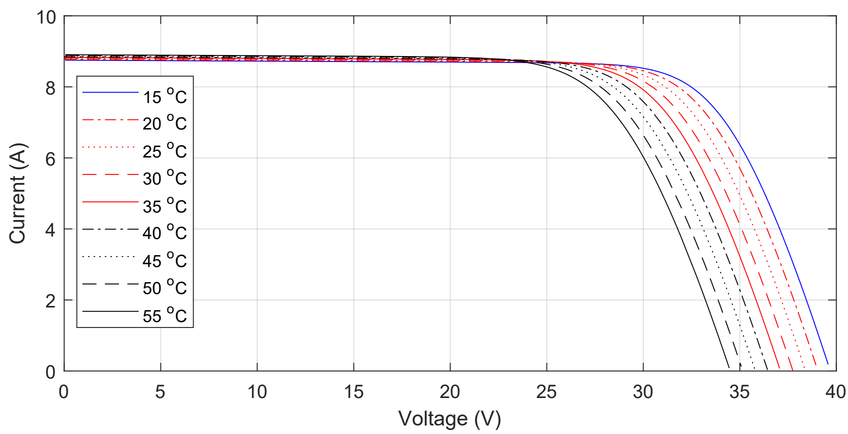


Figure 5.10: Current vs voltage with constant irradiation of 1000 W/m^2 and different levels of temperature

NOCT is usually given in the white paper of the solar panel and is defined as the temperature achieved when a cell is operated with open-circuit, no load attached. The irradiation G hitting the surface of the cell is for the NOCT case defined as $800\,W/m^2$, while the air temperature $T_a = 20\,°C$. T_a is changed to obtain an approximation of the cell temperature given a certain ambient temperature. Under NOCT it is normal for the manufacturer to give values for parameters such as:

- Power output: P_{max}
- Voltage at P_{max}: V_{MPP}
- Voltage at P_{max}: I_{MPP}
- Open-circuit voltage V_{OC}
- Short-circuit current I_{SC}

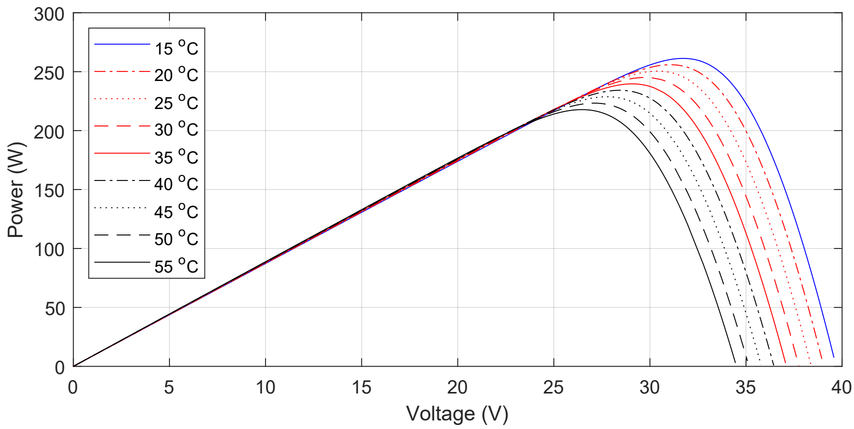


Figure 5.11: Power vs voltage with constant irradiation of 1000 W/m^2 and different levels of temperature

In order to be able to compare one solar panel to another a set of standard test conditions (STC) have been developed in addition to the NOCT. These test conditions have been adopted by manufacturers worldwide and normally consists of values like those listed above. The value for P_{max} is the efficiency the panel will be marketed as having. This evens the playing field and makes it easier to make a decision on which panel to buy. The STC is defined by: Cell temperature $T_{STC} = 25\,°C$, irradiation level $G_{STC} = 1000\,W/m^2$ and air mass value AM of 1.5, which describes the amount of air the light rays from the sun have to pass through before reaching the panel. More information on solar panels can be found in [94].

5.4 DC-DC Converters

The DC-DC converter is a crucial part of any on or off grid solar system. The voltage from the solar panels will in all likelihood either be higher or lower than what the actual demand is. Therefore the voltage must either be increased or decreased in order to meet the demand of the system. This is of course depending on what solar panels are used and how they are connected together. Many solar panels connected in series will for instance create a high voltage but low current and many panels connected in parallel will create high currents and low voltages. There is a trade of here, given the large power losses with low voltages, and the higher cost of equipment capable of containing large currents. There

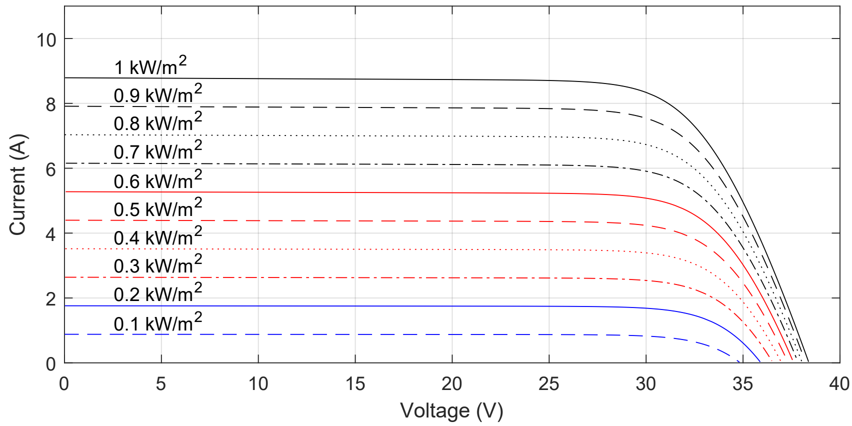


Figure 5.12: Current vs voltage with constant temperature of 25 $^{\circ}C$ and different levels of irradiation

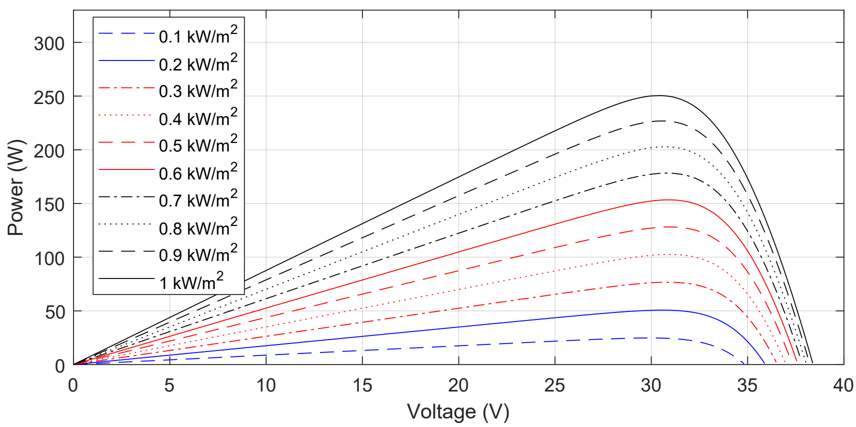


Figure 5.13: Power vs voltage with constant temperature of 25 $^{\circ}C$ and different levels of irradiation

is also an increased cost of having unnecessarily large voltage and a small current as this will have to be converted into suitable voltage ranges.

The choice of DC-DC converter is important considering the efficiency it can reach and the cost of the converter. The three common converter design choices are used in the different cases of whether the voltage needs to be reduced, increased or both. In order to reduce the voltage (step-down) the Buck converter is used. To increase the voltage a Boost converter is chosen. If there is a need to both increase and reduce the voltage then the Buck-Boost converter is selected. This is naturally a more complex converter. There are many other DC-DC converter designs that can provide higher efficiency than those listed above, but they come with a higher cost complexity. More on different DC-DC converters can be found in [97].

5.4.1 Buck Converter

The Buck converter will, as mentioned, step down the voltage from a higher voltage to a lower voltage. In broad stokes this is achieved by opening and closing a switch, so as to get an on-off output, and thereafter low-pass filtering that output with an LC circuit. This yields a continuous stepped down voltage.

The switching is performed using a switch such as a MOSFET. By just using the switch without filtering of the output voltage, the load will see discrete values, one value when the switch is closed and zero when the switch is open. Clearly the load will not see any current and therefore no voltage when the switch is open. An illustration of this simplified case is shown in Figure 5.14. The output voltage is controlled by how long the switch is open and how fast the switching is being performed. This is accomplished by defining a duty cycle, d, where d is the fraction of the switching period that the switch is closed [97]:

$$d = \frac{t_{on}}{t_{on} + t_{off}} = \frac{t_{on}}{T} = t_{on} \cdot f \tag{5.12}$$

The switching frequency f is a design parameter to be set. This enables the computation of the average output voltage V_o:

$$V_{out} = \frac{1}{T} \int_0^T v_o(t) \tag{5.13}$$

There would not be any power loss if an ideal switch is assumed, for most use cases, but in the case of a solar panel, where the power not transferred can be considered a loss, the loss would be proportional to time the switch is open. In addition, this is a pulsed output, which in general is not the desired result after a DC-DC conversion. Therefore the above mentioned LC circuit is included in order to act as a low pass filter. This yields the circuit shown in Figure 5.15, where the output is now purely dc, assuming an infinitely large output capacitor. In general the losses in a real switch is a source of power loss

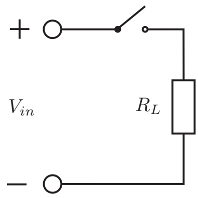


Figure 5.14: Equivalent circuit for simplified switch converter

in a converter. Thus, a real non ideal switch would cause the converter efficiency to be reduced.

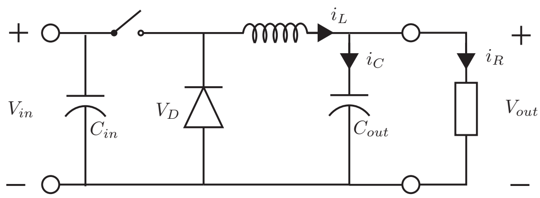


Figure 5.15: Equivalent circuit for buck converter

The Buck converter relies on the energy storage capabilities of both the inductor and capacitor. These two essential components behave differently than a resistor in the face of voltage at their terminals, in the sense that the current across them are not necessarily proportional to the voltage at their terminals. The current in an inductor changes gradually even when the voltage changes abruptly. Where the rate of change in inductor current is proportional to the voltage and inversely proportional o the inductor value L. This yields:

$$\frac{dI}{dt} = \frac{V}{L} \tag{5.14}$$

An instantaneous voltage drop to zero, which is the same as a short circuit, would not change the current in the inductor. In contrast to the current of the inductor, the voltage of a capacitor can only change gradually. This is also true in the case of an abrupt change in current. This rate of change in voltage is proportional to the current and inversely proportional to the value of the capacitor, C:

$$\frac{dV}{dt} = \frac{I}{C} \tag{5.15}$$

A stop in current flow, which is the same as an open circuit, yields a constant voltage at the capacitor terminals. It is clear that the capacitor and inductor are capable of storing energy. Which is a crucial point with the buck converter. Simply put, energy is stored when the switch is closed and discharged when the switch opens. This makes sure that the output is continuous.

The output might now be continuous, but it wont be fixed exactly at a reference voltage because of the constant charge and discharge of the inductor and capacitor. There will in other words be a ripple effect on the output voltage. By using inductors and capacitors with large enough capacities, such that their current or voltage keeps close to the desired value during normal operating conditions, the ripple is reduced to an acceptable minimum.

5.4.2 Dimensioning of a DC-DC Buck Converter

In order to dimension the Buck converter for a specific application, it is necessary to analyze its operation method such that the correct components are used. Several assumptions are needed throughout this process. The first of which is the assumption that the diode remains forward biased when the switch is open. This corresponds to the inductor current remaining positive in that time span, and is thus known as a continuous current [97]. A Buck converter upholding this constraint is termed to be operating in what is known as Continuous Conduction Mode (CCM).

According to [97], a Buck converter has the following properties when operating in steady state:

- The inductor current is periodic
- The average inductor voltage is zero
- The average output capacitor current is zero
- Assuming ideal components the power supplied to the load is the same as the power delivered to the load. If the components are not ideal then the source supplies the losses.

The dimensioning will proceed by looking at the cases of the switch being open and closed, with some additional assumptions to those above. The first addition is to have an output capacitor of a size such that it is capable of keeping the output voltage ripple sufficiently low. The switching period is given as T, where the switch is closed for a time defined by the duty cycle as dT, and open defined by $(1-d)T$. The components are also assumed to be ideal. The input capacitor will be ignored for the time being.

Closed Switch

When the switch is closed the circuit changes from Figure 5.15 to Figure 5.16. The diode is now reverse biased and appears as an open circuit. The goal is to find an expression for the change in inductor current when the switch is closed. Keeping in mind the definition of the inductor described earlier, the voltage over the inductor is seen to be:

$$V_L = V_{in} - V_{out} = L\frac{di_L}{dt} \tag{5.16}$$

This can be rewritten as [97]:

$$\begin{aligned}\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{dT} = \frac{V_{in} - V_{out}}{L} \\ \Delta i_{L,closed} = \frac{(V_{in} - V_{out}) \cdot dT}{L}\end{aligned} \tag{5.17}$$

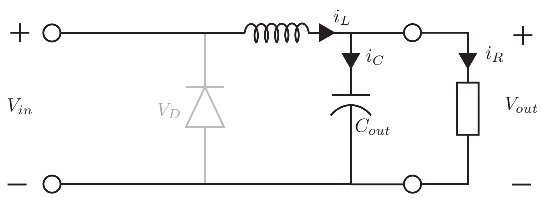


Figure 5.16: Equivalent circuit for buck converter with closed switch. The reverse biased diode is marked in gray

Open Switch

The case of an open switch is shown in Figure 5.17. Now the diode is forward biased and the converter is isolated from the voltage input and the voltage over the inductor is only dependent on the output voltage:

$$V_L = -V_{out} = L\frac{di_L}{dt} \tag{5.18}$$

Which again can be rewritten as:

$$\begin{aligned}\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-d)T} = -\frac{V_{out}}{L} \\ \Delta i_{L,open} = -\frac{V_{out} \cdot (1-d)T}{L}\end{aligned} \tag{5.19}$$

One of the assumptions made was that the converter is operating under steady state. This means that the inductor current is the same before and after the switching occurs. Therefore it is possible to find the output voltage by using Equation 5.17 and 5.19:

$$\begin{aligned}\Delta i_{L,closed} + \Delta i_{L,open} &= 0 \\ \frac{(V_{in} - V_{out}) \cdot dT}{L} - \frac{V_{out} \cdot (1-d)T}{L} &= 0 \\ (V_{in} - V_{out}) \cdot DT - V_{out} \cdot (1-D) \cdot T &= 0 \\ V_{in} \cdot d - V_{out} \cdot d - V_{out} + V_{out} \cdot d &= 0 \\ V_{in} \cdot d - V_{out} &= 0\end{aligned}$$

Thus an expression for the output voltage is found as:

$$V_{out} = V_{in} \cdot d \tag{5.20}$$

Taking into consideration that the duty cycle d mentioned earlier is defined as being between 0 and 1, it is easy to see from Equation 5.20 that the output voltage, V_{out}, of the buck converter indeed must be lower than input voltage, V_{in}.

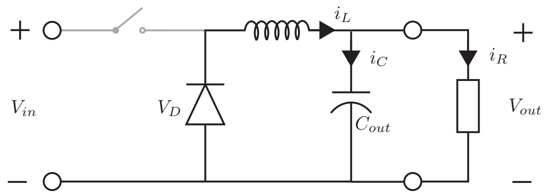


Figure 5.17: Equivalent circuit for buck converter with open switch

Finding The Inductor Value

By looking again at Figure 5.15 it can be seen that the average inductor current has to be the same as the average current going through the load. This makes sense when remembering that the average current through the output capacitor is zero under steady state conditions. The simple relationship is thus given as, $I_L = I_R = \frac{V_{out}}{R}$. By following the reasoning of [97, Chapter 6] and the previous calculations giving the change in inductor current, it is possible to find the maximum and minimum inductor currents as:

$$\begin{aligned} I_{max} &= I_L + \frac{\Delta i_L}{2} = \frac{V_{out}}{R} + \frac{1}{2}\left[\frac{V_{out}}{L}(1-d)T\right] \\ &= V_{out}\left(\frac{1}{R} + \frac{1}{2}\frac{1}{L}(1-d)T\right) = V_{out}\left(\frac{1}{R} + \frac{1-d}{2Lf}\right) \end{aligned} \tag{5.21}$$

$$\begin{aligned} I_{min} &= I_L - \frac{\Delta i_L}{2} = \frac{V_{out}}{R} - \frac{1}{2}\left[\frac{V_{out}}{L}(1-d)T\right] \\ &= V_{out}\left(\frac{1}{R} - \frac{1}{2}\frac{1}{L}(1-d)T\right) = V_{out}\left(\frac{1}{R} - \frac{1-d}{2Lf}\right) \end{aligned} \tag{5.22}$$

The assumption of operating in CCM, the lowest inductor current allowed is zero. By using $I_{min} = 0$ it is possible to solve Equation 5.22 with respect to the inductor L:

$$\begin{aligned} I_{min} &= 0 = V_{out}\left(\frac{1}{R} - \frac{1-d}{2Lf}\right) \\ &\Downarrow \\ L_{min} &= \frac{(1-d)R}{2f} \end{aligned} \tag{5.23}$$

L_{min} is considered to be the absolute minimal inductor value and should therefore be chosen to be more than this in order to make sure that the buck converted is actually operating in CCM.

Finding Output Capacitor Value

In order to keep the voltage ripple at an acceptable level according to the use of the buck converter and to uphold the assumption of constant output voltage, it is necessary to determine the output capacitor value needed. The current going through the inductor must equal the current going through the load. This means that only the inductor current ripple flows through the capacitor, as can be seen from Figure 5.18. The negative part of the ripple removes charge from the capacitor while the positive adds charge. Since the assumption of operating in CCM must still hold, the positive charge forms a triangle. This is shown as the green area in Figure 5.18, Where the base of this triangle is:

$$\frac{dT}{2} + \frac{(1-d)T}{2} = \frac{T}{2}$$

The peak is given as half the current ripple. The crossing between charging and discharging corresponds to the maximum and minimum output voltage, which is illustrated by Figure 5.18 in blue. The charge Q of the capacitor is defined as $Q = CV_{out}$, and this can be extended to $\Delta Q = C\Delta V_{out}$. By using this, the area of the triangle is found as:

$$\Delta Q = \frac{1}{2}\frac{T}{2}\frac{\Delta i_L}{2} = \frac{T\Delta i_L}{8} \tag{5.24}$$

Combining this with the definition of the charge yields:

$$\Delta V_{out} = \frac{T\Delta i_L}{8C} \tag{5.25}$$

By inserting for Δi_L from Equation 5.19 the expression becomes:

$$\Delta V_{out} = \frac{T}{8C}\frac{V_{out}(1-d)T}{L} C = \frac{T^2 V_{out}(1-d)}{8\Delta V_{out} L} \tag{5.26}$$

This is finally expressed as:

$$C = \frac{1-d}{8\left(\frac{\Delta V_{out}}{V_{out}}\right) Lf^2} \tag{5.27}$$

The fraction, $\frac{\Delta V_{out}}{V_{out}}$, defines the output voltage ripple as a design criterion.

Finding The Input Capacitor Value

The input capacitor that was ignored while calculating inductor and output capacitor sizes will be considered again in the following. While not strictly necessary in order to have a functioning buck converter, it does relieve some strain from the power source, as currents can now be supplied more evenly since the circuit is not entirely disconnected while the switch is off. The circuit is now the same as in Figure 5.15. If the power supply is a solar panel, the use of an input capacitor is much more important as the power being supplied to the inductor when the switch is open and resupplied to the buck converter when the switch is closed, would otherwise have gone to waste.

The current through the input capacitor is the current supplied by the power source when the switch is open and the difference between supplied current and inductor current while the switch is closed. The same principles as when calculating the output capacitor is used. During the charging period the the ripple goes from maximum to minimum. This gives:

$$C_{in}\frac{dV_{in}}{dt} = C_{in}\frac{\Delta V_{in}}{(1-d)T} = I_{in} \tag{5.28}$$

Using $I_{in} = dI_{out}$ and solving for C_{in}:

$$C_{in} = \frac{I_{out}d(1-d)T}{\Delta V_{in}} \tag{5.29}$$

In order to find the desired cpacitance of the capacitor the required input voltage ripple must be decided as ΔV_{in}.

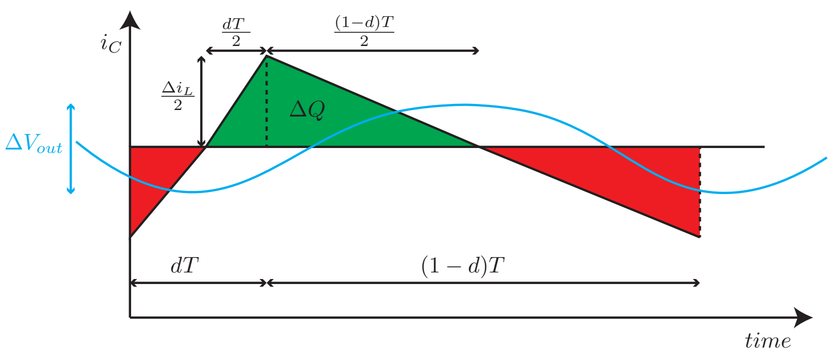


Figure 5.18: Shows the current running trough the capacitor. The green area is where charge is being added and the red area shows the discharge region. The blue overlay is illustrating the voltage over the capacitor and hence the voltage ripple

5.5 Battery Technology in a PV System Perspective

Batteries are an absolute essential part of any stand-alone solar power system. The main function of the batteries is to store produced energy that is not immediately consumed by a load. This stored energy can then be used when the generated power from the solar panels is lower than the demand of the loads. In addition they play an important role in stabilizing voltages and currents by suppressing or smoothing out transients that can occur in solar power systems, as well as supplying surge currents to the loads [15]. This section will give an introduction to the relevant battery technologies for solar power systems as well as some important aspects too keep in mind when choosing what batteries to use.

5.5.1 The Main Components of any Lead-Acid battery

Each battery consists of one or more so called battery cells. Each cell is constructed with a set of negative and positive plates which are divided by a separator. These are submerged in an electrolyte solution. Each cell is normally around 2.1 volts. Thus, for instance, a battery of 24V consists of 12 such cells. One such cell can be seen in Figure 5.19. The plates are made up of an lead alloy framework that supports the active material on the plate. The alloy of this grid is used to strengthen it and has effects on battery performance metrics, such as cycle performance and gassing. The number of plates and their thickness affect what currents can be generated and how well the batteries tackle deep discharges [15]. Thin plates connected together increase the surface area and can therefore provide higher currents, but at the expense of deep discharge capabilities. The amount of active material of the plates defines the capacity of the battery and reacts with the electrolyte solutions that the plates are suspended in. This solution is a diluted sulfuric acid solution (H_2SO_4), which can either be in liquid (flooded), gelled or absorbed in glass mat (AGM). The active material in the positive plate is led dioxide (PbO_2) and the active material in the negative plate is metallic sponge (pb). For led-acid batteries the grid alloy is antimony, calcium or a combination [15]. The separator is placed between the plates to prevent buildup of sulfate on the plates, such that they will not touch and create a short circuit.

Because of gasses produced during charging, the batteries are fitted with a vent that lets the gas escape. For flooded batteries the gas normally escapes during charging, and refilling of distilled water is a necessary maintenance procedure. Designs featuring sealed or valve regulation have a pressure relief mechanism that only opens when the gas pressure is higher than normal, such as when the battery is overcharging. This significantly reduces the maintenance required on the batteries. [15] gives a thorough description of the different types of batteries that are suitable for a PV system installation.

5.5.2 Battery Performance

The capacity of a battery is often given in Ah. This is a unit of measurement that describes how much current could be delivered by the battery. One ampere hour $(1Ah)$ would be the transfer of one ampere over the course of an hour. A battery specified with a 500Ah

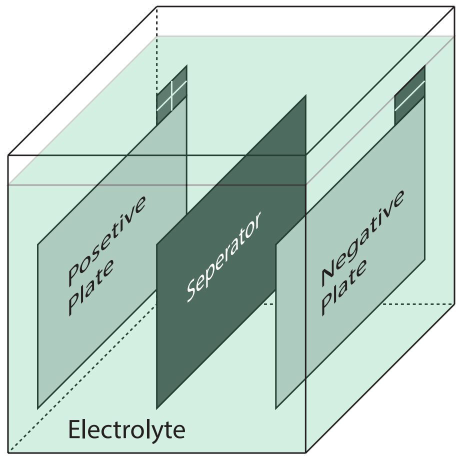


Figure 5.19: Battery cell

capacity would be emptied with a constant 5A draw over 100 hours. As already mentioned, the capacity of a battery depends on different design factors, such as the number, thickness and material of the plates. In addition cut off voltage, temperature, age, discharge rate, depth of discharge and history of the battery affect the capacity [15].

The cut off voltage is the lowest voltage in which the battery is allowed to operate. This is dependent on the rate of discharge and differs between different types of batteries and manufactures. The open circuit voltage is the voltage measured at the battery terminals when the battery has been resting without a load or a charge. This information can be used to ascertain at what state of charge (SoC) the battery is. Doing this requires some information from the manufacturer regarding what voltage equals which percentage of full capacity. The state of charge is defined as amount of energy in a battery and is given as a percentage of the energy that is stored in a full battery.

A very important aspect of a battery usage is the discharging. The opposite of the SoC is the depth of discharge (DoD). The DoD expresses the percentage of energy removed from the battery. Together with the SoC the DoD sums to 100 percent. The allowable DoD is defined as the discharge limit that the battery controller is operating under. For a deep charge battery, the charge controller might for instance allow a discharge of up to 80% of the capacity at a given discharge rate before the battery is disconnected. In general having a low daily and maximum DoD will increase the lifetime of the battery, but with the caveat that the batteries must be dimensioned accordingly, which, probably means a higher cost for batteries with a larger capacity. According to [15] a flooded battery that is kept above 90 percent SoC will provide two to three times more full charge and discharge cycles than a battery witch is allowed to drop to 50 percent SoC before recharging. This indicates that reducing the DoD allowed for daily use to a minimum is of importance to keep the lifetime as long as possible. In general the lifetime of a battery is difficult to estimate unless very strict regimes are kept with relation to the maximum allowable DoD and the daily average DoD. Other important factors to the lifetime is how the battery is charged and also the temperatures the battery are operating at. Higher operating temperatures causes more corrosion of the positive plates and an increase of gassing. An increase of $10°C$ will generally decrease the battery lifetime by a factor of two [15]

5.6 Maximum Power Point Tracking (MPPT)

In order to consistently extract as much power as possible from a solar panel it is necessary to use a method called maximum power point tracking. As mentioned earlier in this chapter, irradiation and temperature has a significant effect on the output characteristics of a panel. Controlling the power being generated requires changing the voltage at the panel output such that the operating point is at the top of the power-voltage curve that was shown in Figure 5.10, 5.11. A simple thought might be to directly connect a battery and a PV panel together in order to have a very simple system. However, the battery would force the PV panel to operate at its voltage and this is without a doubt not the optimal voltage, considering how the operating conditions would change though out the course of a day. A similar idea to connecting a battery directly to the panel is that of connecting a resistive load directly to the panel. Once again, the intersection between the constant load and the I-V curve cannot always occur at the maximum power point. The cases of both a constant load and a constantly imposed voltage by a battery is shown in Figure 5.20,5.21 based on Figure 5.11 and 5.12 respectively. Here the load and battery is represented by the dotted line intersecting the MPP of the first curve, but clearly not intersecting the other curves representing different operating conditions.

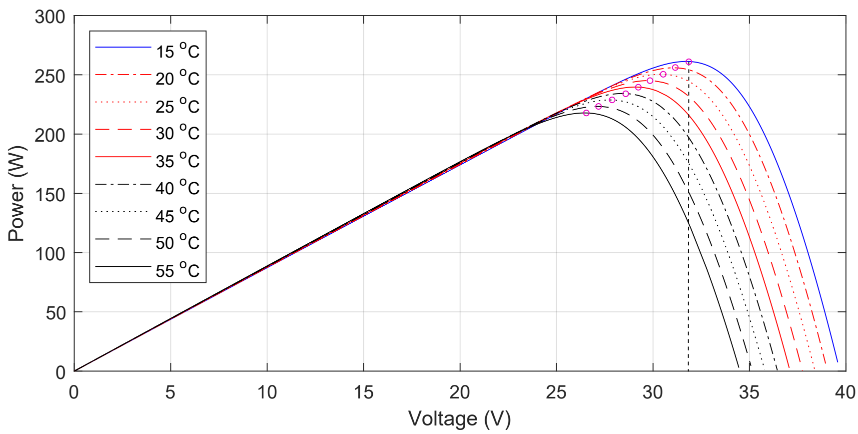


Figure 5.20: One value for V_{pv} will extract the maximum power only in a very specific case as shown where the voltage line intersect with a pink circle

Clearly it is necessary with some sort of a step between the PV panel and the battery. The requirement is that the output voltage and current levels must be kept within a level accepted by the load, as well as having the capability of adapting the input voltage and

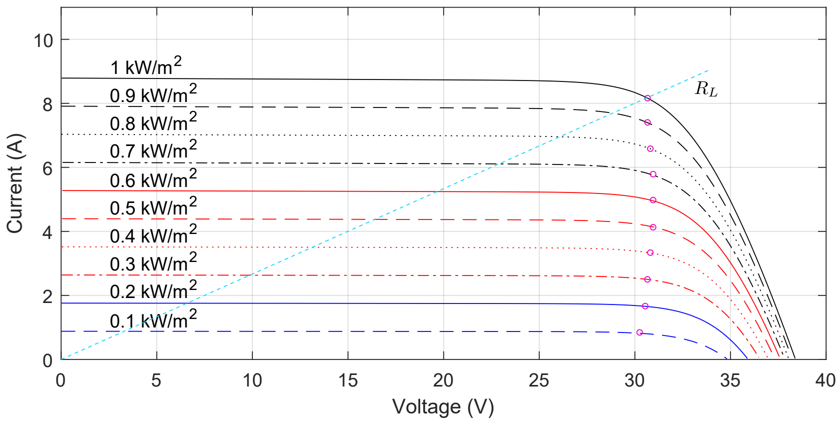


Figure 5.21: One value for the load R_L will extract the maximum power only in a very specific case as shown where the resistor line intersect with a pink circle

current such that the MPP is obtained. The fact that this criteria must be fulfilled during run time, means that the converter needs to be able to track the MPP in real time by changing parameters. Henceforth this converter will be assumed to be a Buck DC/DC converter with the duty cycle d as the control parameter. This is schematically shown in Figure 5.22.

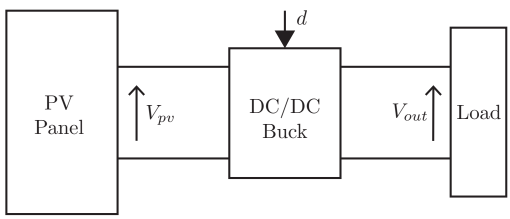


Figure 5.22: Schematic model of duty cycle used together with a PV panel and a load

As was explained in the Section 5.4 on DC-DC converters, the duty cycle d relates to the input voltage from the PV panel and the output voltage to the load by: $d = V_{pv}/V_{out}$. By having a battery on the load side the output voltage will be forced and the panel voltage can be set by adjusting the duty cycle d of the switch. Figure 5.23 shows the effect of changing V_{pv} at various temperature levels and how the voltage means that the maximum power is obtained. This illustrates the reasoning for the name maximum power point tracking. As the temperature and irradiation changes the algorithm for selecting the duty cycle will track the maximum power point based on the current and voltage measured at the terminals of the PV panel. Measurements for the irradiance and temperatures are not often used as this requires expensive equipment that must be placed at various locations if used with large fields of PV panels [96].

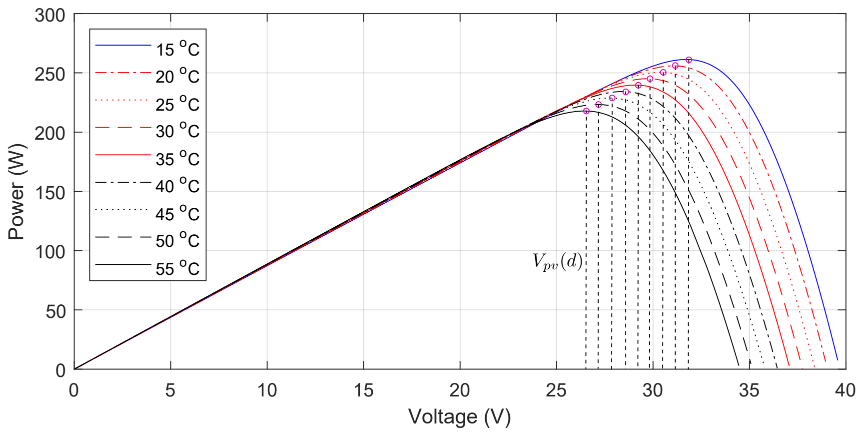


Figure 5.23: Changing V_{pv} enables the tracking of the different maximum power points shown with pink circles

There are a plethora of different algorithms being used in the industry for maximum power point tracking. Some are more popular than others. The most popular methods is the perturb and observe method (P&O) and the incremental conductance (INC) method [96]. The P&O method is the simplest of these two and is less computationally expensive with a good performance in various situations. The INC method is based on the P&O method and improves upon it. The focus here will lie on the P&O method as this is realistically what hardware will use and is often sufficient for modeling purposes [98]. In most cases the MPPT algorithms are implemented with a digital controller as this is cheaper and less complicated to design [96]. The speed of the ADC used with the analog measuring devices for measuring the voltage and current is not critical as the variations in temperature and irradiation that must be tracked are quite slow. Therefore it is possible to use quite cheap microprocessors to implement an MPPT algorithm.

There are methods that are simpler than the P&O and INC approach. These method are called indirect methods as they do not measure the power produced by the PV panels, but either the open-circuit voltage or the short-circuit current. This is in contrast to P&O and INC, which are called direct methods since they do measure the current and voltage continuously, and therefore allow higher precision in a wider variety of operating conditions.

5.6.1 Indirect MPPT Methods

The method works by periodically measuring the open-circuit voltage V_{oc} and relating this to a desired V_{MPP}. A suggestion for such an magic number is proposed in [99] as $76\,\%$. Thus the V_{MPP} is given as $76\,\%$ of the open-circuit voltage V_{oc}. A method based on such assumptions are very simple and easy to implement by having a switch disconnect the panels from the circuit, but does clearly have some limitations. The fact that the panels are disconnected during the time it takes to take a measurement means that power is not being transferred to the load and is thus wasted. A DC/DC switching converter must be used in this approach as well. The same principal holds for using the short-circuit current as a basis for selecting the appropriate I_{MPP}

5.6.2 Perturb and Observe MPPT Algorithm

The perturb and observe method is in the class of direct MPPT techniques. The method is, as the name implies, based on perturbing the PV panels operating point by changing the voltage at the PV terminals. After each perturbation, the resulting current and voltage is measured and the power is calculated. This new power is compared to the power before the perturbation, and if the power increased between the two perturbations then the perturbation is continued in the same direction, if not the voltage is perturbed in the other direction.

If the duty cycle d is used as the perturbation parameter, the voltage is increased by reducing the duty cycle, and decreased by increasing the duty cycle. The size of the perturbation is decided by Δd, which together with the operating speed T_s of the algorithm decides how fast the algorithm responds to changes in operating conditions. These two factors must be decided either by calculations such as those provided in [96] or by trial and error. Figure 5.24 illustrates the workings of the P&O algorithm as a flowchart.

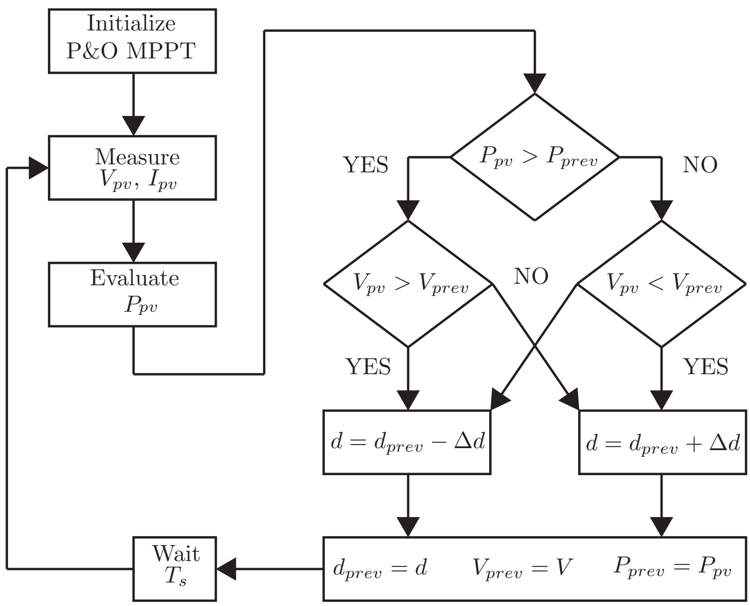


Figure 5.24: P&O MPPT algorithm illustrated as a flow chart

The basic scheme of an implementation using a DC/DC buck converter is shown in Figure

5.25. In order to use the duty cycle d as a control signal a PWM generator must be used such that a discrete on-off signal is delivered to the switch. The operating frequency of the switching between on and off states is defined by this PWM generator and is as mentioned earlier, in Section 5.4, an important factor to decide. This switching frequency also has an impact on the how the MPPT algorithm operates and should be taken into consideration during designing.

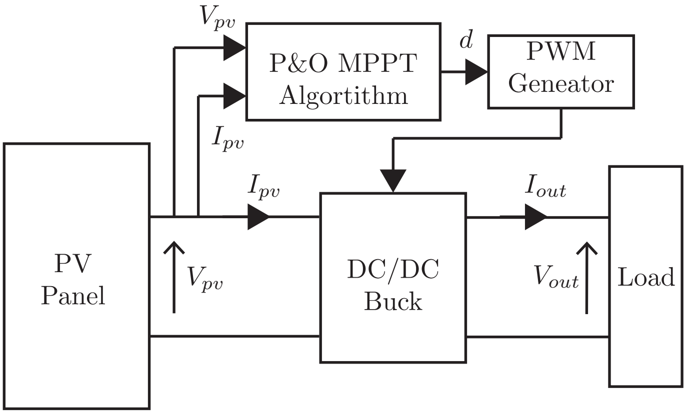


Figure 5.25: Overview of P&O used together with a buck converter and a PWM generator

By using the flowchart in Figure 5.24 a simple example using Figure 5.26 can be solved. For the sake of clarity the P&O is assumed to already have been initialized and that T_0 is the previous step of the algorithm. At T_1 the voltage V_{pv} and current I_{pv} is measured and the power P_{pv} is calculated. The power is then compared to the last power measured and new measurement. In this case the new power increased and so did the voltage. Therefore the duty cycle is changed in order to further increase the voltage such that the power hopefully also increases. This continues until T_3, which is the MPP. In this case it would be advantageous to not keep increasing the voltage as the power would surly decrease. However, the the way the algorithm operates means that it only knows that the power increased between now and the last perturbation, thus, the voltage is further increased and the new state is in T_4. By doing another loop through the algorithm the power has now decreased. this means that the voltage should be reduced. This brings the operating point back to the MPP. These oscillations around the desired MPP will continue to occur and is a side effect of the P&O algorithm.

5.7 PV Panel Modeling

I order to test PV panels under different operating conditions, it can be advantageous to have the possibility of modeling panels to quickly test performance. This can be useful in cases such as estimating the yield of a proposed PV field over time. Most approaches are in one way or another based on the standard PV cell circuit model introduced in Section

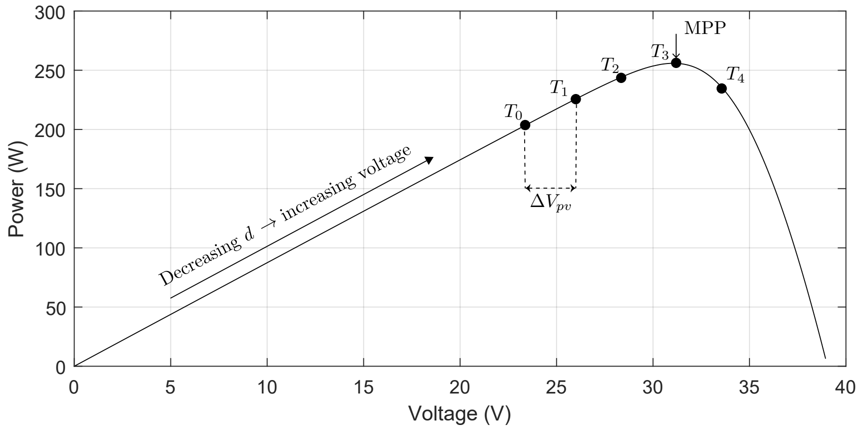


Figure 5.26: Steps taken towards reaching the MPP in a particular situation

5.3.2. In [96, ch 1] Femia shows in detail how to find the values of each of the standard cell circuit elements. If these are known, then it is possible to build panels and large networks of such panels based purely on the circuits. Another approach that is also based on the standard solar cell model is given in [100]. This approach uses newtons method in order to solve an equation for what the current from a panel or a number of panels connected in series would be. This can then be modeled as a current source in a program such as Simulink. There is also a model block called "PV Array" available in the MATLAB Simscape Power Systems toolbox that includes a large number of different PV panels that are ready to be used in simulations. If data measured in field testings of the the PV panels are available then it is possible to use curve fitting methods in MATLAB to make a PV panel model, as is explained in one of Mathworks own webinars [101].

5.8 Designing the Load Profile

The load profile for one refrigerator is based on the graph from the specifications document as explained in Section 2.3. The profile was created with a resolution of one hour. By utilizing the predicted hourly temperature data developed in Section 5.1, the average power used per day, given a normal usage pattern could be found. This is possible if the temperature for the whole day is set equal to the hourly temperature used. This daily consumption was then divided by 24 hours to obtain an approximation of what the consumption would be for one hour given a specific temperature. Data from the graph was manually recorded and a curve-fitting algorithm was used in MATLAB to produce a function for the hourly power consumption given an input temperature. The resulting function was:

$$P_{fridge}(T) = (0.491 \cdot T^2 - 13.26 \cdot T + 173.2)/24 \tag{5.30}$$

Here, T, is the temperature which is assumed to be the same indoor as outdoor. This load profile can be used to create a long sequence of data given the availability of temperature data. By multiplying with the number of refrigerators assumed to be in operation at any given time a complete future load profile can be created. Clearly this is dependent on the refrigerator usage being similar to the test conditions imposed by the manufacturer and that the temperature indoor is accurate enough. Given that the usage pattern is probably very different from a residential application, the accuracy of the load profile might be less than desirable.

It should be noted that Equation 5.30 is only valid for temperatures between $21\,°C$ and $40\,°C$. As this is the temperature range that the graph yields information for. A solution would be to use input a temperature of $21\,°C$ into the equation if the temperature is less than $21\,°C$ or a temperature of $40\,°C$ if the temperature is more than $40\,°C$.

5.9 Implementation in MATLAB & Simulink

The choice of modeling language fell on MATLAB and Simulink. In part because it is a language and tool that is much used among engineering students at NTNU, but also because it is a well supported and versatile platform that enables quick testing and fast feedback. It is very simple to start simulations in Simulink with a large variety of different modeling libraries available.

Specifically the Simscape Power Systems toolbox was used, which provides component libraries and analysis tools for modeling and simulating electrical power systems [102]. It also enables the use of basic components such as switches, diodes and resistors. In order to have a complete model of the system, each component was developed separately while testing with standard Simulink models. In broad stokes the model consists of a PV model, a DC-DC converter model, an MPPT controller algorithm, a battery model and a load model. The overall model should run on a Raspberry Pi, which requires some special considerations to be taken.

5.9.1 Considerations for Running the Model on a Raspberry Pi

The model is intended to be running on a Raspberry Pi and for that reason there are some limitations as to how the model can be implemented using MATLAB and Simulink. While it is officially possible to run MATLAB programs on the Raspberry Pi, this was not the route chosen. It was believed that doing so would have a computational penalty as MATLAB or parts of MATLAB would have to be installed on the RPi. This is undesirable because the goal is to have the model run as fast as possible as well as leaving a small memory footprint since other programs will be running simultaneously. In addition it is desirable to be as little dependent on a MATLAB license as possible.

The way these issues were solved is to use the Simulink Coder toolbox, which allows generating C++ code from the model. The code is generated while keeping the limitations of the RPis ARM architecture in mind. One limitation is for instance the 32bit operative system used which is a bottleneck for the 64bit ARM processor. It is not possible to use a a variable step solver either. Therefore a discrete ode8 (Dormand-Prince) fixed step solver was used.

Other restrictions were also found while making the models and trying to generate C++ code. The code generator would then complain, saying that this or that block/method is not supported by code generation. Thus, the models were change quite few times from working in a normal MATLAB environment to not being able to be changed into C++ code.

5.9.2 PV Panel Model

Having a model for the PV panels being used is a crucial part of modeling a solar energy system. As discussed in Section 5.7, this can be solved in multiple ways. The method shown in [96] would require building each individual cell as a circuit and connecting them together into PV panels. This could very well be accurate, but was not attempted as it was thought to be too computationally expensive to solve with MATLAB. The PV panel model provided in MATLAB was tried, but turned out to be unstable for the particular PV model used. The model is also more or less a black box, which makes it hard to understand what goes on within the model mask. It was decided that a having an understanding of how each component works would be beneficial for understanding and learning as well making it much easier to find problems in the overall model. This meant that the choice fell on the method in [100]. This section will provide the necessary changes that where made to make that approach and code work for the PV panels and their interconnection used in the refrigerator center.

The standard cell model discussed in Section 5.3.2 is used as the basis in the model derived by [100]. This model captures more of the losses and dependencies than the simple model from Section 5.3.1. The diode saturation current I_S and photo current I_{ph} is dependent on the temperature. The series resistor R_S is included such that internal losses due to current flow between interconnected cells and within cells is represented. The parallel resistance is neglected in this model and it is thus a little bit more simple then the standard model.

The script models the I_{pv} from all PV panels connected in series. The string of series panels is then modeled in Simulink by using a current source with the I_{pv} calculated for each series as the input. Two strings of two panels in parallel with each other is then modeled as two current sources in parallel with the same control input I_{pv}. This can be seen in Figure 5.27. The script also takes irradiation and temperature as the input. During the implementation process the cell temperature is used as temperature input because it is easier to interpret the results after simulations. However, when the system is implemented the ambient temperature will be the input. The ambient temperature is then converted into cell temperature according to Equation 5.11.

The parameters that were sett in the MATLAB script in [100] are summarized in Table 5.1 and are partly from the white paper, but some parts were also read from the I-V curves generated by the included MATLAB PV model. The white paper used in [100] included

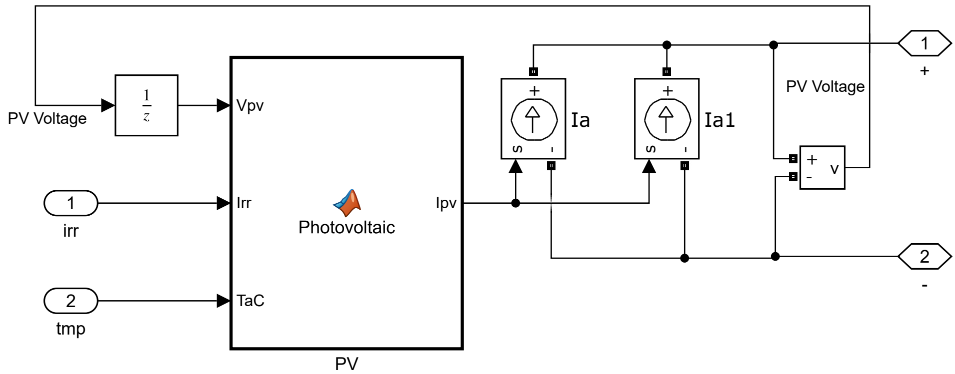


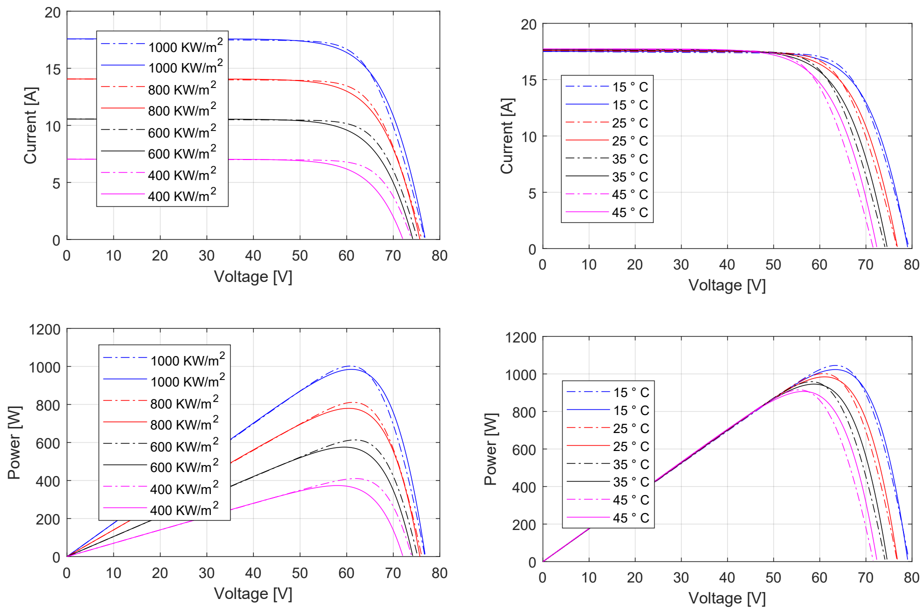
Figure 5.27: PV field modeled as two parallel current sources in Simulink

I-V curves for his panel and this was not available for the panels used in this project. The values reflect the idea of modeling two panels in series. Open-circuit voltage at STC per cell V_{oc}^{STC} is found by dividing the open circuit voltage by the number of cells in a panel.

The diode quality factor m was chosen based on comparing the characteristic curves obtained using different values for m. There is not any information in the white paper suggesting it should be changed to something specific. The only information available is that the silicon is multicrystalline, which is the same as polycrystalline. Without actual data, the value chosen is purely speculation. The closest thing to real data is to use the curves from the model included in MATLAB. Figure 5.28 shows the result of generating characteristic curves with a quality factor of $m = 2$. Temperature and Irradiation is fixed in 5.28a and 5.28b respectively. The results from MATLABs built in PV array block is shown with a dotted line. By using MATLABs results as a reference it can be seen that the results are quite good with fixed irradiation, but with a low irradiation and a fixed temperature the power extracted would be a fair bit lower than MATLABs solution.

A similar conclusion can be drawn from looking at Figure C.2 in Appendix C created with $m = 1.15$. The result here is opposite. There is a good mach for low irradiation that gets slightly worse as it increases. The result of increasing the temperature yields a worse fit than with $m = 2$. Since both solutions has weaknesses the diode quality factor is set to be $m = 1.6$. This will hopefully be a middle way between the two extremes. In Figure C.3 in Appendix C the results can be seen. Using $m = 1.6$ yielded less overshoot with variable temperature. It should be mentioned that comparing to the MATLAB model is not the optimal choice, but here it is the only available option and it is better than not comparing to anything.

V_g was set to $1.12\,eV$ as this is the band gap voltage for silicone. $\frac{dV}{dI}$ at V_{oc} per cell was found by measuring the I-V characteristics the MATLAB block for this specific panel produced. The short circuit current for the test temperature at $1000\,W/m^2$ was also measured form the MATLAB I-V graph. The rest of the values were easily read of straight from the



(a) Temperature fixed at $25°C$ **(b)** Irradiation fixed at $1000KW/m^2$

Figure 5.28: I-V curve on top row and P-V curve on bottom. The dotted line is from MATLABs model and the whole line is based on [100] with diode quality factor $m = 2$

white paper.

Table 5.1: Parameters that need to be set in the PV model. Some values reflect two panels in series being modeled as one large panel. Values are based on the white paper for model YL250P-29b reproduced in Appendix A.2

Parameter	**Variable**	**Value**
Standard test condition temperature	T^{STC}	25 $°C$
Open-circuit voltage at STC per cell	V_{oc}^{STC}	0.64 V
Short-circuit current at STC	I_{sc}^{STC}	8.79 A
Nominal operating cell temperature	T^{NOCT}	46 $°C$
Test temperature	T_2	75 $°C$
Short-circuit current at T_2	$I_{sc}^{T_2}$	7.12 A
Diode quality factor	m	1.6
Band gap voltage	V_g	1.12 eV
Number of cells in series	Ns	120
$\frac{dV}{dI}$ at V_{oc} per cell	$\frac{dV}{dI}\big\|_{V=V_{oc}}/Ns$	-0.0157 V

The script then uses the values found in Table 5.1 in addition to the feedback panel voltage V_{pv}, input temperature and irradiation, to calculate the photo-current I_{ph}, the saturation current of the diode I_S and the series resistance R_S. Finally the PV array current, I_{pv}, through the two panels is found by solving the equation for I_{pv} iteratively with newtons method illustrated in equation 5.31

$$I_{pv+1} = I_{pv} - \frac{f(I_{pv})}{f'(I_{pv})} \tag{5.31}$$

Using Equation 5.10 with Equation 5.31, neglecting the term related to the parallel resistor R_P and setting $I = I_{pv}$ yields:

$$I_{pv+1} = I_{pv} - \frac{I_{ph} - I_{pv} - I_S \cdot e^{\left(\frac{V_c + I_{pv} \cdot R_S}{V_T \cdot m} - 1\right)}}{-1 - \left(I_S \cdot e^{\left(\frac{V_c + I_{pv} \cdot R_S}{V_T \cdot m} - 1\right)}\right) \cdot \frac{R_S}{V_T \cdot m}} \tag{5.32}$$

This can be seen solved iteratively in the code in Appendix B.1.

5.9.3 DC-DC Buck Converter Model

The theory that was employed while implementing the DC-DC converter was presented in Section 5.4. In order to have a good understanding, a detailed model was implemented first. This model consists of the same basic circuit elements as those used in Section 5.4. Figure 5.29 shows the Simulink model of this detailed DC-DC buck converter. Here a PWM generator from the Simulink library is used in order to enable the use of the incoming duty cycle signal. The generated PWM signal is connected to the switch where it is used to determine whether the switch should be open or closed at any given time. In addition a unit delay block is used in order to break an algebraic loop that exists when initializing the model. It is there to make sure the switch has a signal during the very first iteration of the solution.

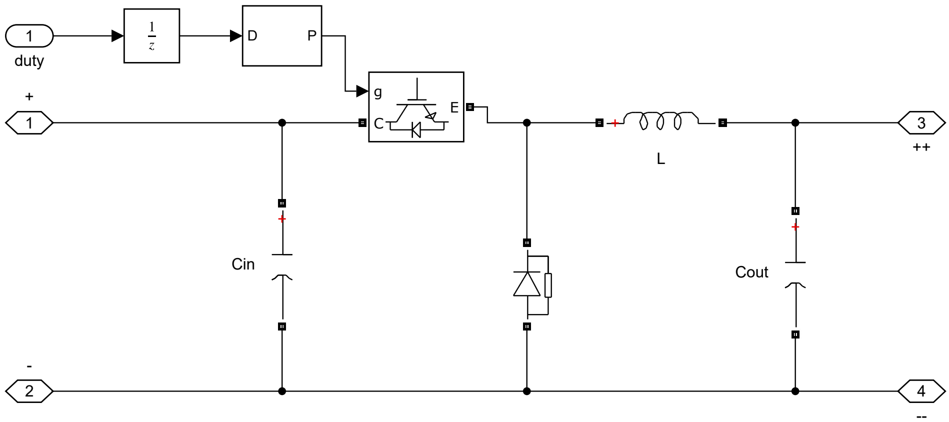


Figure 5.29: Detailed Buck converter model with PWM generator

The switching frequency was set to $f = 50000\,Hz$. This value was chosen as the trade of with having larger capacitors and inductors. The advantage of having a slower switching frequency is that it is possible to simulate faster. The simulation must necessarily be faster than the switching frequency and having a lower frequency is thus advantageous. The idea of making such choices based on simulation speed will be a crucial factor in making design decisions throughout this chapter.

By using Equation 5.20, a duty cycle representing the likely maximum PV voltage produced by the PV field, as described in Section 2.3, and the battery voltage as the output, is computed as:

$$d = \frac{V_{bat}}{V_{MPP}} = \frac{24}{30.4 \cdot 2} = \frac{24}{60.8} = 0.39 \tag{5.33}$$

This duty cycle is used together with Equation 5.23 to find a minimum value for the inductor used:

$$\begin{aligned} L_{min} &= \frac{(1-d)R}{2f} = \frac{(1-0.39)125}{2 \cdot 50000} \\ &= 7.625 \times 10^{-4} F = 762.5\mu F \end{aligned} \tag{5.34}$$

In the above equation the value of R represents an imagined load. Since the goal is to keep the converter within Continuous Conduction Mode (CCM) the size of the inductor is very dependent on this value. By selecting a value that is to large for R the inductor may be selected with a too small value. Therefore the choice of R reflects the smallest load current the refrigerators would have in the model. That would be having one refrigerator running at $21°C$ as this is the lowest temperature indicated in the consumption graph that was shown in Figure 2.4. Equation 5.30 then yields $4.6W$. Under the operating voltage of the battery this equals a load of $R = V^2/P = 24^2V/4.6W = 125\Omega$

To find the value for the output capacitor Equation 5.27 is used together with the previously found inductor value. This gives:

$$\begin{aligned} C_{out} &= \frac{(1-d)}{8\left(\frac{\Delta V_{out}}{V_{out}}\right)Lf^2} = \frac{1-0.39}{8 \cdot 0.005 \cdot 7.625 \times 10^{-4} \cdot 50000^2} \\ &= 8 \times 10^{-6}H = 8\mu H \end{aligned} \tag{5.35}$$

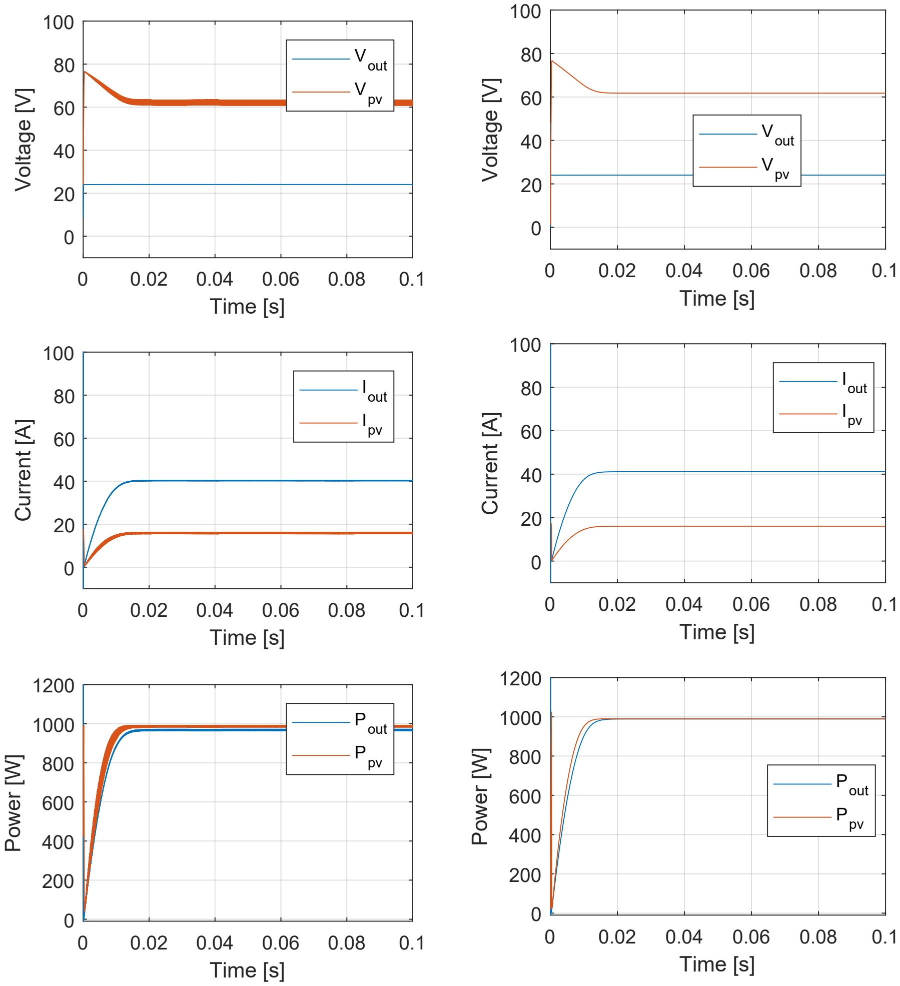
$\frac{\Delta V_{out}}{V_{out}}$ is a design criterion and decides the desired output voltage ripple. Here the output voltage ripple is decided to be 0.5%. The output voltage ripple is not a crucial choice as it will be absorbed by the battery voltage.

The equation for the input capacitor was derived in Section 5.4 which yielded Equation 5.29. This is used together with an input current based on the MPP of the PV field, $I_{MPP} = 2 \cdot 8.24 = 16.48A$. The input voltage ripple ΔV_{in} is set to a fairly high value of 1V. This is fine since ripple on the input side of the converter will not cause damage to the loads as could be the case for the output.

$$\begin{aligned} C_{in} &= \frac{I_{out}d(1-d)T}{\Delta V_{in}} = \frac{16.48 \cdot 0.39(1-0.39)}{1 \cdot 50000} \\ &= 7.841 \times 10^{-5}H = 78.41\mu H \end{aligned} \tag{5.36}$$

Using the PV panel model from Section 5.9.2 with the above DC-DC buck model gave the results in Figure 5.30a. A time step of $T_s = 1e^{-7}$ was used with the ode8 fixed step solver. Using a bigger time step would yield unstable results. It can be seen that the power out from the DC-DC converter is almost the same as that going in. The discrepancy could possibly be resolved by finely tuning the duty cycle with a Maximum Power Point Tracker (MPPT). The delay that can be seen in the settling of the voltage V_{pv} can be attributed to the PV panel model used.

In order to further increase the simulation speed the detailed DC-DC buck converter is switched out for an averaged DC-DC buck converter. This is implemented by using an built-in MATLAB block that is modeled as a switching-function model directly controlled by the duty cycle signal d [103]. This yields a simulation that is approximately 100 times faster than the detailed model. The model is depicted in Figure 5.31. The new DC-DC model is now less accurate, but that is an acceptable price to pay in this application were time is a premium. Figure 5.30b shows a simulation with the same parameters as above, but with a time step of $T_s = 1e^{-5}$. This yields very similar results and at a much higher simulation speed.



(a) Using detailed buck converter from Figure 5.29

(b) Using average buck converter from Figure 5.31

Figure 5.30: Results of a short two short simulations with two different implementations of a buck converter.The PV panel model from Section 5.9.2 and the duty cycle found in Equation 5.33 is employed

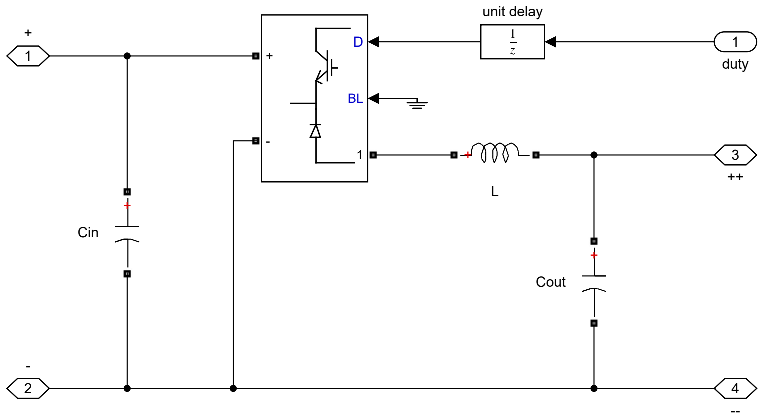


Figure 5.31: Averaged DC-DC buck converter

5.9.4 Maximum Power Point Tracking (MPPT) Model

As already mentioned in Section 5.6 the MPPT plays a vital role in the design of PV based solar power generation systems. The chosen algorithm is the Perturb and Observe (P&O). This is based on its simplicity, computational requirements and its wide use, which is further supported by the argument that it is very likely that this is the approach being used in the charge controller installed in the system to be predicted as discussed in 2.3.1. The flowchart presented in Figure 5.24 illustrates how the algorithm was implemented as a MATLAB script running within a Simulink function block. The Simulink model can be seen in Figure 5.32. A rate transition block is placed between the algorithm and the signal source to account for the different speeds the main model and the algorithm is running at. In Appendix B.2 the code running in the function block is reproduced.

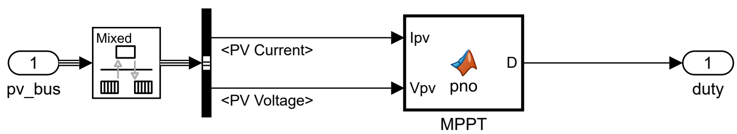


Figure 5.32: Simulink model of P&O MPPT algorithm coded with a MATLAB script

The code follows the flowchart step by step. The parameters are initialized with a first guess, this is chosen as the case when the irradiation is at maximum, and then for each new iteration the duty cycle is changed by a $\Delta d = 0.001$. This result is evaluated in order to make a decision on whether the duty cycle should be changed in the same direction or not. If the previous duty cycle was increased and this yielded a higher power, then the duty cycle will be further increased, if not, the duty cycle is decreased.

Two important parameters must be set in order to have a properly functioning P&O MPPT algorithm operating. These are: the speed at which the MPPT is running, that is the frequency of duty cycle changes sent to the DC-DC converter, and the size of the perturbation. [96] has a very thorough analysis of deciding these parameters. The approach outlined there is a bit too complex and out scope for this project. Instead it was possible to use simple trial and error to tune these to parameters as there is already a restriction at which the MPPT algorithm can run. Clearly it is advantageous to run it slower than the model as a whole, because this requires less computation time. Since the model is running at $T_s = 1e^{-5}$ the P&O must necessarily have a larger time step. The time step of the MPPT was set at $T_{mppt} = 1e^{-3}$ and the Δd was varied to find the above 0.001 to be a good setting. Using a smaller Δd will not yield any tracking and a bigger Δd gives instability and excessive oscillations

To test the MPPT model, step input values for both temperature and irradiation where used. The reason for choosing step changes is that the predicted data obtained for temperature and irradiation based on NASA is given as a value per hour. This was developed in Section 5.1. While it is unrealistic that the changes in temperature and irradiation happen as step changes in the real world, there are no reasons for smoothing the steps as this might in fact yield even more inaccurate results than the NASA values already do. One drawback is that changing in steps yields spikes in the voltage from the PV panel model. The spikes settles fast and will not affect the total power in a significant way. A ten second simulation can be seen in Figure 5.33. The figure also shows the input irradiation and temperature used. The resulting duty cycle looks reasonable, but with some oscillations. Its also worth noting that the duty cycle does not settle all the way back to the starting point when the irradiation returns to full power. This is because the temperature is raised which yields worse performance.

For an input irradiation of $1\,KW/m^2$, which is the case for the first second, the voltage is as expected two times the voltage at the MPP under STC for one panel. From Appendix A.2 this can be seen as $2 \cdot V_{mpp}^{STC} = 2 \cdot 30.4 = 60.8$. Clearly the output current is, and must be, changed by the DC-DC converter in order to be able to set the PV panel voltage. Since the voltage is effectively stepped down from the PV voltage to the battery voltage the current increases from the PV side to the load side.

Figure 5.34 presents the power from two simulations. P_{out} is the power seen by the load side when using the P&O MPPT and P_{out2} is the power produced when the duty cycle is fixed at the optimal $d = 0.39$, given maximum irradiation of $1\,KW/m^2$ and a temperature of $25°C$. As expected the power produced is less than if the MPPT tracker is used. This makes sense given that the MPP is moving with the varying conditions as previously explained in Section 5.6.

5.9.5 Battery Model

The battery model is an important part of the prediction model as this is what keeps track of the battery level, and in the end, that is the most interesting metric for the user. The battery model used was originally the Lead-Acid battery that is included in the Simulink toolbox. This battery is a very detailed model that takes into consideration the different voltages a battery will have given its SoC. The Lead-Acid model does however not take

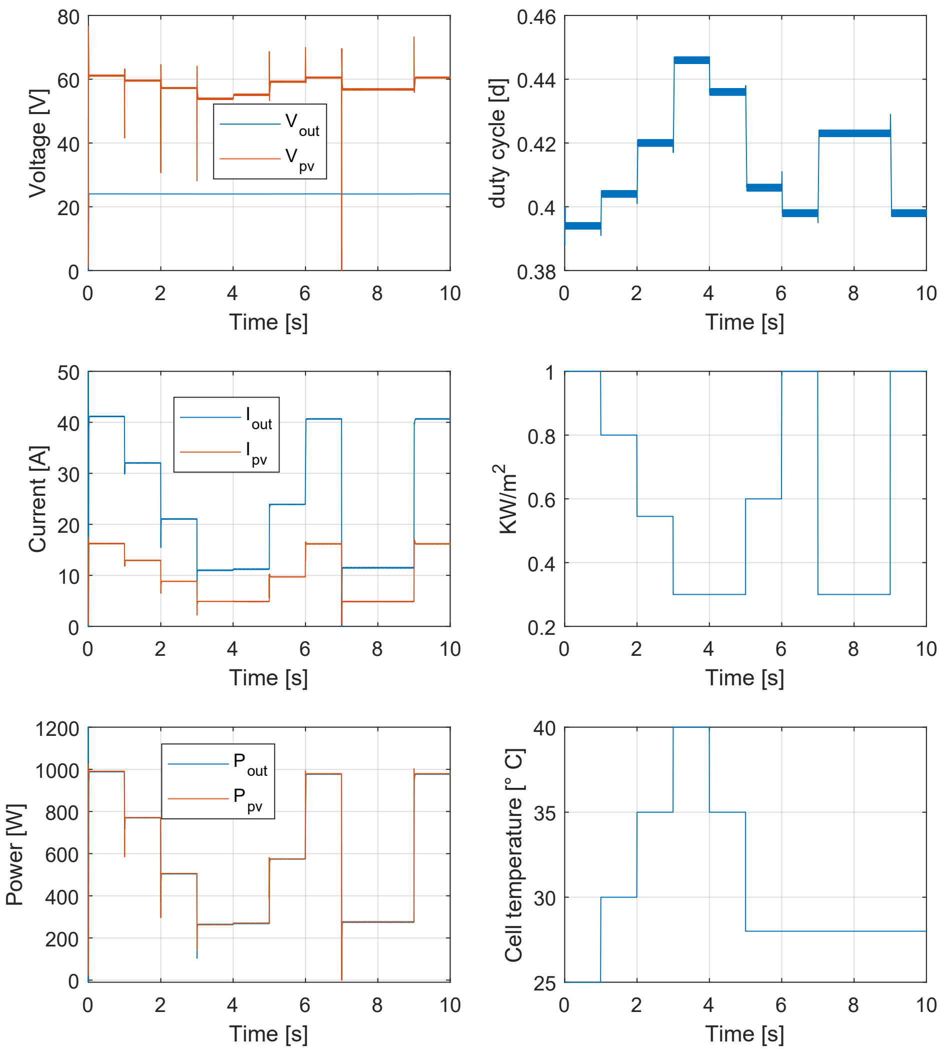


Figure 5.33: Simulation results of using the MPPT tracker

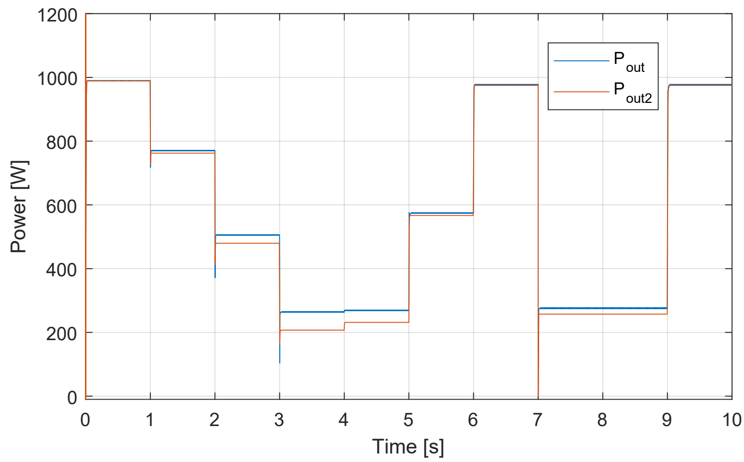


Figure 5.34: Simulation showing the power with constant duty cycle $d = 0.39$, shown as P_{out2}, and using the MPPT, shown as P_{out}

into consideration the effects of deep discharges, temperature and aging. This model was used in the beginning before attempts where made in getting the model to run faster. If the model was to simulate 24 hours of data it would have taken many hours every time a prediction was required. In order to reduce the time it was decided to instead simulate for 24 seconds and then multiply the current going into and out of the battery by 3600 to gain the complete 24 hours.

While this made the simulation run significantly faster it did also make the Simulink battery model useless. The Simulink battery model will only discharge or charge according to the 24 seconds the model is being simulated. Changing the battery to suite the new approach turned out to be impossible because a large part of the model consists of P-code, which is a protected MATLAB script. Such scripts cannot be opened and it is therefore not possible to access the logic within. The fact that it is also impossible to hard-code a SoC change in the battery model during run-time meant that a new battery solution had to be implemented.

A simple Coulomb counter battery was implemented as a replacement for the more accurate Simulink battery. The Coulomb counter battery simply counts the current going to and from the battery. The battery model consists of a voltage source with a current measurement going to a MATLAB script containing the actual Coulomb counter. The Simulink model is shown in Figure 5.35. The script is initialized with the current SoC from the system being predicted as well as the time step of the model and the time difference between simulating in seconds and hours. For simplicity, the battery is assumed to always be operating at 24 volts. The battery capacity in Ampere hours is given by the manufacturer and thus, the maximum capacity is known. The output is the SoC and a battery state set to True if the battery reaches 0%. The MATLAB code can be found in Appendix B.3.

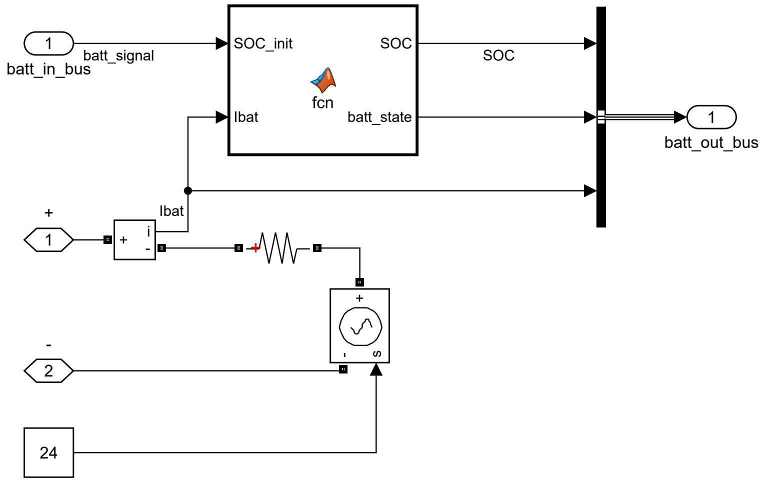


Figure 5.35: Battery Model

5.9.6 Load Model

The goal of the simulation is to use the load profile created in Section 5.8 with the overall model. This requires having a load that can be changed while the model is running. The Simulink toolbox used does not have this capability built in and it is therefore necessary to create a model to accomplish this. The way that seemed to be the simplest was to use a current source controlled by calculating the equivalent current to the resistive load required. The current source takes a signal that can be changed during run time. The model was implemented as in Figure 5.36 and is based on [104].

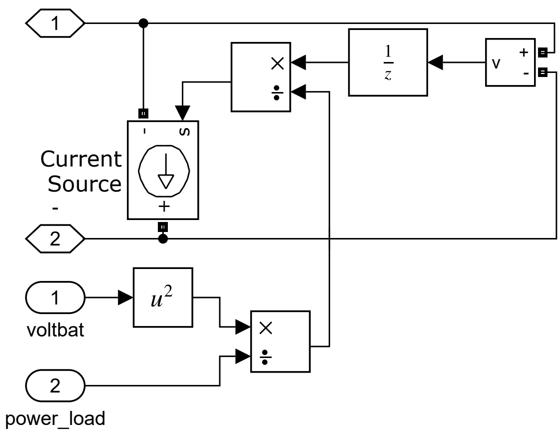


Figure 5.36: Implementation of a variable load based on power inputs from a load profile

Again the unit delay block is used to break an algebraic loop detected by Simulink. In order to use the model, a power signal is feed into the division block. The power is divided by the absolute value of the known battery voltage to gain a restive load value. This is then again transformed into a current value by division with the measured voltage of the load side of the system.

5.9.7 The Whole Model

All the above sub-models models are combined into the Simulink model of Figure 5.37. This model is the top level and shows the available inputs and outputs. The naming of these signals are crucial when c++ code is generated. The outputs are embedded into buses to keep the complexity down. Simulating this model with MATLAB requires the user to connect inputs, and to sink the outputs to a scope, or enable logging. All inputs and outputs have been removed in order to keep the model as simple as possible before generating C++ code.

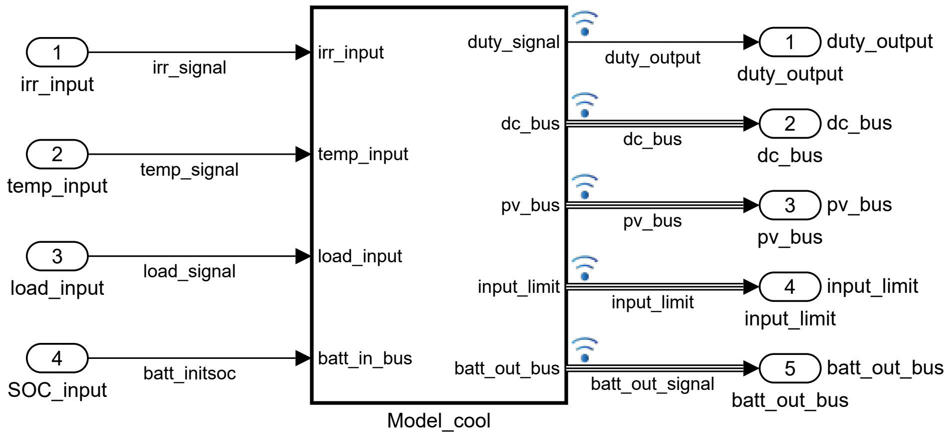


Figure 5.37: Main Simulink model showing the available inputs and outputs

5.10 Implementation on the Raspberry Pi

Implementing the model on a RPi means that C++ code must be generated from the Simulink model. The inputs and outputs of the model must be programmed in C++ as well as the load profile generation based on the inputs.

5.10.1 Generating C++ Code from the Simulink Model

Generating code is accomplished by changing a number of sections. A short summary of the settings that need to be changed in the model preference window is listed below.

- System target file: ert.tlc
- Language: C++
- Check: Generate code only
- Check: Package code and artifacts
- Zip file name: packngo
- Toolchain: GNU GCC Raspberry Pi
- Build configuration: Faster Runs

In addition to these parameters, it is necessary to install Update 4 to MATLAB 2017b, as there is a bug in the base version making code generation fail. Future or previous versions other than MATLAB 2017b might not have this bug. Running the code generation will now yield a large amount of .cpp, .h files and a .mk file. Most of which are cryptic. The main file is called ert_main.cpp by default and is a bare minimum compileable file that does nothing more than develop the environment needed for further code development. The "Zip file name" parameter enables the output of some additional header and C++ files that are needed for the compilation.

5.10.2 Setting up the ert_main.cpp File

In order to run the code like it would in the MATLAB environment, all the inputs and outputs must be defined. The submodels running at different time steps must also be called with the proper time steps. In this case all the models except the MPPT model is running at the same speed. Therefore, a while loop were all models except the MPPT are run at each step and then the MPPT is being executed for each 100 iteration in the while loop. The rate transition block defines how the models should be separated after code generation. That is why all the other submodels can be run with one function call while the MPPT model must be run with another. The main while loop is appended in Appendix B.1. This also shows how external inputs are given to the model. These inputs must be given at each iteration of the loop. This highlights the need of placing names on the signals in Simulink as shown in Figure 5.37, otherwise it is almost impossible to identify which object variable corresponds to which signal in the generated C++ code.

The initialization inputs to the model are handled as an input file that the web interface creates before running the code. This input file consists of six initialization parameters. Each parameter is separated by a new line. The content of each line is shown below.

1. Number of refrigerators to be predicted
2. Hour of day
3. Month
4. Day
5. Year
6. Current battery SoC

The other inputs are naturally the NASA temperature and irradiation data. The temperature data is used for the load profile, while the irradiation data is used for both the load profile and the PV panel model. The irradiation and temperature data is stored as hourly data with one value per one hour of the day on each line. Each day is stored in a separate file with 24 hour date and with a file name indicating the date. Based on the input from the input file, one or more temperature and irradiation data files are loaded into the prediction model.

If the input hour is not at midnight, two 24 hour files will be combined into one 24 hour file based on the hour offset. The combined irradiation file is also returned as a new file since the web interface uses it to display irradiation data along with the prediction results. Since the NASA values are the same for each year, the year input is only used to check if it is a leap year. This is only necessary if the date is February the 28th on a leap year and the hour input is more than midnight. In this case it is necessary to know what the next file to read from is, and it should not move to the next month, but rather to February the 29th.

The load profile used by the prediction uses the temperature from NASA. This temperature is then used as the input for the function developed in Section 5.8. For each of the 24 temperatures, a load total for the same hour is created. This load profile is also given as an output to be used with the interface, in addition to being used in the model.

After running the prediction with the above mentioned parameters, the results are given as two files. One containing a summary of the prediction and another with hourly SoC data. The information of the summary file is given as:

1. Status indicating if SoC reached 0%
2. The time of SoC reaching 0%
3. Final battery SoC

The first output is used to give an indication of whether the simulation reached a 0% battery level. If this is the case then the simulation is effectively stopped as it is not possible to predict how the members of the community will react to a power outage. The second is the time at which the battery reached 0%, and the last is the battery level predicted to be left after 24 hours, given that the requested number of refrigerators are on.

The generation of temperature, irradiation and load profiles where all created in the ert_main.cpp file. This was done so that only one file would need to be changed if the MATLAB model was changed and new C++ code would have to be generated.

5.10.3 Compiling the Code

An executable file must be created by compiling the C++ code. This can be done in one of two ways. Either by using a crosscompiler running on another hardware platform than the RPi or by compiling the code directly on the RPi. The latter was chosen as this is a much simpler procedure, although a little cumbersome with respect to having to move the files to the RPi every-time a change is made in the model.

The prediction model is compiled by utilizing the included makefile. The makefile tells the computer what compiler to use with which files and with what additional options. This is the file with the file ending .mk. The compilation is invoked by navigating to the folder containing the .mk file and running the following command:

```
pi@panelsolar:~/Build/coolingCODE_ert_rtw$ make -f coolingCODE.mk
```

This outputs an executable one directory up with the extension .elf. This file is placed in the same folder as the input files and will produce the output files in the same directory.

5.10.4 Running the Model on the Raspberry Pi

The generated executable .elf file can be executed as a standalone program as long as an input file and temperature and irradiation data are in the same folder. This is how the web server calls the code upon user request. The input file is generated and then the code is executed. The time it takes to run the prediction varies depending on the computational load already on the RPi at that moment. When the RPi is under light load the running time is approximately 7 second, while under strain, the time can increase to around 12 seconds.

Figure 5.38 shows the results of running a typical simulation at 7 in the morning on the 29th of December. The predictor is initialized with a SoC of 30% and running the maximum number of available refrigerators. The plots were generated by logging to a text file in the C++ code and then the data was loaded back into MATLAB in order to generate the graphs. One important conclusion that can be drawn from this example is that the load profile seems to be artificially low. A day in December should be one of the worst sun producing days for the community and when running the maximum load possible from the system it would be reasonable to assume having a decreasing SoC between the start and the finish of the prediction. With the knowledge that the community has been complaining about the system running out of power, it is very likely that the load profile created in Section 5.8 is wrong. The most likely culprit is that the manufacturers usage pattern is very different from that of Calle Santa Rosa. Clearly there is a need for real measurements from the system in order to tune the load profile.

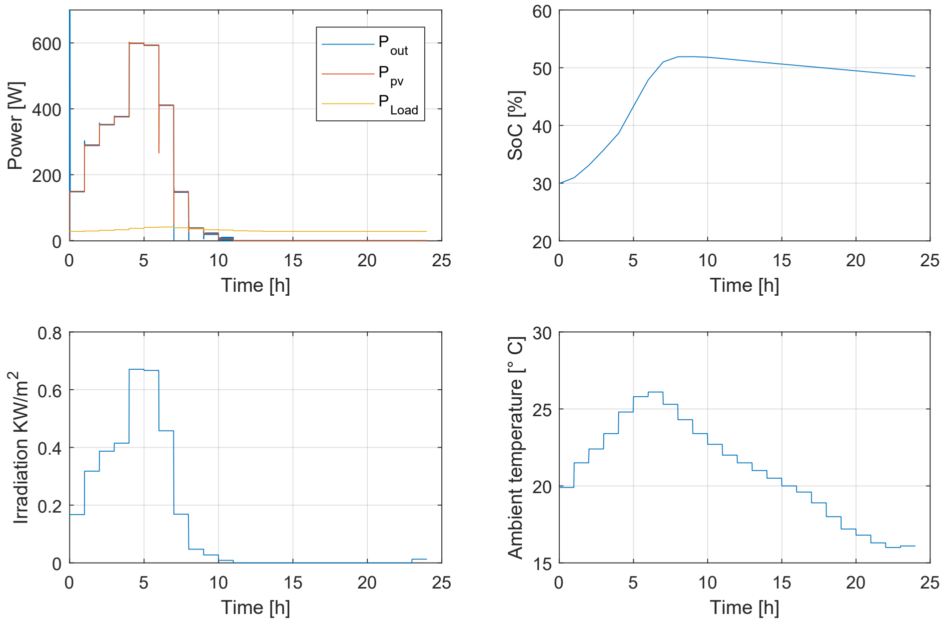


Figure 5.38: Running model on the Raspberry Pi with initial SoC of 30% and with 6 fridges

Chapter 6

Field trip

From 26th of May to 10th of June, a field trip to Colombia was conducted. During this field trip the monitoring system was installed in Calle Santa Rosa. The activities performed and the results obtained during the filed trip will be outlined in this chapter.

6.1 Prior to the Trip

An application was sent to Engineers Without Borders Norway (hereinafter referred to as “IUG Norway”) the 12th of December 2018, to make this thesis a "Master with Purpose". In a "Master with Purpose", IUG Norway collaborate with university professors to enable students to write their master thesis with a humanitarian aspect, and the thesis can be supported financially by IUG Norway if necessary.

The application was approved on the 25th of April 2018, and soon thereafter, arrangements with respect to the field trip could be made. The agreement with IUG Norway included a partnership between NTNU and the La Salle University in Colombia, which entailed that the La Salle Univsity would provide an academic supervisor, Maximiliano Bueno-López, to ensure that proper logistical and security arrangements were made for the students throughout the fieldwork.

In addition, an association founded by supervisor Marta Molinas that operates by applying for funding in realization of renewable energy projects, Ren-PEACE [105], provided both students with financial support with living expenses during the field trip.

6.2 Preparations at the La Salle University

Approximately one week was spent at the facilities of the La Salle University to prepare the activities to be performed in the community of Calle Santa Rosa. We met with the two La Salle students that would support us during the visit to the community, Karen and Alejandro, both students in electrical engineering. They helped translate the User Manual that was to be left in the community to Spanish. They were also introduced to the Installation Manual that contained most of the details about our plans for the activities in the community. In addition they were trained in usability testing because the undersigned would be unable to conduct any usability test with the community members due to the language barrier. In addition, the La Salle current sensors had to be integrated into the system.

6.2.1 Working with the La Salle Current Sensors

The La Salle current sensors were in a worse state than expected. This lead to the sensors being excluded from the monitoring system in the end. There were a lot of signs prior and during the attempt of integrating the sensors that indicated that the sensors were dysfunctional:

- When receiving the boxed sensors, a potentiometer was found loose in the boxes. The circuit drawings in [24] revealed that the potentiometer was a necessary component in the sensor circuit. An image of the sensor is given in Figure 6.1.
- The isolation on the power plug on one of the sensors was damaged, causing a short circuit at one point when experimenting with the sensor.
- Sockets were soldered opposite way in two sensor that were allegedly supposed to be identical.
- As discussed by Lara in [24], the sensors stopped working sporadically and for unknown reasons in his attempt to validate the sensors.

Nonetheless, efforts were made at the La Salle University to try integrate the sensors. An Arduino was bought in order to program the sensors to connect with the monitoring system. In his thesis [24], Lara explains that the microcontroller chip ATMEGA328P was chosen because it can be quickly programmed through the Arduino software and language. The chip was programmed on the Arduino board, and then transferred to the printed circuit board of the sensor.

Originally, it was believed that only the IP-addresses in Lara's Arduino code in [24], page 59, had to be changed, but the code was malfunctional and other changes had to be made before the code would compile. In the end, the sensors were connected to the correct Wi-Fi network. However, the sensor still would not post HTTP requests to read measurements into the database. It is unknown if this problem was due to the software code or due to the electrical circuit being dysfunctional. The fact that the sensor circuit burned the ATMEGA chip twice, which meant that the chip had to be replaced, put an end to any attempt of

Figure 6.1: The La Salle Wi-Fi sensor developed by Lara in [24] to measure current of household appliances.

trying to integrate the sensor with the monitoring system. Our luggage restrictions and the relatively large size of the sensors (approximately 20cm×15cm and 0.5kg) supported the decision of not bringing the sensors to Calle Santa Rosa.

6.3 Installations

The Installation Manual in Appendix G guided the installation process in the community, but problems that had to be solved was encountered along the way. A total of approximately three full days were spent in the community, and around two and a half days were used on getting the system up and running. This section describes the problems that had to be overcome, and thus the compromises that had to be made in the final design solution that was implemented.

Following the installation manual, one of the first things attempted was to connected the RPi to the router that already existed and was used for the collective internet access of the community. The first step is to connect to the router and fix the IP address of the RPi's network interface based on its MAC address. This turned out to be impossible since access to the routers setting were not available as the router is under administrative control by the Colombian government. In addition, the RPi was just out of wireless range of the router using the intended USB Wi-Fi adapter. The extra powerful backup Wi-Fi adapter brought for such an event was unfortunately damaged in transit. The backup Wi-Fi solution that uses the built in Wi-Fi module of the RPi was thus instead used as the primary Wi-Fi connection. This has a more limited range and allows much fewer simultaneous connections. Figure 6.2 shows one of the team members in the installation process in the refrigeration center.

Figure 6.2: Installation Process in the refrigeration center

Installation of the sensor proved troublesome as a damage in transit between Norway and the community had occurred. This was believed to be damaged resistors which would have been difficult to get repaired as we only brought a very limited supply of tools because of stringent luggage restrictions on one of the air crafts. In the end it turned out to be a short circuit that was easily remedied. The sensor could be installed directly in the fuse box as there was space to clamp it around the load wire. The space in the fuse box did not accommodate the small inverter needed to power the RPi and the sensor. Thus, a hole had to be drilled through the fuse box, allowing the RPi and the inverter to be placed on the outside. This was also advantageous for providing the Wi-Fi network with the maximum possible range. The community did not have a suitable drill bit and we had not foreseen such a weather tight fuse box. The solution was to travel to the closest village which luckily had a drill bit that could be used. All of these installations difficulties meant that we were far behind schedule.

When the system was finally up and running and it was time to take measurements to be used for calibrating the load profile of the refrigerators, the system ran out of battery and shut down. This reduced the time available for measuring, analyzing the loads and adjusting the load profile to a few hours before departure the next day, when the sun provided power to the system.

The adjustment of the load profile had to take into account the revelations about the use of the refrigerator center discovered once in Calle Santa Rosa. It turned out that some of the refrigerators were used as freezers by switching the thermostat of the refrigerator to the coldest setting. A freezer uses more energy than a refrigerator, so the number of freezers and number of refrigerators had to be accounted for when measuring the real load.

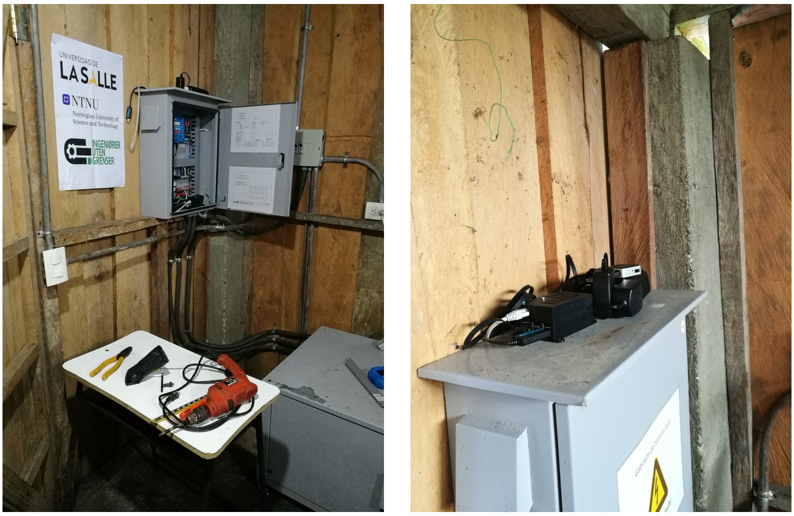


Figure 6.3: The monitoring system was installed inside the refrigerator center. The fuse box is showed to the left, and the equipment of the monitoring system was installed at the top of the fuse box as showed in the image to the right.

The software implemented worked as intended after installing the system, but changes related to the use of both freezers and refrigerators in the community also had to be made in the web interface.

6.3.1 Adjusting the Load Profile

As suspected the pre-calculated load profile was assuming a much lower load. A good option for measuring the real loads would have been to perform current measurements in the community using a Fluke network analyzer, but luggage restrictions prevented us from bringing this type of heavy equipment. The other option was to use the current sensor we brought, however, the time was very limited and the person responsible for the refrigeration center did not have the authority to let us turn of any fridges for an extended time. In order to get some measurements, we were allowed to turn of all except one fridge for a short period of a few minutes. Since one of the fridges was operating in freezer mode this fridge was kept running and the rest were turned off. After measuring for a few minutes the other fridges were turned back on. And the measuring was continued, but now with all units turned on.

Figure 6.4 displays the measurements being made in the short time available. The current data and voltage data from the blue solar was exported from the SQL database and imported into MATLAB for plotting. The sensor data is noisy as expected. The manufacturer claims a 1% accuracy and this more or less corresponds to the results we are seeing. In order to visualize better, a smoothed version is included. This smoothing was accomplished by using a first order Savitzky-Golay FIR smoothing filter with a window size of

31 seconds. It is clearly possible to see the switching nature of the compressor motors used in the fridges. This explains why there are multiple levels of current consumption. The refrigerators are not synchronously turning their compressors on and off. The power consumption is found by multiplying the current with the voltage for each measurement. In the measurement period the voltage linearly increased from 24 to 27.35 volts.

The signals before only the freezer was running is not a part of the controlled experiment and will be ignored. The green circle shows the measurements done while only the freezer was on. The freezer had been continuously on before the fridges were turned off and it is therefor assumed that it was in a stable operating mode. By turning the thermostat to maximum, as the community has done with the fridge, which is here being refereed to a freezer, means that it will almost always run its compressor. Thus the average of this measurement is taken as the freezers power consumption. After a few minutes the remaining fridges were turned back on and the current reading increased to what is seen in the pink circle. The fridges that had been of until now are now all running their compressors and are synchronously drawing power. This is followed by a period where the fridges are turning off again and slowly getting out of synchronization. This is marked by the black circle. The readings after the black circle is what is used to calculate the consumption of a fridge. The average of the power is taken and the previously found freezer average is subtracted. This yield the average power for five fridges. Dividing by five gives an approximation for the consumption of one fridge.

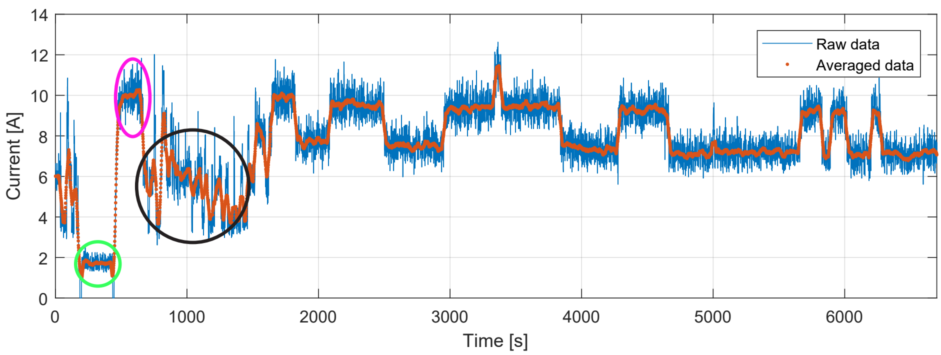


Figure 6.4: Current measurements from the refrigerator center. The measurements before the green circle are of unknown origin as the sensor was connected and disconnected repeatedly. The green circle shows the measurements of just the freezer. The pink circle shows all the refrigerators and the freezer being on. The black area shows the motors switching off.

Since there were now two different operating modes with vastly different power consumption, a second load profile was created such that the number of fridges and freezers could be set individually. The profiles were edited by multiplying with a constant factor to the power consumption calculated in the original load profile. Due to the much higher temperature in the refrigerator center than outside it was also decided to add a constant temperature offset to the load profile such that the differences between the temperature prediction provided by NASA and the hot refrigerator room would be better accounted for. The temperature at 09:00 to 11:00 on which the measurements are based was approximately 26°C.

The load profiles were then created by changing the temperature used and the multiplying factor until a result which yielded a good fit was found.

Unfortunately we forgot to bring a temperature sensor for measuring the temperature inside, but it was considered to consistently be much hotter than outside and it was therefore set to $5°C$. The average freezer power consumption was calculated to be 41 watts. The fridge average became 34 watts. The corresponding multiplication factors where then found to be 4.5 for the freezer and 3.5 for the fridges. This resulted in the load profile from Equation 6.1 for the refrigerators and Equation 6.2 for the freezers.

$$P_{fridge}(T) = \frac{0.491 \cdot (T+5)^2 - 13.26 \cdot (T+5) + 173.2}{24} \cdot 3.5 \tag{6.1}$$

$$P_{freezer}(T) = \frac{0.491 \cdot (T+5)^2 - 13.26 \cdot (T+5) + 173.2}{24} \cdot 4.5 \tag{6.2}$$

To visualize the difference in the load profiles, the same simulation as that from Chapter 5 with the old load profile was ran. This time the input was five fridges and one freezer, the result can be seen in Figure 6.5. It is quite obvious that this yields a much more realistic result than before, given the low irradiation and the fact that the system recently ran out of power with similar settings. The SoC has now slightly decreased instead of having a large increase, as was the case with the old load profile.

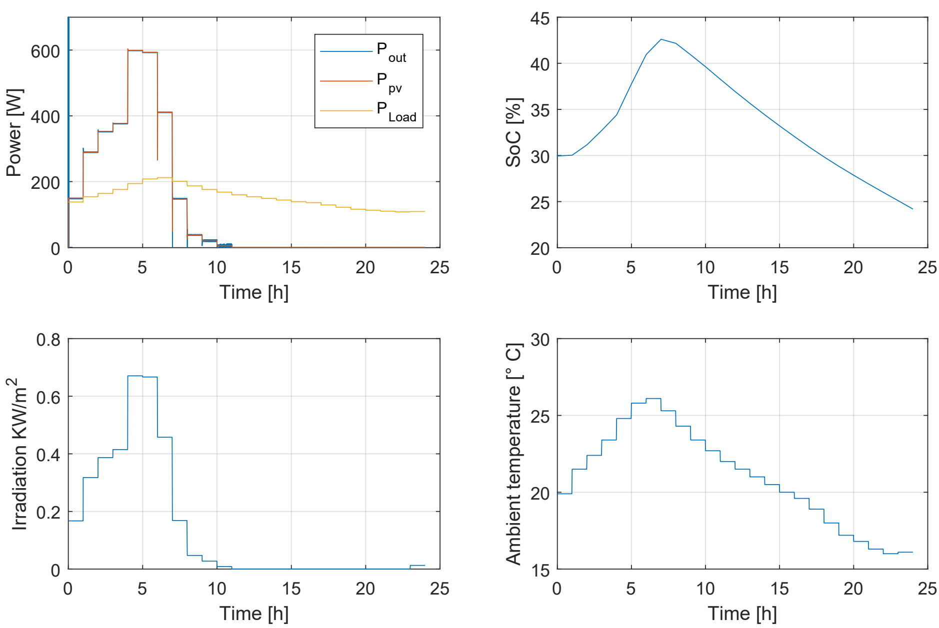


Figure 6.5: Running model on the Raspberry Pi with five fridges, one freezer and with initial SoC at 30%

6.3.2 Final Version of the Web Interface

It was through conversations with the primary user of the monitoring system, the salesman in the refrigerator center, that it was revealed that some of the refrigerators were being used as freezers. The salesman of the refrigerator center also expressed that he would prefer to use more than the current two refrigerators as freezers, but the lack of any informaion on the refrigerator center's energy status made it difficult for him to experiment with anything beyond the recommendations he was given in 2015. A new design for the prediction page was proposed and shown as a paper prototype to the salesman to check whether the new solution would accommodate his needs. The prediction page was thereby changed to give him a tool he could use to evaluate if he could turn on more freezers. This illustrates the importance of user involvement and how new information drives the human-centered design process from one iteration the the next.

The changes that were made were the following. The new prediction page is given in Figure 6.6, and it was changed from the way it looked like in Figure 3.9 in the previous iteration of the design. The user has to select the number of freezers and refrigerators. To the left in the Figure 6.6, it is shown what the page looks like on a computer, before any numbers are selected. The image to the right shows what the page looks like on a smart phone and with numbers selected. Then the Enter button is enabled such that the user is able to run a prediction. It was also discovered that without being connected to the Internet, the clock of the RPi would deviate and not be correct, and for this reason, the labels of the graphs was changed to be "1 hour ago", "2 hours ago" etc., instead of the stating the corresponding hour the measurement belongs to, as showed in Figure 3.7. These changes summarizes the final iteration of the human-centered design process and the final version of the web interface developed.

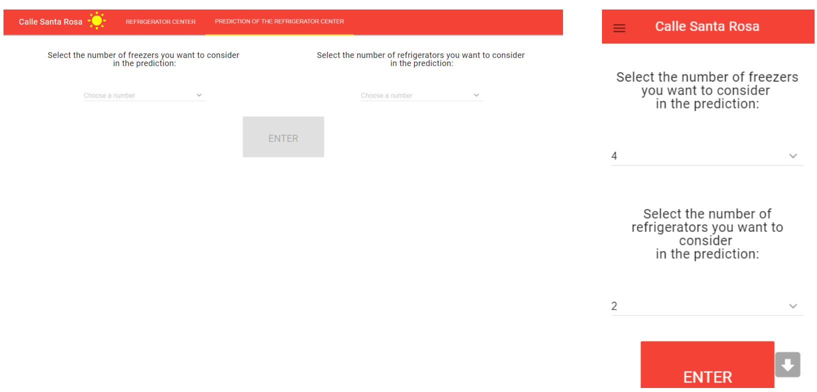


Figure 6.6: The prediction page where the user has to choose a number of freezers and a number of refrigerators to run the prediction for. How it looks on a computer is displayed to the left and on a smartphone to the right.

6.4 Usability Testing in Field

The web interface was tested in a usability test to evaluate the final design version against the usability objectives put forward in the usability requirement specification (see Section 3.4). It was the final version of the web interface presented above that was tested. Following the framework for usability testing in Section 3.6, the usability test in Calle Santa had been planned with the following goals and hypotheses:

Goal: To test the usability objectives, the measurable usability performance and satisfaction criteria specified in the user requirement.

Hypothesis: Many of the objectives will not be met because it is hard to estimate the level of expertise of an indigenous population you have never met, which also resides in a different country, and a smartphone will have a display that is too small to meet the objectives.

A test plan was made beforehand in which tasks had been written and translated and the number of users to be tested had been decided to be five (according to Nielsen's theory in [21]) Preferably five community members that work with the refrigerator center on a daily basis (the Energy Cooperative). Once in the community, the following test users were engaged:

- The administrator of the Communication Technology Center (see Chapter 2) in Calle Santa Rosa, which is equipped with computers and the Internet granted by the government.
- The salesman of the refrigerator center.
- One among the most skilled community members in communications technology.
- A woman that worked as a chef in the neighbouring community building.
- The school teacher and the administrator of the solar panel systems.

The limited Wi-Fi range of the RP's built-in adapter meant that the web interface could chiefly be accessed when inside the refrigerator center, in which the community member would only have access to a smartphone, not a computer. All test users tested the interface on a smartphone to make the test situation as close to the intended real use of the product in the usability test.

There was a big difference between the skills of the participants. The school teacher was undoubtedly more familiar with graphs than the rest and solved the tasks faster than the others. The woman that worked as a chef had very little experience with communications technology, and the usability test turned more into a training session. Pictures of the usability test performed in Calle Santa Rosa is showed in Figure 6.7.

A special observation form was crafted to ease the data gathering for the La Salle University students during the usability test. The two La Salle students supporting us in Calle Santa Rosa had to take the role of both test leader and observer due to our lack of Spanish speaking capabilities. The observation form is provided in Appendix C. The usability

Figure 6.7: The result of a prediction page. How it looks on a computer is displayed to the left and on a smartphone to the right.

performance and satisfaction criteria were transformed into check boxes and questions the students could answer during the usability test so the results could easily be related to the usability objectives.

6.4.1 Test Result for Web Interface Accessed by Smart Phone

The results of the usability test related to the usability objectives put forward in Section 3.4 is presented in the following.

The usability objectives related to the third task expired because the electrical status of the school was put out of the scope of the web interface due to the defective state of the La Salle current sensors.

The usability objectives related to the fifth task, Extended Use, is out of the scope of this thesis because these usability objectives require either long term monitoring of community, or that procedures for the community to report on the use of the system is established. The Extended Use task was included to illustrate how to write usability objectives for long term usage of a product. In the usability test, the test users were instead asked whether they could see themselves using the web page in their work and if they thought the Energy Cooperative should use the interface in their work.

Of the 15 usability objectives that are considered still valid, four of them were not met. Two test users typed the wrong URL, and two test users (not the same ones) were dissatisfied with how the web page was accessed. This was due to the fact that the web page was accessed by typing the correct IP-address (192.168.4.1 in the community) into the web browser instead of the human-readable host names (such as www.google.com) that they were more used to. It is also worth noting that two of the participants used a smartphone for the first time. However, two of the test users accessed the interface by downloading the app, developed in Section 4.3.4, instead. Both of these users reported satisfaction with this way of accessing the interface.

The remaining two usability objectives that were violated was due to the fact that one test user was unable to answer correctly what the energy production of the previous hour was in the refrigerator center, and another test user reported dissatisfaction with how easy it was to find the prediction page. However, referring to the first case, the test user was admittedly able to get the correct answer to the next question, which was the energy *consumption* of the the previous hour in the refrigerator center, after having received some guidance.

Web page access

<u>Effectiveness:</u>
Accuracy: 2/5 typed the URL wrongly the first time.
Completeness: The web site was displayed every time the correct URL was typed.
<u>Efficiency:</u>
The web site loaded within two minutes every time.
<u>Satisfaction:</u>
2/5 test users reported dissatisfaction with how the web page was accessed.

Refrigerator center's electrical status

<u>Effectiveness:</u>
Accuracy: All test users found the right web page.
Completeness:
1) All test users answered correctly what the battery state was.
2) 4/5 test users answered correctly what the energy production the previous hour was.
3) All test users answered correctly what the energy consumption the previous hour was.

<u>Efficiency:</u>
None of the test users used more than 2 minutes to find the right web page.
<u>Satisfaction:</u>
All test users was satisfied with how easy it was to find the web page for the refrigerator center's status and with how easy it was to read the energy production and consumption.

Prediction

<u>Effectiveness:</u>
Accuracy: All test users found the right web page.

Completeness: All test users was able to run a prediction successfully.

Efficiency:

All test users used less than five minutes to produce a prediction

Satisfaction:

1/5 test users reported dissatisfaction with how easy it was to find the page for prediction. All test users reported satisfaction with how easy it was to run a prediction.

Extended use

The salesman in the refrigerator center expressed that he found the web interface very useful when asked if he would use the web interface in his future work when deciding the number of freezers and refrigerators he could have running, despite the fact that he had never used a cell phone before. The community's school teacher and administrator of the solar panel systems when he was asked whether he thought the web interface could be useful in meetings when deciding upon the operation of the refrigerator center. He believed the interface will be very important for them because it allows them to know the appropriate level of the batteries.

Chapter 7

Discussion

This project is an interdisciplinary one, including system modeling, sensor selection, and software system architecture. Many of the topics that were treated or touched upon were unfamiliar to the authors and led to a very steep learning curve. This is a necessity when the end goal is an actual product comprised of many different technologies working together. The downside is that it is unfeasible to cover all topics in great detail, and that some simplifications had to be made in order to make it all come together. A discussion of the necessary details related to this is provided in the following.

7.1 The Human-centered Design Approach

Human-centered design stress the importance of continuous involvement of the users. With the real users located in a remote country and also inaccessible in the sense of communication technology, the prerequisites for implementing the Human-centered design process were not optimal. Nevertheless, it was desirable to include the methods of HCD to increase the possibility of creating a product with high usability. Admittedly, one is not guaranteed to obtain a successful product simply by following the guidelines of ISO 9241-210. However, it increases the likelihood of product success in a number of aspects, such as improving user experience and reducing discomfort and stress when using the product, according to [18].

It is important to note that it should not be expected that the usage of interaction design principles in this thesis reflects the novelties of the research field, as the usage is one of novices. This project was used by the authors as an opportunity to put principles of human-centered design into practice for the first time. However, the best of efforts were made in order to incorporate the fields practices into the project, due to the belief that this would only enhance the quality of the product further.

The level at which the Human-centered design process was implemented can be disputed. For example, the ISO standard 9241-210 provides a sample procedure for assessing applicability and conformance with the process (Annex B in [18]), but this was considered outside the scope of the case study. Further, inspection-based evaluation methods in which usability experts put themselves in the role of a user to investigate how the interface complies with design heuristics, is by ISO 9241-219 considered one of the most widely used approaches to user-centered evaluation. Also this was decided to be outside the scope of this thesis, although it is indisputable that evaluation of the interface by usability experts would only have increased the usability of the interface. Simply put, compromises had to made in order to make sure the time limit of the case study was adhered to [2].

Admittedly, human-centered design is concerned with addressing the whole user experience, which goes beyond measuring usability. In [16], Preece et al. define user experience goals among the primary objectives for an interactive product, and distinguishes between desirable and undesirable aspects, e.g. that the product should be enjoyable and not boring to use. Preece et al. use several categories (functional, data, environmental, user characteristics, usability goals and user experience goals, more details can be found in [16], p.353-360) to identify what they claim are key requirements for a product, but does not provide a formal framework as the one used to specify the usability measures from ISO 9241-11 [17]. The user requirements specified as a part of the Human-centered design process in this thesis was limited to only include measurements for usability, which was yet another compromise that was made.

With respect to the usability testing, it was detected that a number of five test users did not enable a sufficient distinction in order to evaluate whether the usability objectives had been met. For a lot of the objectives, a ten percent limit had been set. For a number of fives test users, that means none of the test users could fail or report dissatisfaction for the usability test to be successful. For example, only one of the test users reported dissatisfaction with how the interface could be accessed, but this lead to a dissatisfaction rate of 20 %, meaning that the less than 10 % dissatisfaction limit was not met, which may be misleading as it was in fact only one individual that reported dissatisfaction on that matter. The solution to this problem is unclear. A smaller distinction rate than 20 % is desirable, but increasing the number of test users would also increase the time and effort it takes to conduct the usability test, and Nielsen argue in [21] that usability testing with more than five test users is a waste of resources.

One principal of the human-centered design listed in [18], that has yet to be mentioned, is that the design team should include multidisciplinary skills and perspectives. ISO 9241-210 lists ten skill areas that could be needed in a design and development team. To mention a few, this includes user interface expertise, business analysis, user management and hardware and software engineering. With the nature of how a master thesis is performed, experts within each required skill area could naturally not be engaged. Instead, the authors had to take the expert role in all the domains required in the design team, hoping that the width of our interdisciplinary research field, cybernetics, had provided us with the sufficient tools to embark on a project of this type. Both students obtained a good understanding of the context of use, although the development of the electrical model could admittedly have been completed without great knowledge of the customs of the community. This enabled discussions and allowed at least more than one person's perspective to be included in the end delivery.

7.2 Hardware Setup

The hardware that was opted for performed reasonably well and more or less as expected. However, some issues with the hardware occurred, and these will be explained in the following paragraphs.

The RPi had enough computing power to run both the web-server and the prediction at the same time. Using the RPi as an access point would put a lot more strain on it, so the number of simultaneous Wi-Fi connections was limited to five. During the implementation phase back in Norway, two of the RPi's USB ports broke. Knowing that the RPi is a widely used product and is in general considered reliable, it was decided to replace it and assume that this was a hardware issue that would not repeat itself.

During the installation of the monitoring system in the community, there were issues with the Wi-Fi range of the intended Wi-Fi adapter. The goal was for it to connect to the router used in the school, but the router turned out to be just out of range for the adapter. The fact that the powerful spare Wi-Fi adapter did not work either made it difficult to achieve the originally intended installation explained in 4.2.6. This made the secondary problem of not having administrator access to the router less of a problem. This was however a problem that had not been thought of beforehand. In retrospect it makes sense that the government would prefer to control the assets handed out through a governmental aid program. Doing better research on this topic should have been done. It was however difficult to obtain as such information from a community where the required knowledge for answering technical questions is lacking.

Having actual Internet connection on the RPi was never considered to be very likely. This is why the web-server was designed as a local network solution. Disregarding the security aspect and the fact that the RPi is limited to the number of HTTP requests it can serve simultaneously due to its computational power, it would not be much work to make it available over on the Internet if Internet access proved possible. This would have given the opportunity to access the database and monitor the data being collected. Having access to the measurements would mean that updates to the prediction model could have been deployed after leaving the community. Even if the Wi-Fi range problem had been solved, this might not have been a possibility as the Internet access from the CTC in the community is based on entering codes into a captive website. These codes only have a short validity period of a few hours based on the amount of money payed for each code. It might have been possible to call someone responsible for the governmental Internet solution and make sure that the RPi would have had permanent access, but it was never attempted because the RPi was out of range anyways.

Although the data sheet of the Aims Dynamic AIMH021 DC current sensor [62] states that the sensors yields no offset, an offset was experienced when testing the sensor in Norway. A power generator was used to feed a known current through the opening of the sensor, and the respective measurement was read into the RPi using the Raspio Analog Zero ADC. The average current measurement based on 200 measurements for eight different amplitudes each, ranging from 1-50 A, was calculated. A current offset of 0.55 A was identified. The extent to which the offset is environmentally dependent is unknown, since it was not possible to bring the equipment necessary for a similar analysis in Calle Santa Rosa. It is also not known whether this offset is solely due to the sensor. Inaccuracies to the measurements may have been introduced by the Raspio Analog Zero ADC converter. Nonetheless, the current offset detected in Norway was included in the Python scripts for current measurement readings in Calle Santa Rosa.

7.3 Software Setup

In this section, the most important aspects of the software implementation will is remarked. First, considerations on how energy calculations was made in the system will be presented. Then, the experiences of using Material Design Lite as the front-end framework and Highcharts as the JavaScript charting library is discussed.

One important aspect to mention when talking about the software setup, is that assumptions were made in the calculations of the energy consumption. Energy production and consumption is an accumulation of power over time, but the current sensors and the controller in the system provide only instant measurements of the current and voltage. The energy produced and consumed was calculated by assuming constant power from one measurement reading to the next. Energy calculations for the refrigerators was easy, because the time interval of how often the current measurements from the DC current sensor should be read was determined in the Python script. A time resolution of one second was decided, and the power was considered constant in this second in order to calculate the energy consumption ($energy\ consumed = current\ power \cdot 1/3600\ hours$).

The calculation of the energy produced by the solar panels was not equally simple. The data sheet of the communication protocol [70] promised a one second interval between the data blocks, but it was observed in the database that the time interval was irregular. Thus, the time of the previous update had to be retrieved from the database in order to calculate the energy production of the solar panels ($energy\ produced = current\ power \cdot time\ since\ last\ update$). However, this introduced a problem. In the case of the charge controller malfunctioning and not sending data for a period of time, or if the RPi was shut down for a period of time, the time from one database update to the next would grow large and possible lead to a huge energy production update. To avoid this problem, it was included in the code that the database would not be updated if the time from one update to the next was more than ten seconds.

Using the Material Design Lite front-end framework had its pros and cons. It was a great way to get a website up and running in a short period of time, but the grid it includes for page layout was experienced as restrictive later in the design process when trying to comply with the specific needs expressed by the test users. Using plain CSS, which is still one of the most popular approaches to styling web pages [53] and offers the Flexbox module [106] for page layout, should possibly be considered.

The Highcharts JavaScript library is highly recommendable. It exist a vast number of JavaScript charting libraries. Higcharts was chosen because it was the library used to make the monitoring platform in [24]. It was experienced as a greatly flexible graph library. The library did not lack support for any of the changes to the functionality that was desired. It is easy to use and learn as long as the user is already familiar with JavaScript.

7.4 MATLAB Modeling

The choice of using MATLAB was great as long as the goal was to get a simulation to work. In the beginning of the modeling, it was not yet decided that an RPi would be used to run the simulations of the model, and to get the simulations to run on the RPi proved to be a lot more work than if a computer would have been used. Partly because there are a lot of restrictions on how a model can be built in order to use C++ code generation, as discussed in Section 5.9.1. These restrictions are poorly documented as they also depend on what architecture the code should run on. This resulted in a lot of trial and error to get a model to work both in the normal simulation environment and also as code on the RPi.

A substantial amount of work has to be done each time a change is made to the model. Code must be generated and transferred to the RPi. Some additional C++ library files needs to be manually added to the generated files. The generated main file has to be edited each time as the content is mostly dummy data, but occasionally small things seem to change between two iterations of the model. After that, everything has to be compiled. This is quit laborious in the long run. The reward is code that runs quite fast, which in the end is the most important. Some differences were also noticed in the results from running the code in the MATLAB environment and on the RPi. Although the differences were not big, it is enough to question the accuracy of the conversion process.

Unfortunately, MATLAB is not open source software and in this project, where all the other software components are, it might be better to use an open source alternative in order to truly make the system affordable and reproducible.

PV Model

The PV model was an essential component in the electrical modeling. The white paper of the solar panels to be modeled did not provide all the information needed to model the panels using the script from [100]. This lead to the usage of MATLABs model for extracting additional parameters. In the end, MATLABs model was used as a measure of the implemented model accuracy, but it is obviously not the most desirable comparison to make. Having a real data set or I-V curves from the manufacturer would be the ideal scenario.

The data from NASA was based on data from 1985-2005, and to base the model on more accurate real-time measurements taken at the site would obviously yield more accurate prediction results. This has the drawback of requiring measurements over time using expensive equipment.

MPPT model

The MPPT model that was implemented uses voltage and current measurements directly from the PV panels. [96] argues that using the measurements from after the DC-DC converter would help capture the dynamics of the DC-DC converter. Then, the power would be maximized based on what the load sees and not on what the PV panels can produce. While this was not attempted here, it might be a point for improvement of the overall model.

Load Profile

The load profile was adjusted according to the data that was gathered from a very short time window, approximately two hours in total. Ideally, the current and voltage measurements would extend over a whole year together with temperature data from inside and outside of the refrigerator center. This would provide the foundation for a more precise load profile. If the openings and closings of the refrigerators could be measured along with the mass of new food added to, and cold food removed from the fridges, then an even better model could be created. This could possibly even capture usage patterns related to seasons for fruit harvesting and fishing.

Model Verification

Proper model verification was not performed. This could have been done by collecting data from the system for 24 hours and then compare the predicted results with the real measurements. An improvement on this could be to measure the incoming global irradiance using a pyranometer and use this as the irradiance input, while at the same time measuring the temperature in the refrigeration center and use this as the temperature input. The plan was to attempt the first procedure. It was also considered bringing a pyranometer, but in the end as little equipment as possible had to be brought along due to luggage restrictions.

Battery Level Limit

The recommended minimum battery level line that is set in the interface is intended to show the operator of the refrigerator center that going below this battery level can be damaging for the batteries. The hope is that this will prevent the community from letting the batteries run completely empty or close to completely empty, as this is highly damaging for the longevity of the batteries, as discussed in Section 5.5 and in [15]. The limit was set to 50% as this is the lowest DoD recommended. The effects of the DoD on the specific batteries being used can be seen in Figure 2.5. The difference between a 30% and a 50% DoD limit is almost 800 cycles. This is a significant difference in longevity. The best would therefore be to set the limit at 30%, but with the knowledge of how they use the system and with the fact that it was designed with an autonomy of only four days, it is a bit extreme. It is unsure whether it is possible to keep the batteries above 50% at all times. It might cause them to have to run fewer refrigerators than what they wish or have been doing so far, but it would mean that their system will last longer. Replacing the batteries is expensive. Hopefully, setting a visual limit for them might improve the longevity of the batteries.

7.5 Open Source Support in Rural Electrification Projects

Support for open source communication by the producers of photovoltaic system equipment seems to rather be the exception. The open source communication protocol by Victron Energy, explained in Section 4.2.5, was a contributing factor when choosing which of the village's photovoltaic systems to monitor. It was experienced as an necessity in the development of an affordable monitoring system for Calle Santa Rosa, which will be elaborated in the following.

The communication with the Outback controller in the school building, which can be read more about in Section 2.3.2, depend on a proprietary communication protocol that one has to buy system management devices from Outback to make use of. This seem to be the more traditional approach among the producers, and the company's system management devices are often expensive. The system management devices from Outback [107] all cost more than $200, whereas less than $45 dollars was paid for the VE.Direct to USB interface cable that was required to make use of the open surface protocol of Victron Energy.

Thus, in our viewpoint, open source support should be an important concern when choosing equipment for a microgrids and photovoltaic solar system. It facilitates the development of alternative, more affordable monitoring solutions that can enable owners of microgrids in rural areas to utilize the microgrid to the fullest.

Chapter 8

Conclusion and Future Work

A monitoring system for a PV solar energy production system was developed and implemented in an indigenous community, in rural Colombia, the Calle Santa Rosa Indigenous Community. The main objective was to provide decision support to the local community to they could better exploit their micro-business. The monitoring system was designed and implemented as a joint project between Norwegian University of Science and Technology and the La Salle University in Colombia [2].

The fact that the monitoring system was successfully installed shows that development of rural electrification projects need the use of technology in different fields, and alliances between countries (in this case Colombia and Norway) can support this development. This is a promising result because speed of growth of rural electrification projects can be increased when the development can happen in collaboration with developed countries where the level of technical knowledge is higher.

The Human-centered design process from the ISO standard 9241-210 was used to overcome the cultural differences between the developers and the users, and served as a great tool to guide the work process and to keep the community's needs at the center of the case study. However, the case study also shows the importance of including the real users [2]. Most of the satisfaction criteria put forward in the monitoring system's user requirements were met in a usability test performed in the community with the indigenous.

A Raspberry Pi was used to host the web interface locally in the rural area. It served as a great tool throughout the case study as a lightweight computer that is affordable, which was a contributing factor in making the overall monitoring system cheap [2].

The entire code base can be consulted by requesting it from the authors. The focus of the thesis is not to provide the exact details of the code written, but to rather convey the steps taken and the different kind of scripts needed when implementing the monitoring system. This consideration applies particularly to Section 4.3, where the software of monitoring system is accounted for.

8.1 Future Work

Most importantly, follow-up of the operation of monitoring system installed in the Calle Santa Rosa Indigenous Community is a necessity in order to evaluate the success of the project. The latest update received was that the monitoring system was still functioning three days after our departure.

For future rural electrification projects of this type, in which a human-centered design approach is adopted, user experience designers should be engaged to give some validity to the methods and techniques applied. The undersigned where novices in the field of interaction design and applied the principles of human-centered design to the best of their ability. The first step towards increasing the validity of the interface developed in this project would be to conduct inspection-based evaluation methods with usability experts. In inspection-based evaluation methods, usability experts evaluate the interface, identify usability problems and thus provide recommendations on how to increase the usability of the interface.

Getting access to the data in the database that is being collected in Calle Santa Rosa could potentially be used to improve the prediction model. The data might reveal a need to add losses in the DCDC converter and could possibly highlight the need for an update of the load profile. Also, it might be beneficial to change the software used for modeling to an open-source alternative in order to reach a wider audience. This would require a complete rework of the prediction model. Work could also be put into improving the battery model as this is currently a very simplified model. Installing a new, working, powerful Wi-Fi module connected to the CTC would also widen the user base in the community by inviting a larger audience to use the system. Then the interface could also be accessed by the computers located in the CTC. This could prove to be a valuable learning platform for other individuals than those working in the refrigeration center.

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Appendix

A White Papers

A.1 Charge Controller of the Refrigerator Center

**SmartSolar Charge Controller
MPPT 100/50**

SmartSolar Charge Controller	MPPT 100/30	MPPT 100/50
Battery voltage	12/24V Auto Select	
Rated charge current	30A	50A
Nominal PV power, 12V 1a,b)	440W	700W
Nominal PV power, 24V 1a,b)	880W	1400W
Maximum PV open circuit voltage	100V	100V
Max. PV short circuit current 2)	35A	60A
Maximum efficiency	98%	98%
Self-consumption	10 mA	
Charge voltage 'absorption'	Default setting: 14,4V / 28,8V (adjustable)	
Charge voltage 'float'	Default setting: 13,8V / 27,6V (adjustable)	
Charge algorithm	multi-stage adaptive	
Temperature compensation	-16 mV / °C resp. -32 mV / °C	
Protection	Battery reverse polarity (fuse, not user accessible) PV reverse polarity Output short circuit Over temperature	
Operating temperature	-30 to +60°C (full rated output up to 40°C)	
Humidity	95%, non-condensing	
Data communication port	VE.Direct See the data communication white paper on our website	
ENCLOSURE		
Colour	Blue (RAL 5012)	
Power terminals	13 mm^2 / AWG6	
Protection category	IP43 (electronic components), IP22 (connection area)	
Weight	1,3 kg	
Dimensions (h x w x d)	130 x 186 x 70 mm	
STANDARDS		
Safety	EN/IEC 62109-1	

1a) If more PV power is connected, the controller will limit input power.
1b) The PV voltage must exceed Vbat + 5V for the controller to start.
Thereafter the minimum PV voltage is Vbat + 1V.
2) A higher short circuit current may damage the controller in case of reverse polarity connection of the PV array.

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victron energy
BLUE POWER

A.2 Solar Panel

YGE 60 Cell 40mm SERIES

Powered by YINGLI

YL260P-29b
YL255P-29b
YL250P-29b
YL245P-29b
YL240P-29b
YL235P-29b
YL230P-29b

ABOUT YINGLI GREEN ENERGY

Yingli Green Energy Holding Company Limited (NYSE: YGE) is one of the world's largest fully vertically integrated PV manufacturers, which markets its products under the brand "Yingli Solar". With over 4.5GW of modules installed globally, we are a leading solar energy company built upon proven product reliability and sustainable performance. We are the first renewable energy company and the first Chinese company to sponsor the FIFA World Cup™.

PERFORMANCE

- High efficiency, multicrystalline silicon solar cells with high transmission and textured glass deliver a module efficiency of up to 16.2%, minimizing installation costs and maximizing the kWh output of your system per unit area.
- Tight positive power tolerance of 0W to +5W ensures you receive modules at or above nameplate power and contributes to minimizing module mismatch losses leading to improved system yield.
- Top ranking in the "TÜV Rheinland Energy Yield Test" and the "PHOTON Test" demonstrates high performance and annual energy production.

RELIABILITY

- Tests by independent laboratories prove that Yingli Solar modules:
  - ✓ Fully conform to certification and regulatory standards.
  - ✓ Withstand wind loads of up to 2.4kPa and snow loads of up to 5.4kPa, confirming mechanical stability.
  - ✓ Successfully endure ammonia and salt-mist exposure at the highest severity level, ensuring their performance in adverse conditions.
- Manufacturing facility certified by TÜV Rheinland to ISO 9001:2008, ISO 14001:2004 and BS OHSAS 18001:2007.

WARRANTIES

- 10-year limited product warranty[1].
- Limited power warranty[1]: 10 years at 91.2% of the minimal rated power output, 25 years at 80.7% of the minimal rated power output.

[1] In compliance with our Warranty Terms and Conditions.

QUALIFICATIONS & CERTIFICATES

IEC 61215, IEC 61730, MCS, CE, ISO 9001:2008, ISO 14001:2004, BS OHSAS 18001:2007, SA 8000, PV Cycle

ELECTRICAL PERFORMANCE

Electrical parameters at Standard Test Conditions (STC)									
Module type			YLxxxP-29b (xxx=P_{max})						
Power output	P_{max}	W	260	255	250	245	240	235	230
Power output tolerances	ΔP_{max}	W	0 / 5						
Module efficiency	η_m	%	15.9	15.6	15.3	15.0	14.7	14.4	14.1
Voltage at P_{max}	V_{mpp}	V	30.9	30.6	30.4	30.2	29.5	29.5	29.5
Current at P_{max}	I_{mpp}	A	8.41	8.32	8.24	8.11	8.14	7.97	7.80
Open-circuit voltage	V_{oc}	V	38.9	38.7	38.4	37.8	37.5	37.0	37.0
Short-circuit current	I_{sc}	A	8.98	8.88	8.79	8.63	8.65	8.54	8.40

STC: 1000W/m^2 irradiance, 25°C cell temperature, AM1.5g spectrum according to EN 60904-3.
Average relative efficiency reduction of 5% at 200W/m^2 according to EN 60904-1.

Electrical parameters at Nominal Operating Cell Temperature (NOCT)									
Power output	P_{max}	W	188.3	184.7	181.1	177.9	174.3	170.7	167.0
Voltage at P_{max}	V_{mpp}	V	28.1	27.9	27.6	27.2	26.6	26.6	26.6
Current at P_{max}	I_{mpp}	A	6.70	6.63	6.56	6.54	6.56	6.42	6.29
Open-circuit voltage	V_{oc}	V	35.9	35.7	35.4	34.5	34.2	33.8	33.8
Short-circuit current	I_{sc}	A	7.27	7.19	7.12	6.99	7.01	6.92	6.81

NOCT: open-circuit module operation temperature at 800W/m^2 irradiance, 20°C ambient temperature, 1m/s wind speed.

THERMAL CHARACTERISTICS

Nominal operating cell temperature	NOCT	°C	46 +/- 2
Temperature coefficient of P_{max}	γ	%/°C	-0.45
Temperature coefficient of V_{oc}	β_{Voc}	%/°C	-0.33
Temperature coefficient of I_{sc}	α_{Isc}	%/°C	0.06
Temperature coefficient of V_{mpp}	β_{Vmpp}	%/°C	-0.45

OPERATING CONDITIONS

Max. system voltage	1000V_{DC}
Max. series fuse rating	15A
Limiting reverse current	15A
Operating temperature range	-40°C to 85°C
Max. static load, front (e.g., snow and wind)	5400Pa
Max. static load, back (e.g., wind)	2400Pa
Max. hailstone impact (diameter / velocity)	25mm / 23m/s

CONSTRUCTION MATERIALS

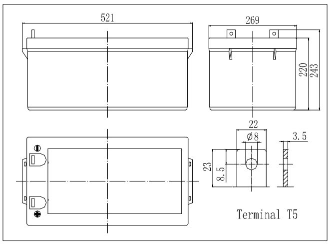
Front cover (material / thickness)	low-iron tempered glass / 3.2mm
Cell (quantity / material / dimensions / number of busbars)	60 / multicrystalline silicon / 156mm x 156mm / 2 or 3
Encapsulant (material)	ethylene vinyl acetate (EVA)
Frame (material / color / anodization color / edge sealing)	anodized aluminum alloy / silver / clear / silicone or tape
Junction box (protection degree)	≥ IP65
Cable (length / cross-sectional area)	1100mm / 4mm^2
Plug connector (type / protection degree)	MC4 / IP67 or YT08-1 / IP67 or Amphenol H4 / IP68

- Due to continuous innovation, research and product improvement, the specifications in this product information sheet are subject to change without prior notice. The specifications may deviate slightly and are not guaranteed.
- The data do not refer to a single module and they are not part of the offer, they only serve for comparison to different module types.

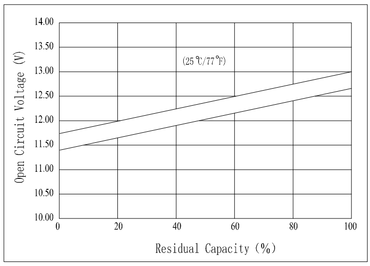
A.3 Battery Used in the School

MT122550(12V255Ah)

Dimensions



The Relationship for Open Circuit Voltage and Residual Capacity (25°C)

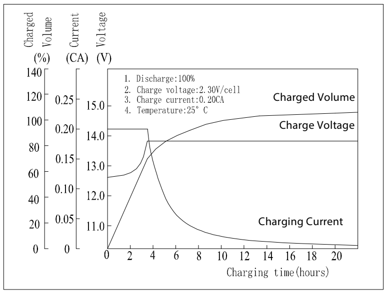


Specifications

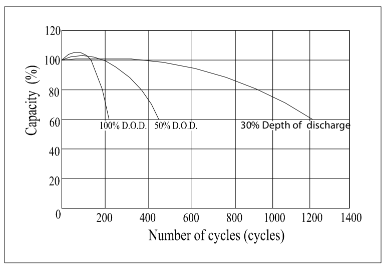
Nominal Voltage		12 V
Capacity(10HR, 25℃)		255 Ah
Dimension	Length	521mm (20.5inch)
	Width	269mm (10.6inch)
	Height	220mm (8.66inch)
	Total Height	242mm (9.53inch)
Approx. Weight		78kg (172lbs)
Internal resistance (Fully charged, 25℃)		Approx. 2.6m
Capacity affected by temperature (10HR)	40℃	102%
	25℃	100%
	0℃	85%
	-15℃	65%
Self-discharge (25℃)	3 month	Remaining Capacity: 91%
	6 month	Remaining Capacity: 82%
	12 month	Remaining Capacity: 65%
Nominal operating temperature		25℃±3℃ (77℉ ±5℉)
Operating temperature range		-15℃~50℃ (5℉ ~122℉)
Float charging voltage(25℃)		13.50 to 13.80V
Cyclic charging voltage(25℃)		14.50 to 14.90V
Maximum charging current		75A
Terminal material		Copper
Maximum discharge current		1800A(5 sec.)

- AGM and VRLA technology;
- Recognized by UL & CE;
- ABS container. Orange, Blue or Black Color.

Charging Characteristics(25℃)



Cycle Life(25℃)



Note: Floating life at 20℃ designed for 10 years.

Constant Current Discharge Characteristics (A, 25℃)

F.V/TIME	5min	10min	15min	30min	60min	3h	5h	10h	20h
9.60V	775	525	415	265	163	63.9	45.7	25.4	13.4
10.2V	736	499	398	254	156	63.0	45.0	25.2	13.3
10.8V	692	469	378	242	149	61.7	44.1	25.0	13.2

Constant Power Discharge Characteristics (Watt, 25℃)

F.V/TIME	5min	10min	15min	30min	60min	3h	5h	10h	20h
9.60V	8138	5670	4557	2973	1858	752	540	303	161
10.2V	7731	5387	4374	2854	1784	741	532	300	159
10.8V	7267	5063	4156	2712	1695	726	521	300	158

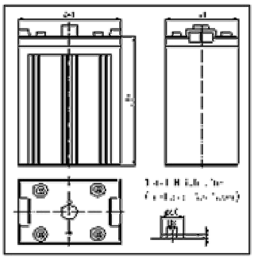
WWW.MTEK-SA.COM 2009

A.4 Battery Used in the Refrigerator Center

MT25000S (2V500Ah)

Valve Regulated Lead Acid Battery

MT25000S
2 volts 500Ah



MT25000S having its design life of 20 years @ 25 degree Celsius for floating application and around 1200 cycles for 30% depth of discharge for cyclic application.

As our product were all rechargeable , highly efficient, maintenance free & leakage proof usable in all positions and it meets the standards of JISC, BS, DIN, IEC etc.

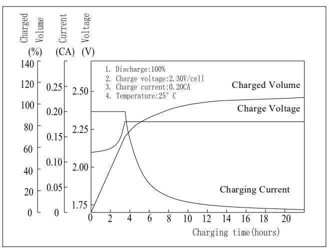
We're ISO9001certified &UL approved as well as CE

Our containers were all ABS resin and grades were : UL94-HB, UL94V-0 & UL94V-2 (flame retardant types could be arranged).

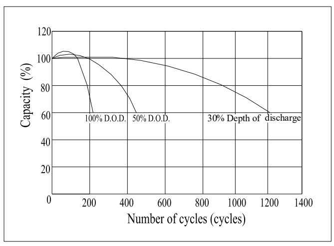
Specification

Nominal voltage	2 volts
Capacity	500 ampere hours @25℃, 10 hours rated (cut off voltage 1.80V/cell)
Dimension	L: 214 mm W: 174 mm H: 349 mm TH: 358 mm
Weight approx.	30 kg or 66.2 pounds
Internal resistance	Approx. 0.4 mΩ
Self-discharge rate	Approx. 3% per month @ 25 degree Celsius
Operation temperature range	Discharged: -15 to 50 degree Celsius (5 to 122 degree F)
	Charging: 5 to 35 degree Celsius (41 to 95 degree F)
	Storage: 0 degree to 40 degree Celsius (32 to 104 degree F)
Floating charge voltage	2.25 to 2.30 volts (-3mv / degree Celsius)
Cyclic charging voltage	2.42 to2.48 volts (-4mv / degree Celsius)
Maximum charging currant	100 ampere (A)
Boost/equalizing charge	Not required
Terminal type	Copper
Container material	General ABS resin

Charging Characteristics(25℃)



Cycle Life(25℃)



Constant Current Discharge Characteristics (A, 25℃)

F.V/TIME	5min	10min	15min	30min	60min	3h	5h	10h	20h
1.60V	1125	742	607	405	292	130	89.2	50.8	26.3
1.70V	1069	705	583	388	280	128	87.8	50.3	26.1
1.80V	1004	663	554	369	266	125	86.1	50.0	25.9

Constant Power Discharge Characteristics (Watt, 25℃)

F.V/TIME	5min	10min	15min	30min	60min	3h	5h	10h	20h
1.60V	1969	1337	1112	758	556	256	176	101	52.7
1.70V	1871	1270	1067	727	534	252	173	100	52.2
1.80V	1758	1194	1014	690	507	248	170	100	51.9

A.5 Refrigerators

DC Refrigerators and Freezers

Energy Efficient Refrigeration

Save on costs with ***SunDanzer***™ DC refrigerators and freezers. These high efficiency refrigerators and freezers have exceptionally low energy consumption requiring smaller, less expensive power systems and low operating expense.

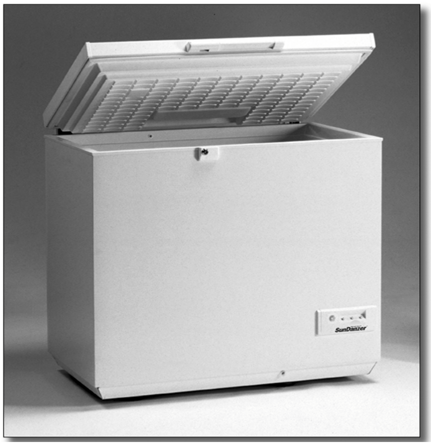
High quality construction provides excellent reliability and long life. Super-insulated cabinets feature 11cm of polyurethane insulation with powdered-coated galvanized steel exterior and aluminum interior. A zero maintenance, brushless, thermostatically controlled DC compressor operates on 12 or 24 VDC. A patented low-frost system reduces frost and moisture build-up for low maintenance. These chest-style refrigerators and freezers are easy to clean using the drain hole at the bottom of the unit.

With thick insulation and a refrigeration system optimized for solar, SunDanzer refrigerators and freezers provide outstanding economical and reliable operation.

Low energy consumption is the key that allows SunDanzer refrigerators and freezers to be cost effectively powered from solar, wind, fuel cells or batteries. This technology allows refrigeration in remote locations were it was previously unavailable or prohibitively expensive.

Applications:

• Remote homes	• Cabins
• Eco-Resorts	• Medical Clinics
• Remote Stores	• Markets
• Disaster Preparedness	• Farms
• Beverage Vending	• Boats and Marine
• Churches & Schools	• Traveling Vendors
• Villages	• Missionaries
• Ice Making	• Micro-enterprises



SunDanzer™ units are manufactured in a highly automated factory by one of the worlds leading appliance manufacturers to SunDanzer's stringent standards for quality and efficiency.

Features:

- **Runs on a single 75W module in most climates!**
- **12 or 24 VDC with low voltage disconnect for battery protection**
- **Environmentally friendly CFC-free refrigerant (R-134a)**
- **Rugged scratch resistant galvanized steel exterior**
- **Easy to clean aluminum interior**
- **Lockable lid with interior light**
- **Patented low-frost system**
- **Automatic control with adjustable thermostat**
- **Baskets for food organization**

11060 Dyer D-12 El Paso, TX, USA • +1(915) 821-0042 • Fax +1(775) 201-0236
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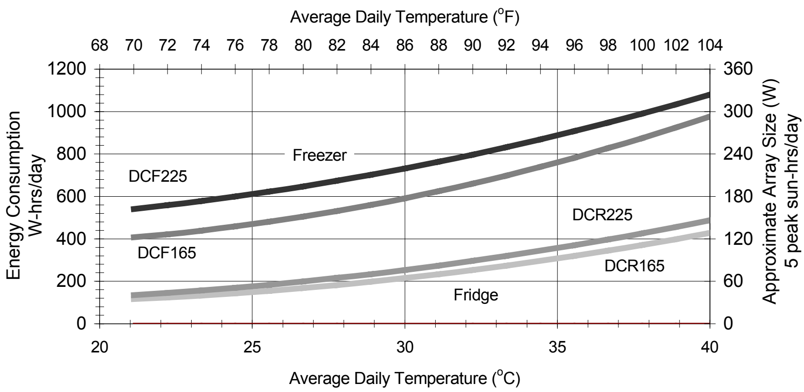
DC Refrigerators and Freezers

Daily Energy Consumption - Standard Test Conditions* 12VDC			
Model	**21.1°C (70°F)**	**32.2°C (90°F)**	**43.3°C (110°F)**
DCR165	77Whrs / 6.5AH**	168Whrs / 14AH	348Whrs / 29AH
DCR225	90Whrs / 7.5AH	198Whrs / 17AH	393Whrs / 33AH
DCF165	272Whrs / 23AH	441Whrs / 37AH	766Whrs / 64AH
DCF225	360Whrs / 30AH	532Whrs / 44AH	817Whrs / 68AH

*Standard Test Conditions: No door openings, refrigerator 3°C (38°F), freezer -12°C (+10°F).

Energy Consumption-Typical Residential Use Pattern*



* Estimated energy consumption; residential application assuming average door openings and change of contents. Performance can vary significantly with different use patterns. Approximate array size assumes a typical solar day, 5kwh/m2 POA insolation, and PV system efficiency of 70% of manufacturers nameplate rating . NOTE ENERGY CONSUMPTION AND ARRAY PERFORMANCE CAN VARY ON LOCATION AND APPLICATION.; CONTACT YOUR SUNDANZER REPRESENTATIVE FOR ASSISTANCE IN SYSTEM SIZING FOR YOUR SPECIFIC APPLICATION!

Physical & Electrical Specifications

Input Voltage	10.4-17VDC (12V)	*Refrigerator T Range:	-1 to 9°C (30 to 48°F)
	22.8-31.5VDC (24V)	*Freezer T Range:	-18 to -5°C (0 to 23°F)
Power (typical-max)	40 - 80W	165 Exterior Dim:	93.5W x 66.5D x 87.6H cm
Fuse Size:	15A @12V 7.5A @24V		36.8W x 26.2D x 34.5H in
Ambient T Range:	10 to 43°C (50 to 109°F)	225 Exterior Dim:	119W x 66.5D x 87.6H cm
			46.9W x 26.2D x 34.5H in

Part No.	Description	Capacity	Shipping Dimensions	Shipping Weight
DCR165	DC Refrigerator	165 L 5.8 ft^3	102W x 76D x 94H cm 40W x 30D x 37H in	54.4 kg 120 lbs
DCR225	DC Refrigerator	225 L 8.0 ft^3	127W x 76D x 94H cm 50W x 30D x 38H in	63.5 kg 140 lbs
DCF165	DC Freezer	165 L 5.8 ft^3	102W x 76D x 94H cm 40W x 30D x 37H in	54.4 kg 120 lbs
DCF225	DC Freezer	225 L 8.0 ft^3	127W x 76D x 94H cm 50W x 30D x 38H in	63.5 kg 140 lbs

A.6 Charge Controller Used in the School

FLEXmax Specifications

	FLEXmax 60 - FM60-150VDC
Nominal Battery Voltages	12, 24, 36, 48, or 60 VDC (Single model - selectable via field programming at start-up)
Maximum Output Current	60 amps @ 104º F (40ºC) with adjustable current limit
Maximum Solar Array STC Nameplate	12 VDC systems 900 Watts / 24 VDC systems 1800 Watts / 48 VDC systems 3600 Watts / 60 VDC Systems 4500 Watts
NEC Recommended Solar Array STC Nameplate	12 VDC systems 750 Watts / 24 VDC systems 1500 Watts / 48 VDC systems 3000 Watts / 60 VDC Systems 3750 Watts
PV Open Circuit Voltage (VOC)	150 VDC absolute maximum coldest conditions / 145 VDC start-up and operating maximum
Standby Power Consumption	Less than 1 Watt typical
Power Conversion Efficiency	98.1% @ 60 Amps in at 48 VDC System voltage - Typical
Charging Regulation	Five Stages: Bulk, Absorption, Float, Silent and Equalization
Voltage Regulation Set points	10 to 60 VDC user adjustable with password protection
Equalization Charging	Programmable Voltage Setpoint and Duration - Automatic Termination when completed
Battery Temperature Compensation	Automatic with optional RTS installed / 5.0 mV per °C per 2V battery cell
Voltage Step-Down Capability	Can charge a lower voltage battery from a higher voltage PV array - Max 150 VDC input
Programmable Auxilary Control Output	12 VDC output signal which can be programmed for different control applications (Maximum of 0.2 amps DC)
Status Display	3.1" (8 cm) backlit LCD screen - 4 lines with 80 alphanumeric characters total
Remote Display and Controller	Optional Mate or Mate2 with RS232 Serial Communications Port
Network Cabeling	Proprietary network system using RJ 45 Modular Connectors with CAT 5e Cable (8 wires)
Data Logging	Last 128 days of Operation - Amp Hours, Watt Hours, Time in Float , Peak Watts, Amps, Solar Array Voltage, Max Battery Voltage Min Battery Voltage and Absorb for each day along with total Accumulated Amp Hours, and kW Hours of production
Hydro Turbine Applications	Consult factory for approved Turbines
Positive Ground Applications	Requires two Pole Breakers for switching both positive and Negative Conductors on both Solar Array and Battery Connections (HUB 4 and HUB 10 can not be used for use in positive ground applications)
Operating Temperature Range	Minimum -40° to maximum 60° C (Power capacity of the controller is automatically derated when operated above 40° C)
Environmental Rating	Indoor Type 1
Conduit Knockouts	One 1" (35mm)on the back; One1" (35mm) on the left side; Two 1" (35mm) on the bottom
Warranty	Standard 5 year / Available 10 Year
Weight - Unit	11.65 lbs (5.3 kg)
- Shipping	14.55 lbs (6.4 kg)
Dimensions - Unit	13.5 x 5.75 x 4" (40 x 14 x 10 cm)
- Shipping	18 x 11 x 8" (46 x 30 x 20 cm)
Options	Remote Temperature Sensor (RTS), HUB 4, HUB 10, MATE, MATE 2
Menu Languages	English & Spanish

OutBack Power Systems™

A.7 Inverter Used in the School

GVFX 60Hz/120V Specifications

07/2015

Models:	GVFX3648
Nominal DC Input Voltage	48VDC
Continuous Power Rating (@ 25°C)	3600VA
AC Frequency/Voltage	60Hz / 120VAC
Continuous AC RMS Output (@25°C)	30AAC
Idle Power	**Full**: ~23W **Search**: ~6W
Peak Efficiency	95%
Typical Efficiency	93%
Total Harmonic Distortion	**Typical**: 2% **Maximum**: 5%
Output Voltage Regulation	±2%
Maximum Output Current	**Peak**: 70AAC **RMS**: 50AAC
AC Overload Capacity	**Surge**: 6000VA **5 Seconds**: 5000VA **30 Minutes**: 4000VA
AC Input Current Maximum	60AAC
Grid-Interactive Voltage Range*	108 to 132VAC
Grid-Interactive Frequency Range*	59.3 to 60.5Hz
AC Input Voltage Range	108 to 132VAC
AC Input Frequency Range	55 to 65Hz
DC Input Voltage Range	42 to 68VDC
Maximum DC Current (@ Rated Power)	90ADC
Continuous Battery Charger Output	45ADC
Certifications	ETL Listed to UL1741, CSA C22.2 No. 107.1
Temperature Range	**Rated**: 0 to 50°C (power derated above 25°C) **Maximum****: -25 to 60°C
Warranty	Standard 5 year, available 10 year
Weight (lb/kg)	**Unit**: 61 / 28 **Shipping**: 67 / 31
Dimensions H x W x L (in/cm)	**Unit**: 12 x 8.25 x 16.25 / 30.5 x 21 x 41 **Shipping**: 21.75 x 13 x 22 / 55 x 33 x 56

OutBack POWER
member of The alpha Group™

www.outbackpower.com

B Code

B.1 Matlab PV Model

```
function Ipv = Photovoltaic(Vpv,Irr,Ta)

%% REFERENCE PAPER:
% Francisco M. Gonzalez-Longatt,
% "Model of Photovoltaic Module inMatlabTM",
% II CIBELEC 2005.

%% Solar panel: Yingli YL250P-29b
% photovoltaic.m function calculates solar array current with a
% given voltage, irradiance and temperature
% Ipv = photovoltaic array current (function output)
% Vpv = photovoltaic array voltage
% Irr = irradiance (1 Irr = 1000 W/m^2)
% TaC = Cell temperature (in celsius degrees)

%% Constants

% Boltzman's constant:
k = 1.38e-23;
% charge on an electron:
q = 1.60e-19;
% Diode quality factor
m = 1.6;
% Band gap voltage
Vg = 1.12;
% Number of cells conected in series:
Ns = 60*2;
% 25C degrees in Kelvin:
T_STC = 273 + 25;
% Open circuit voltage per cell at T_STC temperature
Voc_STC = 38.4*2/Ns;
% Short circuit current at temperature T_STC
Isc_STC = 8.79;
% Nominal Operating Cell Temperature:
T_NOCT = 46;
% Test temperature read from ,matlabs I-V curve
T2 = 273 + 75;
% Short circuit current for one panel at Irr = 1 and T2
Isc_T2 = 8.98;
% from ambient input to cell tempeature
TaC = Ta + ((T_NOCT-20)/0.8) * Irr;
% Photovoltaic array working temperature
TaK = 273 + TaC;

%% Calculation of the photocurrent Iph
```

```
% K0 constant is determined from I_sc vs T (EQUATION 4)
K0 = (Isc_T2 - Isc_STC)/(T2-T_STC);
% (EQUATION 3)
Iph_T1 = Isc_STC * Irr;
% Photocurrent (EQUATION 2)
Iph = Iph_T1 + K0*(TaK-T_STC);

%% Calculation of saturation current of the diode IS

% (ECQATION 6)
IS_STC = Isc_STC/(exp(q*Voc_STC/(m*k*T_STC))-1);
% Diode saturation current
IS = IS_STC*(TaK/T_STC).^(3/m).*exp(-q*Vg/(m*k).*((1./TaK)-(1/T_STC)));

%% Calculation of the series resistance Rs,

% (EQUATION 8)
Xv = IS_STC*q/(m*k*T_STC)*exp(q*Voc_STC/(m*k*T_STC));
% dV/dI at Vco pers cell
dVdI_Voc =  -0.94/Ns;
% Resistance per cell (EQUATION 7)
Rs = -dVdI_Voc - 1/Xv;

%% Calculation of the PV array current, Ipv

% Thermal voltage
V_T = k*TaK/q;
% PV voltage per cell
Vc = Vpv/Ns;
Ipv = zeros(size(Vc));
% Ipv = Iph - I0.*( exp((Vc+Ipv.*Rs)./Vt_Ta) -1) (EQUATION 1);
% Solve for Ipv: f(Ipv) = Iph - Ipv - I0.*( exp((Vc+Ia.*Rs)./Vt_Ta) -1) = 0;
% Newton-Raphson method: Ipv2 = Ipv1 - f(Ipv1)/f'(Ipv1)
for j=1:5
  Ipv = Ipv - ...
  (Iph - Ipv - IS.*( exp((Vc+Ipv.*Rs)./(V_T*m)) -1))...
  ./ (-1 - (IS.*( exp((Vc+Ipv.*Rs)./(V_T*m)) -1)).*Rs./V_T*m);
end
```

B.2 Matlab P&O MPPT

```
function D  = pno(Ipv,Vpv)
    persistent Vprev Dprev Pprev

    if isempty(Dprev)
        Dprev = 0.39;
        Vprev = 70; %Vpv;
        Pprev = 1000; % Vpv * Ipv;
    end

% Initialize algorithm parameters
deltaD = 0.001;

% Calculate measured array power
Ppv = Vpv*Ipv;

% Increase or decrease duty cycle based on conditions
if (Ppv-Pprev) ~= 0 % Power is either increasing or decreasing
    if (Ppv-Pprev) >= 0  %power increased
        if (Vpv-Vprev) > 0 % voltage increased last time
            D = Dprev - deltaD; % keep increasig
        else % voltage is smaller now than last time
            D = Dprev + deltaD; % reduce voltage
        end
    elseif (Ppv-Pprev) < 0 % power was reduced
        if (Vpv-Vprev) > 0 % voltage increased
            D = Dprev + deltaD; %decrease voltage
        else %voltage decreased
            D = Dprev -  deltaD;  %increase voltage
        end
    else
        D = Dprev;
    end
else
    D = Dprev;
end

if D > 1
    D = 1;
end

% Update internal values
Dprev = D;
Vprev = Vpv;
Pprev = Ppv;
```

B.3 Matlab Battery Model

```
function [SOC,batt_state]  = ccBattery(SOC_init, Ibat)
    persistent Cbat Cbat_prev init Timestep time_dif

    if isempty(init) % Initialize
        Cbat = 500 * 60*60; %Total battery capacity in As
        Cbat_prev = Cbat * SOC_init / 100; %initialize battery capacity
        Timestep = 1e-5; % known timestep
        time_dif = 3600; %known time difference
        y = SOC_init; % output SoC
        init = 1; % Sett initialization to only run once
    else
        % Update battery capacity by assuming 1 second is 1 hour
        % In other words: bultiply by 3600 and the timestep
        Cbat_prev = Cbat_prev + Ibat * Timestep * time_dif;
        % Store SOC
        y = (Cbat_prev/Cbat)*100;
    end

    if y > 100 % Keep 100% as the maximum capacity
       y = 100;
       batt_state = 1; % Indicates SOC > 0
    elseif y < 0
        y = 0;
        batt_state = 0; % Indicates SOC = 0
    else
        batt_state = 1; % Indicates SOC > 0
    end

SOC = y;
```

B.4 C++ Main While Loop

```
// Main simulation loop. Running for 24 simulation seconds with a timestep of t
while (tt < 24) { // While time is les than 24s
        iFloor = floor(tt);
        // setting inputs to the simulation for each timestep
        // change input from file when next whole second
        coolingCODE_Obj.coolingCODE_U.irr_signal = irrProfile[iFloor];
        coolingCODE_Obj.coolingCODE_U.temp_signal = tempProfile[iFloor];
        coolingCODE_Obj.coolingCODE_U.load_signal = loadProfile[iFloor];
        // Running one step of the main simulink block
        coolingCODE_Obj.step0();
        // running mppt alogo 100times slower at Ts = 0.001
        tmppt++;
        if (tmppt >= 100){
                coolingCODE_Obj.step1();
                tmppt = 0;
        }
        // Checking if SOC reached zero and if so, when
        if (coolingCODE_Obj.coolingCODE_Y.batt_out_bus[1] == 0 && status != 0){
                status = 0;
                statusTime = iFloor;
        }
        // Checking if SOC reached 50% and if so, when
        if (coolingCODE_Obj.coolingCODE_Y.batt_out_bus[1] < 50 && status50 != 0){
                status50 = 0;
                statusTime50 = iFloor;
        }
        // save SOC at end of each hour (second)
        if (iSOC == 100000) { // 1/1e-5. stor SOC at end of every hour
                /*save to vector*/
                SOChour.push_back(coolingCODE_Obj.coolingCODE_Y.batt_out_bus[0] );

                iSOC = 0;
        }
        iSOC++;
        // increasing time counter by adding the timestep
        tt = tt + t;
}
```

B.5 Index.php

```
<?php
  $page_id = 1;
?>

<!DOCTYPE html>
<html>
<head>
    <?php include dirname(__FILE__)./includes/head.php; ?>
</head>

<body>
  <!-- Container absolute positioned in right corner, only displayed if page is scrollable-->
  <div id="scrollArrowContainer">
    <img src="./images/arrow-down-box.png" />
  </div>

  <!-- Adding navigation layout -->
  <div class="mdl-layout mdl-js-layout mdl-layout--no-desktop-drawer-button">
    <?php include dirname(__FILE__)./includes/header-nav.php; ?>

    <!-- Main content goes here-->
    <main class="mdl-layout__content">

      <?php include dirname(__FILE__)./includes/mobileHeader-nav.php;?>

      <div id="indexLoadingGrid" class="mdl-grid" style="margin-top:70px">
        <div class="mdl-cell mdl-cell--12-col">
          <center>
            Cargando datos del centro de refrigeracion...
            <div class="mdl-progress mdl-js-progress mdl-progress__indeterminate"></div>
          </center>
        </div>
      </div>

      <!-- This div will show after the database has been queried and data is returned -->
      <div id="indexDataGrid" class="mdl-grid mdl-grid--no-spacing" style="margin-top:70px; display: none;">

        <div id="refrigeratorChart" class="mdl-cell mdl-cell--9-col" style="padding:10px">
        </div>

        <div id="batteryContainer" class="mdl-cell mdl-cell--3-col mdl-cell--8-col-tablet mdl-cell--4-col-phone">
          <div class="mdl-grid mdl-grid--nesting" style="width: 100%">
            <div id="batteryImage" class="mdl-cell mdl-cell--6-col"></div>
            <div id="batteryText" style="mdl-cell mdl-cell--6-col" ></div>
          </div>

        </div>
      </div>
```

```
    <div class="mdl-grid">
    <div id="infobox" class="mdl-cell mdl-cell--12-col" style="display:
        none;">
      <h6>Explicacion</h6>
      <p>Energia producida por el sol: Esta es la energia que el sol
          produce y alimenta el sistema de generacion.</p>
      <p>Energia consumida por los refrigeradores: Esta es la energia
          que los refigeradores necesitan para su funcionamiento. </p>
      <p>Nivel de la bateria: Esta grafica muestra el estado actual de
          las baterias del sistema.</p>
```

B.6 DCsensor.py

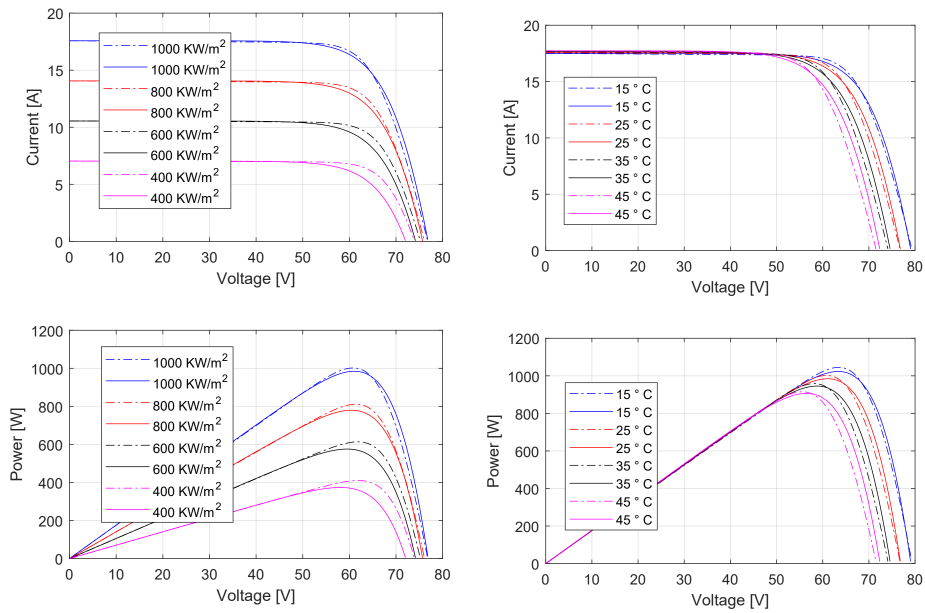
```python
#!/usr/bin/python

# Converting digital output to measured DC
# current in refrigerator center.
from connectDatabase import connect
from mysql.connector import errorcode
from gpiozero import MCP3008
from time import sleep
import sys

try:
    conn = connect();
except mysql.connector.Error as err:
    if err.errno == errorcode.ER_ACCESS_DENIED_ERROR:
        print("Something is wrong with username or password");
    elif err.errno == errorcode.ER_BAD_DB_ERROR:
        print("Database does not exist")
    else:
        print(err)
else:
    try:
        burdenResistor = 165; # ohm
        sensorResolution = 50/0.016; # Amps/Amps
        timeRes = 1; # 1 sec time resolution

        # Reading from A0, channel 0, from SPI device 0
        adc = MCP3008(channel = 0, device = 0);

        # Read input every second
        while True:
            # Outputs a float from 0-1.0, multiplying with
                reference value.
            floatInput = adc.value;
            voltage = 3.3*floatInput;

            # Current is transduces to a 4-20mA range
            currentOutput = voltage/burdenResistor; # I=U/R
            current = 0;
            watts = 0;
            Wh=0;
            if (currentOutput >= 0.004): # To test, set <= 0.00
                current = sensorResolution * currentOutput- 12.5;
                    # y = a*x+b
                current = current + 0.5497;
                print('Calculated measured current in cord: ' +
                    str(current));
                # Fetching last voltage reading
                cursor = conn.cursor(dictionary=True);
```

```
                readQuery = ("SELECT * FROM controller ORDER BY time DESC LIMIT 1;");
                cursor.execute(readQuery);
                row = cursor.fetchone();
                lastVoltage= row["mainVoltage"];
                # Assuming constant power usage in the NEXT time interval
                watts = current * lastVoltage; # unit W
                Wh = watts * timeRes/3600;
            cursor = conn.cursor();
            data = (current, watts, Wh)
            insertQuery = "INSERT INTO sensorDC (current, watts, energy) VALUES (%s, %s, %s);"
            cursor.execute(insertQuery, data)
            conn.commit();
            cursor.close();
            sleep(timeRes);
    finally:
        conn.close();
        #print('\nAverage current measured: '+str(sum(currentArray)/len(currentArray)));
        #print('Number of measurements: ' +str(len(currentArray)));
        print("Connection closed");
```

B.7 JavaScript Code Initiliazing a Highcharts Chart

```
function makeHighchart(timeSeries, dataProduction, dataConsumption){
  var colorRed = $(".mdl-color--primary").css("background-color");
  var colorYellow = $(".mdl-color-text--accent").css("color");
  Highcharts.chart('refrigeratorChart', {
    chart: {
      type: 'column',
      marginRight: 20
    },
    title: {
      text: 'Energia producida y consumida las ultimas 24 horas'
    },
    xAxis: {
      type: "category",
      categories: timeSeries,
      crosshair: true,
      tickmarkPlacement: 'on', // To enable column on tick
      labels: {
        step: 1,
        rotation: -40
      }
    },
    yAxis: {
      min: 0,
      title: {
        text: 'Energia (kWh)'
      },
      offset: 10
    },
    tooltip: {
      valueDecimals: 2,
      valueSuffix: ' kWh'
    },
    credits: {
      enabled: false
    },
    plotOptions: {
      series: {
        borderColor: '#000000',
        pointPlacement: 'on'
      },
    },
    series: [{
      name: 'Energia producida por el sol',
      data: dataProduction,
      color: colorYellow
    }, {
      name: 'Energia consumida por los refrigeradores',
      data: dataConsumption,
      color: colorRed
    }]
  })
};
```

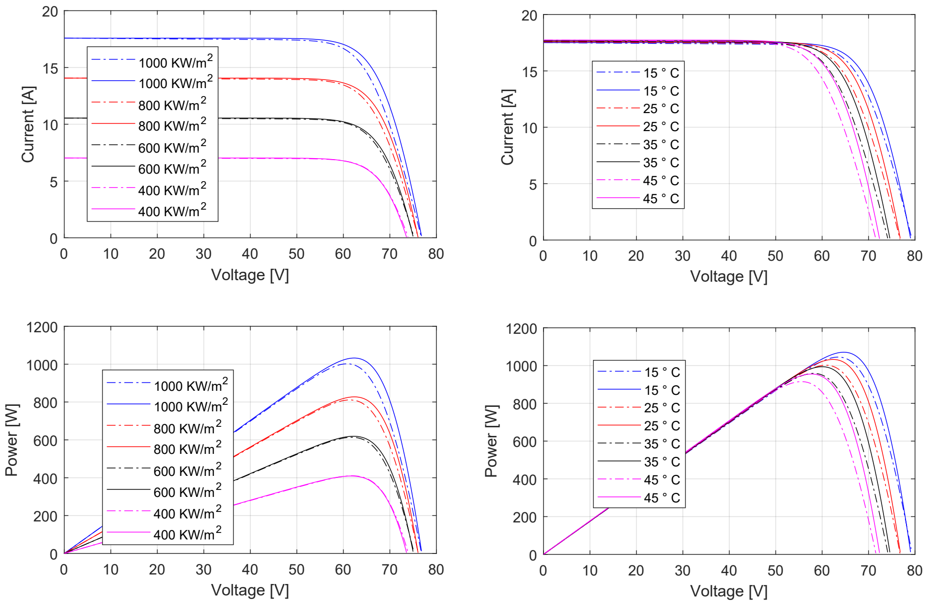
C PV Simulations



(a) Temperature fixed at $25°C$

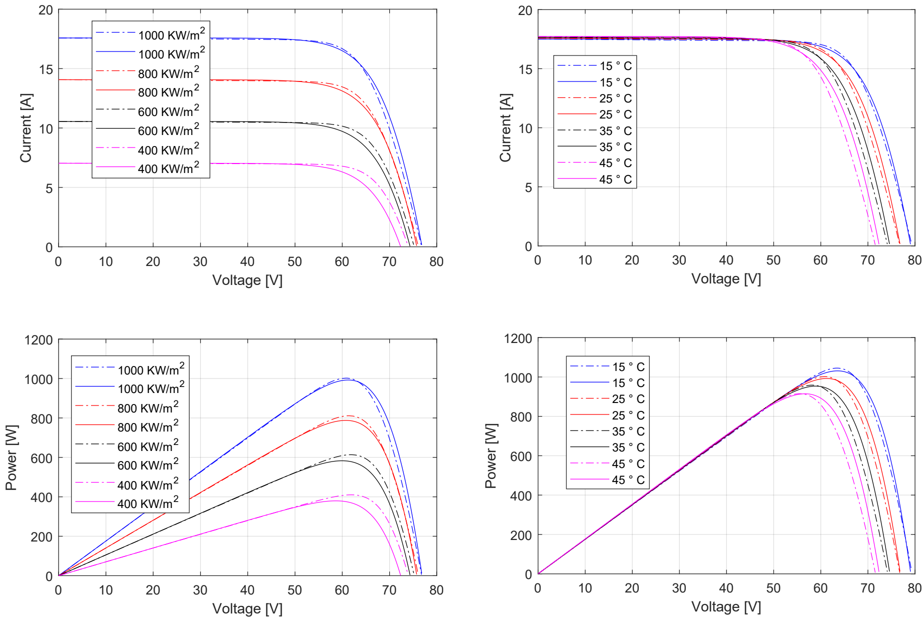
(b) Irradiation fixed at $1000KW/m^2$

Figure C.1: I-V curve on top row and P-V curve on bottom. The dotted line is from Matlabs model and the whole line is based on [100] with diode quality factor $m = 2$. Identical to Figure 5.28. Reproduced here for simpler comparison with the figures that were placed here in Appendix C instead of in Chapter 5



(a) Temperature fixed at $25°C$ **(b)** Irradiation fixed at $1000KW/m^2$

Figure C.2: I-V curve on top row and P-V curve on bottom. The dotted line is from Matlabs model and the whole line is based on [100] with diode quality factor $m = 1.15$



(a) Temperature fixed at $25°C$ **(b)** Irradiation fixed at $1000KW/m^2$

Figure C.3: I-V curve on top row and P-V curve on bottom. The dotted line is from Matlabs model and the whole line is based on [100] with diode quality factor $m = 1.6$

D Context of Use, Prior to the Installation

Users

Users	Salesman	Community member
User type	Primary	Secondary
Skills:		
System skill/knowledge	In the Energy Cooperative, two of the five members are devoted to sales. They operate the refrigerator center on a daily basis, taking take turns working either the morning shift from 8 am to 1 pm or the afternoon shift 1 am to 6 pm. Since the installations of 2015, they have performed the following tasks on a daily basis: ● Reevaluating the number of running refrigerators, hence, if they should increase or decrease the capacity of the refrigerator center, by taking into account the solar irradiation, the current stock and what deliveries to expect during the day. ● Helping the inventory responsible that the salesman work the shift together with, to prepare food for storage, e.g. using a blender to process fruit into juice. ● Serving customers who wants to buy something stored in the refrigerators. ● Calling the community technicians whenever in doubt of thow to manage the system. ● Weekly meetings with the community technicians and the rest of the Energy Cooperative to discuss the operation of the refrigerator center. ● Twice a week they report to the Cabildo together with the rest of the Energy Cooperative about the status of the refrigerator center and hand over the money they have earned to the community.	The typical community member is engaged in fishing and hunting practices, agriculture or handicrafts, and did not have much experience with electricity prior to the installations in 2015. Although not all community members work directly with the photovoltaic systems as the Energy Cooperative does, the systems influence the life of everyone in the community. Each family received a portable solar panel powered lantern during the installment project in 2015, which provides illumination in their homes after the sun goes down, making it possible for the children to study and the women to continue making their handicrafts. In a community survey from 2014, 41 of 42 participants said that they would like new production process for increased revenue, and the cooling center has made it possible for the fishers, hunters, and farmers to sell their production and earn money.
Level of training	The operators received special activities training during the installment process in 2015.	The installments in 2015 included social appropriation and knowledge transfer activities performed by the La Salle University. In the village with over 300 inhabitants, about 15 people received special activities training related to the newly established work group they were attending to, and more than 50 people were trained in technical, environmental, social and some financial aspects related to the system. However, the whole community was aware of the activities going on. Most of the community members touched, moved and helped during the installment process, and each

		work group make regular reports to inform the rest of the community about their work that they present during community meetings.
Language skills	Siapidara Eperara is both the name of the indigenous group and the primary language they speak. Spanish is their second language and that they learn in school from they are about 8 years old. They understand Spanish sufficiently well for it to be used on a web page they will interact with. Siapidara Eperara is very different from Spanish and cannot be understood by spanish speakers.	Same as for the primary user. Siapidara Eperarais is their native language, and Spanish their second language
Personal attributes:		
Age	40	38
Gender	Male	Male
Attitude and motivation	• Wants to give his children a good education and ease the life of his wife, who cooks, makes handicraft and carries home water. • For himself, he would like a home TV, and a 24/7 electricity service. • Wants to keep the life in the village a peaceful one, living in harmony with the spiritual forces that guide the different worlds in their cosmological belief, while at the same time managing the refrigerator center in a sustainable way, increasing the number of production processes and revenue.	• Would like new production process to increase their revenue. • Wants the children in the community to get a good education. • Would like 24/7 electricity service, and desires a TV at home, and if possible, also a fridge, a radio and a fan. • Is open to learn more about electricity. • Wants to live in harmony with the spiritual forces and finds it important to preserve the environment.

Tasks

Tasks:	**Checking the refrigerator status**	**Meeting with the technicians**	**Meeting with salesmen**
Task number	1	2	3
Task breakdown	1. Checks the number of running refrigerators. 2. Checks what the inventory. 3. Considers the solar irradiance of the last couple of days. 4. Get to an agreement on how much should be	1. The Energy Cooperative and the technical committee meets to find out how many refrigerators they assume should be running. 2. They decide by taking into account the solar irradiation of the last	1. Representatives from the Energy Cooperative calls for a meeting with the producers whose products they have to remove from the refrigerator center due to not enough storage considering the assumed

	expected to arrive for storage today. 5. Decided if they should turn on or off any refrigerators. 6. If they want to change number of running refrigerators, they may call one in the technical committee to confirm that they can proceed with their intentions safely. 7. If they turn off a refrigerator and need to throw products, they meet with the affected producer(s) to explain the situation.	days and what they expect of sun the next couple of days. They also consider the current inventory of the refrigerators, and what to expect of deliveries. The best months for production is July to September and more fish and fruit has to be stored, so their decision depend on the season.	available electricity or because the products are overdue. 2. A salesman and one of the inventory responsible of the refrigerator center explains the situation to the affected. 3. The affected producers are given back their products. 4. If the affected producer is unhappy with the situation or a fast decision has to be made, the two inventory responsible in the refrigerator center have the authority to remove goods from the refrigerators. So far, this procedure has not generated any problems in the community.
Task frequency	Twice a day, also in the weekends. When the first work shift starts at 8 am, and when the second shift ends at 7 pm.	At a fixed time every Monday and Friday after 6 pm.	It is not possible to establish a periodicity for these meetings. They are established on a day to day basis, whenever regarded necessary by the operators of the refrigerator center.
Task user	Two representatives from the Energy Cooperative. One salesman and one inventory responsible.	All five representatives of the Energy Cooperative (the one handling the money, the two salesmen and the two responsible for handling the inventory) and all five technicians from the technical committee, if possible.	E.g. a salesman and an inventory responsible from the Energy Cooperative meets with the affected producers.
Physical and mental demands	It can be uncomfortable for the Energy Cooperative representatives to take decisions that affects the income of other community member, who can become disappointed and perhaps angry when they do not earn the money they expected. Especially since the workers in the refrigerator center do not have any proof to substantiate the decision they make as it is based on experience and intuition.	The equipment of the solar panel system is owned by the community. The Energy Cooperative and the technicians are committed to manage the refrigerator center in the best way possible, taking everyone's interest into account. However, their actions may be difficult to justify to the community as they have no decision-making tools they can use to substantiate the decisions they make, which is based on prior experience and intuition. If other community	Worry and distress may be experienced by the refrigerator center responsibles, because they may find it uncomfortable to break the news of low income to other community members which may be (or conceived as) due to bad management of the refrigerator center.

		members feel that the refrigerator center is badly managed at their expenses, the rest of the community can lose the trust to the Energy Cooperative and the technicians, making their work stressful. However, the community has a great confidence in all its members, which is why such problems has not yet happened.	
Task output	Either the same number of refrigerators is kept running, or a number of refrigerators are turned on or off.	The number of running refrigerators, hence they may turn some refrigerators on or off.	The food and drinks that has been stored the longest is removed from the refrigerator center and given to the owner, who will not receive a a sales revenue despite the fee he paid in the first place to store his products.
Risk resulting from error	If they turn off a refrigerator although the system actually has electricity to power more, less products can be stored and both the producers and the cooling center will lose money. If they turn on one refrigerator too much, they will experience a power shortage. Then they will turn on one refrigerator again one by one, waiting up to 3 hours in between, depending on the sun, until they have reached a suitable number of running refrigerators.	If they turn off a refrigerator although the system actually has electricity to power more, less products can be stored and both the producers and the cooling center will lose money. If they turn on one refrigerator too much, they will experience a power shortage. Then they will turn on one refrigerator again one by one, waiting up to 3 hours in between, depending on the sun, until they have reached a suitable number of running refrigerators.	The producers can loose income if the electricity generated is at a higher level than what is assumed by the refrigerators center workers.

Equipment

Equipment	**Refrigerators**	**Fuse box**	**Blender**	**The photovoltaic system**	**The sales booth**
Specification	Hardware	Hardware and software	Hardware	Hardware	Hardware and service.
Product description	Six refrigerators are located in the refrigerator center. Loaded with food and drinks for preservation and marketing. This includes fish, meat,	The fuse box is located in the same room as the refrigerators, near a 1 m*1.5 m box containing the batteries. Includes a controller without a	Located in the cooling center. It is powered using the AC power distribution line drawn from the photovoltaic system at the	The photovoltaic panels are located at the rooftop of the cooling center. Should not require maintenance the first five years, so the monthly	The refrigerator center is approximately a 2 m wide * 4 m long house only 15 m from the school in the community center. It is staffed

	juice, beer, soda and water.	display.	school to the cooling center.	income primarily goes to increase system capacity. A monthly base amount goes to repair or replace parts.	by a salesman and a inventory responsible from the Energy Cooperative everyday 8 am to 6 pm, who sell and prepare products for storage in the refrigerators.
Major function	Food and drink preservation. Has allowed the community to generate new business idea for the products they grow, enabling the collection of over $330 U.S. monthly. They turn of the refrigerators by unplugging them from the power socket.	Contains the fuses they use to turn of the refrigerators. The controller unfortunately does not provide any information that they can use to decide the state of the solar panel system and how much electricity they have in their batteries.	Used to make juice and some sort of an ice cream of the fruits they receive.	To generate energy to charge the batteries in the refrigerator center and power the refrigerators.	The farmers, fishers and other producers in the village can pay a small fee to store their food for sale in the refrigerator center. The money from the sales goes directly to the producer himself, but the money fee and the earnings from selling fruit, juice and other drinks goes to the refrigerator center and can be used to expand the electricity system by e.g. more batteries.

Environment

Environ ment	**Organizational**
Structur e:	
Manage ment structure	The "Cabildo", a council of of about ten men, governs the village with about 500 community members. The "Cabildo" manages the external relations of the community. The governor is elected approximately every second year.
External relations	Calle Santa Rosa is the biggest and most resourceful village in an area consisting of 5-6 nearby smaller communities after the governmental initiative of electrifying Calle Santa Rosa in 2015. The smaller communities are of indigenous heritage or afrodescendentes, and the villages are approximately 15 minutes apart, whereas the nearest bigger city Timbiquí is approximately two hours away by boat. The other smaller communities desire funding similar to the one Calle Santa Rosa received.

	Due to the level of resources in Calle Santa Rosa, cultural activities with the other communities is hosted here. The smaller communities are invited to dances, various sporting activities or activities related to religion in one of the bigger houses in the village that serves the purpose of a church. Members of the other communities visit Calle Santa Rosa to buy food and drinks from the refrigerator center. Then they come by boat, usually after 2 pm. The community of Calle Santa Rosa continuously seeks additional governmental funding. In the Cabildo, one person has the responsibility to stay up-to-date with the different governmental web sites to check for resources to various community projects.
Organizational aims	Typically, the community would search for funding to build more houses and to improve the school and the spiritual center, which is an old building that needs maintenance. At the time of the last La Salle University visit, the community seeked funding for public illumination through street lights and community toilets as they only have private toilet facilities in their homes.
Job function	Most of the inhabitants do not have a formal job that includes a contract with a company. They are primarily farmers, fishers or hunters, and the women serve their family and makes handicraft for sales. Their work Monday to Friday, and Saturday and Sunday is considered the weekend and are days off, but this depends on the season. The work practices of the village often yield the community members a lot of free time during the day. Normal activities related to work is from 8 to 13. Especially in the afternoon most community members have freetime, which they will spend in the school with the PCs and TV. The community host a lot of meetings during the week to spend their free time. For instance, the community will have a meeting about 2 times per week about the refrigerator center and the solar panel systems, including the whole community. They also host community meetings to agree on what they would like governmental funding for.
Work practices	● Fishing: The fishermen will start their work day around 5 in the morning and return with their catch around 9. They have a second shift that starts later in the afternoon, which they return from around 16 o'clock. ● Hunting: The hunters leave return to the village around 16 with their catch. ● Farming: The farmers' work depend on the month. In specific months they have to start the work before the river floods the village. Then they work from about 6 o'clock in the morning until 11. They have their personal farms about 15 minutes away from the village, and they grow banana, sugar canes and oranges, among other things. They sell their production either to the village's cooling center, or they will travel to nearby bigger city, Timbiquí, to sell their production there. Timbiquí is approximately a two hour boat ride away and has multiple shops. ● Other professions in the village is construction worker, either in the village building homes or in the city Timbiquí. Around 10 % work in the city, Timbiquí. The city workers come home to the village only in the in the weekends, bringing along the money they have earned. ● The women work primarily with handicrafts, making decorative bead jewelries. They sell their handicrafts in Calle Santa Rosa or sometimes they go to Timbiqui to sell in the weekends. During the morning and until lunch, they will cook for their family. Often they will eat the same for lunch and dinner, which enables the women to work approximately from 1 pm to around 9 pm. ***Should rather have a document that is less specific to include in the thesis, keeping the details in this one?***

	Most people work in agriculture and are farmers. They practice farming in the rainforest, with private farms growing banana, corn, sugar cane, rice, cassava and beans. Agriculture is supplemented with hunting and fishing. The women do handicraft for sales. The children go to school to the age of five to 16?
Work groups	The following two work groups related to the photovoltaic system was established as a part of the installation project in 2015: <u>The Energy Cooperative</u> ● The solar panel systems is owned by the entire community. The Cooperative is committed to manage the systems in the best way possible, taking everybody's interest into account. ● Five members: A women handling the money, two salesmen (a man and a woman) and two inventory responsibles who make agreements with the other community members to sell products for them. ● The inventory responsibles receive the products from producers (e.g. fishermen, hunters and farmers) who have to pay a small fee for storage in the refrigerator. The producers receives a receipt and the entire sales revenue if his product is sold. The producers can also pay the fee with fruits, as the community members usually do not have much money. Only the fee and the money from selling fruits and drinks goes directly to the income of the refrigerator center. ● The intention of the installed photovoltaic system from 2015 was for it to be close to maintenance free the first five years, so the income would primarily go to system expansion by buying more batteries or solar panels. ● The Energy Cooperative has to answer to the Cabildo. Twice a week they meet with the Cabildo to report the status of the refrigerator center. The Cabildo decides the selling prices in the refrigerator center and collects the earnings of the center. ● Supervises the work of the other work groups. <u>A technical committee:</u> ● 5 members in total. ● The community was asked if any of its member had prior work experience with electricity, and three men were recognized. Two additional men were taught from scratch by the La Salle University's initiative in 2015. ● Being a technician is not a full time job, so the technicians have other jobs in addition, such as farming. However, always one technician is supposed to be on duty. They respond to calls from the daily workers in the refrigerator center and do maintenance work such as cleaning the solar panels. ● They have a book with instructions that they have to adhere to, which they received during the installation process in 2015. If a big problem occurs that they are not able to fix themselves, they have the opportunity to call the La Salle University for help or the vendor of the broken equipment, but this has not happened so far.
School	The children go to school at the age of 5 to the age of 18, and they receive breakfast in school at 8 am everyday. This is a governmental initiative to encourage education and a healthy diet in the indigenous communities. The children will usually go home for lunch before returning to school, and the school day ends about 14 pm.
Attitudes and culture:	
Family	The social structure of the community is based on a family organized agricultural labor. In average, a family consist of seven family members, with two or three being children. A part from the father and mother, the rest of the family members can be grown-up children, aunts, uncles or grandparents. Although the religious spiritual leader is a women, the community is a patriarchy with the father or the grandfather functioning as the head of the family. However, the women in the community are growing more confident, and a woman is responsible for handling the refrigerator center's money, because the community have big respect for their women and trust their women more.

	Money in the family is in general considered a luxury. They do not pay taxes, and the money can be spent buying food from the refrigerator center that they normally do not have access to. For instance, their usually lunch could be rice and potatoes, but when they have money they can treat themselves with meat bought at the refrigerator center.
Experience with technology	Most of the people in the community has become acquainted with communication technology and the Internet by using the computers in the digital kiosk. In 2014, prior to the photovoltaic systems were installed, only two family heads answered in a survey that they would communicate with others using cell phones. The rest would use the river to get in contact with someone outside the community. Today, it is estimated that each family owns about two smartphones. They typically buy the smartphones in the nearby bigger city Timbiquí, and a typical brand of the smartphones they buy is Alcatel Mobile. They connect the smartphones to the Wi-Fi at the school, but sometimes the Internet access is bad due to poor weathering conditions like when it rains a lot. The richest family in the community have been able to buy private diesel generators to have in their homes, giving electricity to power a satellite TV that they also have bought for instance. However, it is often the case that these families for periods do not have money for gasoline, and the electricity plants will stay unused for months.
Policy on use of computers	During school hours, from 8 am to 2 pm, the computers in the digital kiosk is dedicated to the school. After 2 pm, all community members can book a time slot in which they can use the computers, and it is usually fully booked until around 6 pm in the weekdays. However, students using the computers for homework are always prioritized, and other community members have to pay a small fee to use the computers, e.g. a dollar for an hour. You also have to pay if you want to use the printer. It is common that people from other villages that do not have received this governmental program visit Calle Santa Rosa to use the computers. They typically use to computers for the following: ● Social networking, such as checking Facebook. ● Regular internet surfing, such as watching Youtube and checking the news. ● Some grown up community members attend a special university for indigenous people that facilitate remote education. The attendees will visit the university (which is four hours away) only occasionally, and study at home by using the community computers. ● To access new types of knowledge. For instance, a community member may want to learn have to play the guitar, and then he would use the computer to search for this kind of information. ● Researching opportunities to get governmental funding. ● Watching cartoons.

E Observation Form for Usability Testing in Calle Santa Rosa

Date: Time:

Test person: Unit used to test: Computer ☐ Smartphone ☐

Age: Gender: Other:

Observer:

Task 1 if on computer: Type in the URL/web page access	
Typed correct URL?	Yes ☐ No ☐
Was the web page displayed?	Yes ☐ No ☐
Loading time:	(just count the seconds inside you, make an estimate)
Other problems and possible solutions:	
Task 1 if on smartphone: Scan the QR-code. Click Download. Find the newly installed app, etc.	
Was the web page displayed?	Yes ☐ No ☐
Describe problem if any occurred:	
Task 2: The battery level in the refrigerator center	
Did the user find the right web page? (it is the starting page, but only check this box if the user understands that the starting page shows the status of the refrigerator center)	Yes ☐ No ☐
Time used before the right page was found:	(just count the seconds inside you, make an estimate)
Did the user answer the correct battery level?	Yes ☐ No ☐ Didn`t know ☐
Other problems and possible solutions:	
Task 3: The energy produced by the sun to the refrigerator center during the previous hour	
Did the user answer	Yes ☐ No ☐ Didn`t know ☐

correctly?	
Other problems and possible solutions:	
Task 4: The energy consumed by the refrigerators during the previous hour	
Did the user answer correctly?	Yes ☐ No ☐ Didn`t know ☐
Other problems and possible solutions:	

ONLY IF MEMBER OF THE ENERGY COOPERATIVE:

Task 5: Visit the web page that allows you to run a prediction for the refrigerator center	
Did the user find the right web page (and was sure of it)?	Yes ☐ No ☐
Other problems and possible solutions:	
Task 6: Run a prediction to see if the system can run with 3 freezers and 3 refrigerators.	
Did the user answer correctly?	Yes ☐ No ☐ Didn`t know ☐
Time used before the right recommendation was found:	(just count the seconds inside you, make an estimate)
Other problems and possible solutions:	

Questions after the test:

The following questions should be answered with Yes/No, but thoughts they share should be written down/reported.

1. Are you satisfied with how the web page was accessed?
   Yes ☐ No ☐
   Opinions expressed:

2. Are you satisfied with how easy it was to find the battery level of the refrigerator center?
   Yes ☐ No ☐
   Opinions expressed:

3. Are you satisfied with how easy it was to find the web page for the refrigerator center?
   Yes ☐ No ☐
   Opinions expressed:

4. Are you satisfied with how easy it was to read energy consumption and prediction on the web page for the refrigerator center?
   Yes ☐ No ☐
   Opinions expressed:

ONLY IF MEMBER OF THE ENERGY COOPERATIVE:

5. Are you satisfied with how easy it was to find the web page for prediction?
   Yes ☐ No ☐
   Opinions expressed:

6. Are you satisfied with how easy it was to run a prediction for a number of freezers and refrigerators?
   Yes ☐ No ☐
   Opinions expressed:

7. Would you use the web page in your work when deciding the number of refrigerators to run in the refrigerator center?
   Opinions expressed:

8. Would you use the web page in meetings? With technicians, the whole Energy Cooperation and/or in meetings with community members to explain them why there is not room for the food they want to store in the refrigerators?
   Opinions expressed:

Ask any other questions if necessary:

F User Manual

This user manual explains how to use the website for Calle Santa Rosa. The web site can be used to view the following information: Battery level in the refrigerator center, energy production and consumption in the refrigerator center, and energy consumption in the school. For the Energy Cooperative, the website can be used to get a recommendation on how many refrigerators they have enough energy to power the next 24 hours, based on the expected radiation from the sun.

Contents/Tasks

1. How to access the website

Using a computer:

1. Obtain the address of the website from the printed A4 paper on the wall next to the printer in the digital kiosco. This address is found under point 1 of the paper. The address should be on the form: http://192.168.1.100
2. Enter the above address into the URL field in your prefered Web Browser and press enter.

Using an Android smartphone:

1. Download the Android application using one either method a or b
   a. Scan the QR-Code printed on the same paper as the address above. This take you to a webpage where you can download the application named PanelSolar.apk.
   b. Enter the address in point 2 of the A4 paper on the wall next to the printer in the digital kiosco into the browser on your phone. This will take you to a webpage where you can download the application named panelsolar.apk.
2. Install the downloaded application on your android. If the phone complains about the application coming from an unknown source enable installations of applications from unknown sources by:
   a. From a Home screen, navigate: **Apps icon > Settings**.
   b. Tap one of the following: (options vary depending upon device)
      i. Security
      ii. Fingerprints & security
      iii. Lock screen and security
   c. Perform one of the following as appropriate:
      i. Tap **Unknown sources** to enable or disable. (Enabled when a check mark is present)
      ii. Tap the Unknown sources switch to turn on 

 or off 

.
   d. Review the disclaimer then tap **OK**.
3. Launch the newly installed application called PanelSolar with a yellow sun on a red background
4. Press the button corresponding to the WiFi network you are connected.

2. How to find the battery level in the refrigerator center

1. Assuming Task 1 has been completed.
2. If you are on a computer: Locate the text field called “CENTRO DE REFRIGERACIÓN” in the red navigation bar on the top of the page and press this.

   If you are on a smartphone: Press the  icon in the top left corner to reveal a new menu. In this menu press the text field called “CENTRO DE REFRIGERACIÓN”.
3. A loading bar will appear: “Cargando datos del centro de refrigeración...”
4. Locate the large green battery icon . The battery level is indicated by the level of green colour filling the battery as well as the percentage number displayed to its immediate right.

3. How to find energy production and consumption in the refrigerator center

1. If you are on a computer: Locate the text field called “CENTRO DE REFRIGERACIÓN” in the red menu bar on the top of the page and press this.

   If you are on a smartphone: Press the  icon in the top left corner to reveal a new menu. In this menu press the text field called “CENTRO DE REFRIGERACIÓN”.
2. A loading bar will appear: “Cargando datos del centro de refrigeración...”
3. The energy production and consumption are shown as colored bars. Each bar indicates the level of production or consumption in the hour written below. Energy production and consumption is shown for the last 24 hours, with the current time to the right. The yellow bar shows the energy produced by the sun. The red bar shows the energy consumed by the refrigerators. The taller the bar, the more energy. The energy is measured in kWh (1000 watts per hour).

4. How to get a recommendation on how the number of refrigerators that can run in the refrigerator center (for Energy Cooperative Members)

1. If you are on a computer: Locate the text field called “PREDICCIÓN” in the red menu bar on the top of the page and press this.

   If you are on a smartphone: Press the  icon in the top left corner to reveal a new menu. In this menu press the text field called “PREDICCIÓN”.
2. There are two columns, one called "Select the number of freezers you want to consider in the prediction "and another callec " Select the number of refrigerators you want to consider in this prediction ".
3. Below each text field, there is an indication that says "Choose a number", select a number for the number of freezers and another for the number of refrigerators. Remember that the sum of the number of freezers
   and the number of refrigerators must always be 6.
4. After selecting the correct number of freezers and refrigerators, click "ENTER".

5. A loading bar will appear: “Usted seleccionó 6 refrigeradores y ahora la solicitud está siendo procesada…”
6. A popup window with a message about the result will appear.
   If the message starts with “Muy bien!!”, it is expected that there will be enough energy to power the selected number of refrigerators.
   If the message starts with “Ten cuidado!!”, the battery level is expected to sink below the minimum recommended battery level, and the number of selected refrigerators is *not* recommended.
7. Click “CONTINUAR” to remove the popup box and to see the graphs behind.
8. The left graph shows how the battery level is expected to change in the coming next 24 hours with the selected number of refrigerators. The battery level should not drop below the blue line. The blue line marks the recommended minimum energy level.
9. The right graph shows the expected energy consumption and production in the coming next 24 hours. The yellow bar shows the energy expected to be produced by the sun. The red bar shows the energy expected to be consumed by the selected number of refrigerators.
10. If the number of selected refrigerators was successful, you can try to run a prediction for a higher number of refrigerators.

G Installation Manual

This document was used to support the installation process of the monitoring system in Calle Santa Rosa and to effectively communicate the work to the engineers from La Salle University in the preparations for the installation.

Prerequisites:

- Raspberry Pi
- Raspberry Pi customized case
- MicroSD card for the Raspberry Pi with the correct image written to it.
- AC Power supply to Raspberry Pi
- USB WiFi Adapter
- Wireless router pre-configured with static IP for the Raspberry Pi's ETH0 interface.
- VE.Direct to USB cable
- DC current sensor
- AC Power supply to DC current sensor
- 2(TBC) La Salle University WiFi current sensor
- Multimeter

- (DC-to-DC converter for the Raspberry Pi
- DC-to-DC converter for DC current sensor)

1. Insert Micro SD card into the Raspberry Pi
2. Mount the Raspberry Pi in the fuse box of the refrigerator center.
   The casing of the Raspberry Pi has 4 screw holes.

3. Power the Raspberry Pi by DC-DC, DC-AC-DC from school or DC-AC-DC from 24 V.
4. Configure wireless interfaces on the Raspberry Pi:
   a. Access web interface of the school's router and set a static ip address for the Raspberry Pi's WLAN1 interface (the USB WiFi adapter) using its MAC address.
   b. Physically connect the Raspberry Pi to the preconfigured router via Ethernet. This gives the ETH0 interface IP-address 192.168.1.101 based on its MAC address.
   c. Connect a laptop to the wireless network created by the router. SSID: CalleSantaRossa, PWD: Columbia
   d. Connect to the Raspberry Pi over SSH

e. Edit the Raspberry Pi's WPA configuration file for WLAN1 by adding the SSID and password of the school's WiFi network.
f. Enable WLAN1 interface on the Raspberry Pi and connect to the school WiFi network
g. Enable WLAN0 interface creating PanelSolar network for accepting connections directly to the Raspberry Pi.

5. Connect the BlueSolar charge controller to the Raspberry Pi via the VE.Direct USB cable.

6. Install the DC current sensor:
   a. Power the DC current sensor using the power supply (either AC or isolated dual DC-DC converter)
   b. Account for the sensor offset in the current script of the Raspberry Pi.
   c. Connect the Raspberry Pi to the current sensor by using an Ethernet cable.

7. Measure the state of charge of the solar panel system battery before the sun rises: Measure the voltage and compare it to the manufacturer graph. Initialize the Coulomb counter with the measured state of charge.
8. Install the La Salle sensors:
   a. Configure the Arduino code to make the sensors connect to the right WiFi network and to make the sensors send their HTTP requests to the Raspberry Pi.

    b. Insert each La Salle sensor into the current circuit of the appliance they will monitor, choosing the correct version (up to 5 A or 20 A) for the appliance.
9. Let the Raspberry Pi run for 24 hours to collect current data.
10. Analyze the data and if necessary account for differences in the generated load profile and the measured load.
11. Prepare and configure the Android application
    a. Reconfigure and build android application .APK to reflect the static IP address of the raspberry pi.
    b. Publish panelsolar.apk application to http://STATIC-IP/download/panelsolar.apk so that it is downloadable from the website
    c. Make a QR code from the download link Print the QR code and hang it up in the school for the people to scan and in that way get access to the application

H Other

H.1 Article Written for IUG Norway

IUG «Master med Mening» Project in cooperation with NTNU, RenPeace and Universidad de La Salle in Colombia.

It all started while we (Vegar Aabrek and Ingvild Forseth) were closing in on the finishing line of our project in the 9th semester at NTNU. In that same period, we had to make a decision on whether we wanted to continue with our current project or if we wanted to choose something new. Both of us had a wish to do something out of the norm for our master thesis. This led to us contacting the NTNU IUG chapter. IUG told us that there were no currently planned projects suitable for students from the Engineering Cybernetics department, but that they knew of one professor at our department that had worked with IUG previously. Thus, our next step was to contact Professor Marta Molinas and set up a meeting. In the meeting Molinas told us about two projects she knew of in Columbia. Her contact was Maximiliano Bueno-Lopez. At that time, he was working with Molinas at NTNU although still holding a professor position in Bogota, Colombia. Through a new meeting with both Molinas and Lopez we learned that the two projects were both related to solar power generation in two separate indigenous communities located in Cauca municipality. One of these projects where in the finishing stage, but still had some funding left. The other project had a pending application for funding from the Columbian government. To keep our options open, two master thesis project description were written, such that if the new project gained funding we would be able to that while if the funding fell through we could still work on the already funded project. The wish was to see a project from start to finish. The preliminary project description of the project in the that already had funding read as follows:

“Firstly, the existing production process system based on solar energy in the Calle Santa Rosa indigenous reservoir in Colombia will be studied and modelled. The aim is to research the implementation of different sensors in the system, enabling sensor fusion, and also look at the possibility of further development of the system. Future development would involve adding new power sources to the system and handle them in an optimal way. The sensor fusion part also includes presentation of the results in an efficient way, a monitoring system, which by the use of graphical user interfaces would enable the community to manage the system themselves in a sustainable way.”

Fast forward a month. Our projects are delivered and its January. The funding for the new project fell through and a decision had been made for us. We grabbed the first opportunity to start working. 4th of January to be precise. This would give us 22 weeks to the deadline. As with the start of any project, and especially so after being absorbed in our last project the previous semester, the start felt quite chaotic. The focus was gathering information about the community and the currently implemented system that we wished to monitor. In this respect Lopez was invaluable, sourcing all the information he could find. Ranging from project reports from previous students to tech specifications of the components and pictures from the community in Calle Santa Rosa. We were lucky having Molinas helping us keep organized by setting weekly deadlines for our progress with meetings to keep her in the loop.

While working on the project we kept in contact with IUG to make sure the progress of turning our master into a “Master med Mening” was moving along. Most of the work was done by Lopez, acting as the contact for the University of La Salle which was our partner organization in Columbia, and Molinas as the contact for NTNU and her organization RenPeace.

In the beginning of February, the IUG NTNU chapter invited us to hold a presentation about our project for students that has shown an interest in writing a future “Master med Mening”. We represented the segment of ongoing projects. There was also a presentation by Haakon Duus and the project he finished in 2015. This turned out to be a good opportunity to talk to him face to face as his work had already been a big part of our source material. After the presentations were finished, the hard core of the spectators peppered us with questions on how we had started our process towards a “Master med Mening”. We happily obliged by answering all we could.

The progress of our application with IUG started slowing down after the focus shifted to the security situation in Columbia. While the situation with the FARC guerilla was resolved in 2015 through a peace agreement between the Columbian government and FARC, the responsibility of La Salle university had to be resolved together with the Colombian government. This turned out to be a lengthy proses and something that would remain unresolved until the very last moment. This uncertainty of whether there would be any field trip at all lead us to apply for a one-month extension on our delivery date. This preemptive action would give us enough time to travel if the issues were resolved.

Lopez had a planned trip to Colombia in April and our hope was his presence in Columbia could help speed up the process. Thus, a tentative departure date was set to be the 18th of May.

In April we were making good progress, but our hopes for a field trip were waning. We had instead set a goal of getting Lopez to gather data for us at the community as a last resort. Now we worked towards delivering the project within the original deadline. At this point we had firmly decided on the scope of our project. Our goal was now twofold: The first and most important task was to enable the community to know how much power was left in the batteries of their refrigeration center. The secondary mission would be to enable them to predict how many of the six refrigerators they could be running for the next 24 hours without getting to a critical battery level. These two objectives would be accomplished by running a webserver with an interface on a Raspberry Pi (RPi). The RPi would also be capable of running a quick 24-hour simulation to predict the power consumption and production of their system.

Suddenly, at the end of April, like lightning from a clear sky, at least for us, IUG approved our application. Now everything happened at once. New dates were set to be 26th of may to 10th of June. We lucked out by getting the last available slot for vaccines and tickets had to be bought. Our focus shifted from writing the thesis to getting all the practical elements working. Enclosures for hardware had to be 3D printed or fabricated and code was changed in order to facilitate changing parameters easier in the field. We also had to complete an online safety course.

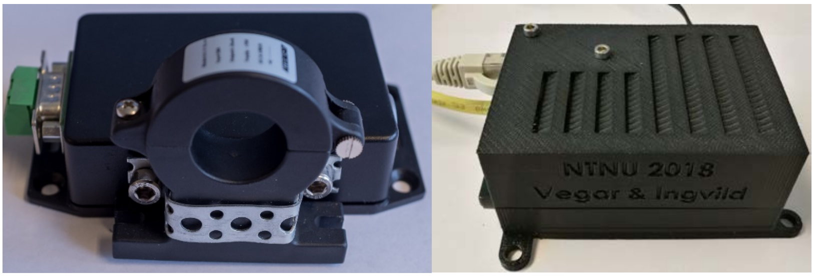


Figure 1: Sensor and Raspberry Pi mounted in cases

The plan for our stay in Columbia was staying in Bogota the first week so that we could prepare everything for our trip to Calle Santa Rosa. We would work in the community for four days before returning to Bogota and spending the remaining days working on a paper for the GHTC 2018 conference, explaining our project.

When we landed in Bogota Lopez met us at the airport whereupon he brought us to our accommodations. To our surprise the accommodation turned out to be two individual rooms with on suite bathrooms at one of the university campuses. As planed the first week revolved around working with scattered sightseeing when going out for lunch and dinner with other students and professors. Here we also had the opportunity to meet the two students (Alejandro Muñoz Rincón and Karen López) from La Salle that would accompany us and Lopez to the community. Their task was to help us with the installation procedure and to be sorely needed translators. Our Spanish was just not up to par.

Figure 2: Lunch with some students from La Salle

Some of the preparations we had to make was for instance to plan what to bring. We had a 10Kg limitation on one of the aircrafts to the community. Therefore, we had to limit what tools, equipment and personal belongings we could bring.

Figure 3: This Fluke network analyzer didn't make the cut

Our trip to Calle Santa Rosa consisted of first taking a plane to Cali and then taking another smaller plane to Timbiqui. From Timbiqui we had a 1-hour boat ride through the jungle before reaching the community. In Timbiqui we were met by two representatives from the community who would drive the boat. After having a traditional lunch with them at a local restaurant we went shopping for food, water, and mosquito nets. After finishing the shopping round in the city, we ended up with five mosquito nets, more than enough clean drinking water and enough rice, eggs, and canned tuna to already look forward to a real meal when we would come back.

Figure 4: Having Lunch with the two community members (in white shirts) that met us in Timbiqui

The trip up the river proved highly enjoyable. The path varied from very wide to super narrow. Here we saw many smaller settlements as well as one larger "village" that is only 15 minutes from

Calle Santa Rosa. The areas we passed through used to be heavily influenced by FARC, but are now much safer for foreigners and Colombians alike.

Figure 5: Closest neighboring village of significant size

When we finally arrived in Calle Santa Rosa we were greeted by the community leader who showed us to the classroom on the second floor in the school where we would sleep and have our base for the next four days. The rest of that evening we spent setting up our mosquito nets and making our first of many meals consisting of rice and tuna. At this point it should be noted that our food choices stemmed experiences Lopez had on previous visits to the community where one student got sick, possibly from the water used for cooking.

Figure 6: The view of Calle Santa Rosa on our arival

Figure 7: Alejandro putting the finishing touches on his bed for the next few nights

The following day we spent our time getting our equipment up and running. That is, a raspberry pi connected to a current sensor. This turned out to be more work than imagined. First of all we had network hardware issues we had not foreseen. In addition to a sudden sensor malfunction. Those two problems took us over a day to solve before we were finally ready to install our components in the fuse box of the refrigeration center. Finally having this installed would enable us to do usability testing of the interface as well as doing measurements to tweak our theoretical load profile. The physical installation was not done until the afternoon the day before we would leave. We turned out to be very unlucky. A period of low solar irradiation meant that the system was now completely out of power and we were not able to do any measurements. This meant that we had to do the measurements, analyze those measurements, edit the load profile and do the usability test before our boat left at 14 the very last day. We did manage to get to the finish line, but it was close.

Figure 8: Usability testing of interface with a member of the group in charge of the refrigerator center

Needless to say, the whole experience was a lot of work from morning to night. And if there is one thing we have learned from the experience it is that its better to have to much equipment than too little when working in such rural areas. Be prepared for anything. We thought we were. We weren't. Lesson learned.

Figure 9: The Team gathered before departure: Alejandro, Karen, Ingvild Maximiliano, Vegar and our local contact Alexander

Figure 10: Their soccer field

Figure 11 Vegar and Ingvild before departure

Figure 12: meeting with community after arrival to explain what we were going to do

Figure 13: Lopez holds a meeting before departure with an explanation of what we accomplished and how it can be used

H.2 GHTC 2018 Paper

Design and Implementation of a Monitoring System for Decision Support in a Micro-business Based on Solar Energy Microgrid in Rural Colombia

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***Abstract*—Rural electrification schemes are necessary for social and economic development. In several countries of Africa, Asia and Latin America this issue is fundamental and some governments have adopted new policies to increase service coverage, a case that has been studied with interest is Colombia. In 2014, the Government presented the Law 1715 for Regulating the Integration of Non Conventional Renewable Energies into the National Energy System. This Law aims to increase penetration of renewable energy in the country; and in 2016 the Peace Treaty between the Colombian Government and the Fuerzas Armadas Revolucionarias de Colombia (FARC-EP) was signed. These two events have paved the way towards a new country in which rural development based on technological advances and renewable energy becomes trend. This paper presents a case study that illustrates how technology has transformed the life of one community in the rural area in Colombia by triggering economic development. The technological proposal is the design of a monitoring interface for a refrigeration center. The processes of design, implementation and validation with the rural community are presented.**

***Index Terms*—Educational Technology, Capacity building, Monitoring, Rural Electrification, User Interface.**

I. Introduction

Two big problems afflict the world's population in energy terms, the vertiginous increase in the use of fossil fuels to meet energy needs and the lack of electricity in remote isolated areas [1], [2]. According to the World Bank, currently 1.2 billion people do not have access to electricity and 2.8 billion do not have access to clean cooking facilities, particularly in rural areas [3], [4] . Therefore, one of the main challenges in the energy sector is the need to make more energy available at affordable prices, especially in the developing countries. In Colombia, more than 2 million people in rural areas do not have electricity service, which represents about 4% of the total population of the country [5]. According to the report of the rural mission in Colombia carried out by the National Planning Department (DNP), energy, cellular coverage and the Internet, which were introduced as technological changes, are now indispensable and they have a character of public goods. This increases their importance considering the impact they can have on productive inclusion. The case of Colombia draws particular attention as this country is emerging from an armed conflict spanning more than 50 years. Colombia is now trying to incorporate into the society all the people who participated in this conflict, most of whom live in rural areas. A way to achieve this is to build new production systems to generate jobs, which, obviously use some form of energy. In 2015, the national government, with some universities and companies, implemented solutions that sought to satisfy problems in communities of non-interconnected zones. As a part of these solutions, the project: Electrification for cold chains and access to Information and Communications Technology was implemented. The project made it possible to bring energy to one educational center and to create a new space that works as a refrigeration center today [6]. The system has only been monitored by the contact with the community, who reports the state of the generation system and the profits generated by the sale of products from the refrigeration center. This is a limitation because the community does not have the information to operate the system properly. In this paper, we present a review of the current state of the energy transition in Colombia and we report a case study that includes the design and implementation of a monitoring interface for a solar generation system that operates in an indigenous reservation in Colombia.

II. Design Process

Human-centered design is an approach that asserts focus on the users' needs is of vital importance in order to create interactive systems that are effective. The users of the monitoring system discussed in this paper is an indigenous community in Colombia, which implies that big cultural differences were indeed present between the developers and the users of the system. Cultural differences can be hard to overcome and thus prevent developers from obtaining a sufficient understanding of the users' need. The human-centered design process from [7] was applied to overcome this issue, together with usability heuristics well-established in the field of user interface design. In the following section, background theory of the human-centered design process and the applied usability heuristics is provided. It also includes a site description, which is a summary of the understanding of the community that was obtained following the human-centered design process.

A. Human-centered Design Process

The International Organization of Standardization (ISO) provides a framework for human-centered design in ISO 9241-210 [7]. The standard includes a four-step process of human-centered design, that defines the following design activities to be necessary in the development of any interactive system:

1) Understanding and specifying the context of use
2) Specifying user requirements
3) Producing design solutions
4) Evaluating the design

It is important to remark that one of the principles of human-centered design is that the process should be iterative. This means that each design activity should be revisited at appropriate times in order to refine the outcome (a specification or a design solution). The principle of iteration is based on the fact that users are usually better to express their needs in response to a developed solution, and any new information obtained should be reflected in the specifications and the requirements to keep the user in focus.

The planning of the human-centered design approach should take into account the resources available. The time horizon of this case study was 6 months with a field trip to the indigenous community at the end. The primary resource for identifying the user needs prior to the field trip was the previous project developed by the Universidad de La Salle in 2015 [6]. In addition, the bachelor project [8], "Monitoring system for the consumption of electric energy in a household", was researched as a similar product in order to get pinpoints on what a monitoring should include, and used to get some understanding of the energy situation in Colombia.

Understanding and specifying context of use was conducted by following the context of use example in ISO standard 9241-11 [9]. ISO standard 9241-11 defines usability and explains how to specify information necessary in order to evaluate the usability of a product. The result was a document specifying the users, tasks, equipment and environment through selected attributes considered relevant for the case study.

ISO standard 9241-11 was also used to provide a framework for specifying the user requirements [9]. User requirements was specified for each of the tasks in the context of use. According to ISO 9241-210, the usability requirements should include measurable usability performance and satisfaction criteria [9]. The usability measures includes effectiveness (accuracy and completeness), efficiency (accuracy and completeness related to the resources spent, for instance time) and satisfaction (the extent users are free from discomfort). For instance, one of the user requirements specified that less than 10 % of the users should report dissatisfaction with how the interface was accessed.

Producing design solutions involved taking into account the context of use and implement prototypes to test design solutions. Firstly, a paper prototype was produced in order to find out how the web interface should be designed before actually implementing it, and two iterations of an implemented web interface have been tested in order to achieve the design solution that was brought to Calle Santa Rosa.

Evaluation of the designed solutions were performed through usability tests. In the usability test the user interacts with the prototype or the design solution in a controlled setting by completing a set of tasks. The following steps were used to plan a usability test (freely translated from [10]):

1) Formulate the goal with the test, a hypothesis and develop a test plan.
2) Acquire test users. The test users can be selected randomly or through a stratified selection, in order to make sure any user segment is represented.
3) Prepare necessary material and context for the test.
4) Pilot test.
5) Choose test leader.
6) Conduct usability test (involves ten additional steps).
7) Transform the data to discoveries and recommendations.

The user interacts with the prototype or design solution requires the additional steps that are presented in the following list (freely translated from [10]).

1) Introduce yourself.
2) Explain the purpose of the test.
3) Tell the participant that he or she can end the test whenever they want, in case they feel uncomfortable at any point.
4) Describe the test equipment and the restrictions of the prototype.
5) Teach the participant how to "think out aloud", because it is the only way to get access to the mental model the user forms of the system.
6) Explain that you can not help during the test.
7) Ask if the participant has any questions. Else, start the test.
8) End the test by first giving the participant the chance to state any opinions. Then ask questions to collect any loose ends.

It is important that the participant knows that it is the interface that is being tested and not her or his abilities. Otherwise, the test user may be reluctant to express the mental model (by sharing the reasoning behind the actions made, "thinking out aloud") he or she has of the system, because he or she is afraid of having the "wrong" conception of the system. It is exactly the uninfluenced mental model that the participant forms of the system that is of interest, because the goal is that it deviates as little as possible from the design model the interface is intended to convey, in order for it to be easy to use. More can be read on this subject in [11].

Any important observations made during the usability test were noted in a special observation form. The observation form included a column for the relevant task, for the problem identified and for proposed solutions that e.g. the user proposes during the test or in the discussion after the usability test. The discoveries of the usability tests were used to improve the interface to the next iteration. For instance, one iteration of usability tests revealed that the users had a tendency not to use the scrolling functionality of the page to find information they needed in order to complete the tasks they were given. For this reason, an arrow icon was included in the bottom right corner of each web page as a signified of the scrolling functionality to the user. In the last usability test with the real users in Calle Santa Rosa, the usability tests was used to evaluate the final design version against the usability performance and satisfaction criteria put forward in the user requirement specification. E.g. it was measured how many of the test users in Calle Santa Rosa that reported dissatisfaction of how the interface was accessed, in order to evaluate if the goal of less than 10 % dissatisfaction rate was met.

B. Design principles

In addition to the principles of human-centered design provided by ISO, well-established usability heuristics for user interface design were used to guide the design process. Jakob Nielsen and Don Norman started the Nielsen Norman Group (NN/g) [1] in 1998, and has ever since been one of the leading voices in the field of user experience. Norman states in [11] designed the principles based on psychology and the nature of human. Thus, the idea was that despite cultural differences between developers and users, it is possible for developers to follow design principles of universal character to increase the probability of developing a product with high usability. The following ten usability principles for user interface design by Jakob Nielsen were used for this purpose, and are described in more detail in [12]:

1) Visibility of system status
2) Match between system and the real world
3) User control and freedom
4) Consistency and standards
5) Error prevention
6) Recognition rather than recall
7) Flexibility and efficiency of use
8) Aesthetic and minimalist design
9) Help users recognize, diagnose and recover from errors
10) Help and documentation

The result from following these usability heuristics manifest on the web site. For example, usability heuristic, explains the reasoning for introducing load bars on the page when the user has to wait for data to load from the database that is included in the monitoring system. Usability heuristic ten, is the reason why a user manual was written as a list of steps on how to carry out the typical user tasks that were identified using the interface.

[1]https://www.nngroup.com/

C. Site Description

In 2015 the community of Calle Santa Rosa had a solar power system installed in cooperation with the Universidad de La Salle [6]. One of the purposes of this system was powering six refrigerators used by the community for preserving produced goods by the community. In Fig. 1 it is possible to see one of the refrigerators manipulated for one community member.

Fig. 1. Refrigerator manipulated by one of the community members.

The system has given the opportunity of preserving food for longer periods and has grown into a micro-business where drinks and food are sold to the members of the community as well as to other neighbouring communities that do not have access to cold drinks or food requiring refrigeration for storage.

The system that was installed in 2015 consists of four $YingliYL250P - 29b$ solar panels providing a maximum power of $1000watts$ at peak irradiation. These panels are connected as two parallel strings of two panels in series, yielding a total open circuit voltage V_{oc} of $76.8\,V$ and a short circuit current I_{sc} of $17.58\,A$ with standard test conditions (STC). The panels are controlled by a BlueSolar Charge Controller 100/50. This controller can handle an inputs of up to $1400watts$, $100volts$ and $50amperes$. The controller provides one input for the panels and one combined output for the batteries and the loads. The controller provides very limited feedback to the user through three status indicator diodes. It does however provide an output port where additional equipment can be connected in order to read output data from the system. The storage medium installed are twelve, 2 volt single cell AGM batteries connected in series that together provide $24V$ to the system. There are six $SunDanzerDCR165$ refrigerators installed that run directly from the $24V$ of the system. These fridges are well suited for the application by having a low power consumption combined with thick insulation. Since the system is only intended for powering the six DC fridges there was no need for installing an inverter.

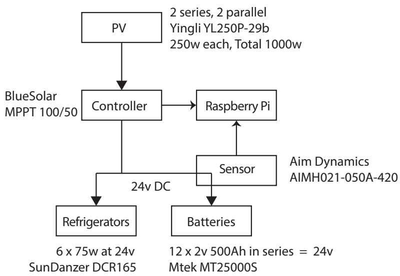

Fig. 2. Schematics of the installed system

The system was installed with a calculated autonomy of four days, but the highly variable conditions of the rain forest has provided longer periods where the power generated has been lower than the consumption. The consequence is that the batteries will from time to time run out of power with no warning to the operators of the refrigeration center. In addition to not knowing when the batteries are close to becoming empty, it is also difficult for the operators to know when the capacity is high and there may be a surplus of energy available.

III. Implementation

To accommodate the community's needs as explained in the previous section, the goal of the case study was decided to be twofold:

- To provide an interface in which the current State of Charge (SoC) is displayed.
- To provide an option to predict how many fridges can safely be run in the next 24 hours without getting to a dangerously low battery level.

This section includes details about the prediction model developed for the latter goal, the implementation process of the monitoring system in Calle Santa Rosa, and how the web interface installed in Calle Santa Rosa looks like.

A. Hardware

The entire system was implemented using a Raspberry Pi 3 model B (RPi) as the main hardware platform. The RPi was connected directly to the BlueSolar charge controller using a Ve.Direct USB connection cable produced by the manufacturer of the charge controller. This enables communication between the RPi and BlueSolar charge controller such that system information like PV panel power, output voltage and output current could be read using an open source protocol. Since there is only one output on the controller in use, the current to the load must be measured using an additional sensor. This makes it possible to separate the current going to the battery from the current going to the load. The used sensor was an Aim Dynamics $AIMH021-050A-420$ unidirectional DC hall effect sensor. This sensor was chosen mainly because it can be opened and thus does not require disconnection of cables in the installed system. In addition, the measurement signal is provided as current readings in the range of $4-20mA$. Current signals are less susceptible to noise in long signal carrying cables. Both of these features are major advantages when a sensor needs to be placed in a remote system where the conditions are unknown. The biggest drawback of using the sensor is the fact that it needs a $\pm15vdc$ power supply which is not commonly found with a $24vdc$ input. The current sensor was connected to the RPi through a $MCP3008$ external Analog to Digital Converter (ADC). The current measurement were calculated as the voltage over a resistor and the ADC was then connected to the RPi's GPIO pins. In addition to the on-chip WiFi module, an additional USB WiFi adapter was used. The idea being that the external USB module would connect the RPi to a router and the internal WiFi would act as an access point and thus providing a fall back network in case the router or the USB module would go down. Fig.3 shows the structure of the implemented system.

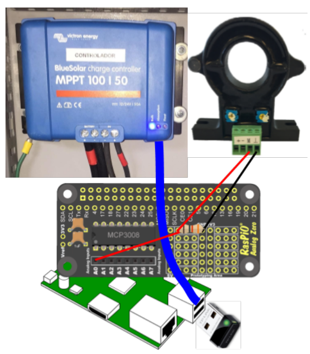

Fig. 3. Hardware setup showing the Aim Dynamics sensor, BlueSolar and WiFi module connected to the RPi

The web site that is the interface of the monitoring system runs on a LAMP stack on the RPi with MariaDB as the database solution to store energy measurements from the BlueSolar and the Aim sensor, PHP as the server-side scripting language and Google Material Design Lite was used as front-end framework to design the web site using HTML, CSS and JavaScript. The software implemented worked as intended after installing the system, but some changes in the interface design had to be made to accommodate the needs of the users that was revealed in conversations with the community

members about how they use the refrigerator center.
Upon installation in the community the RPi was attempted to be connected to the router that already existed and was used for the collective internet access of the community. The first step is to connect to the router and fix the IP address of the RPi's network interface based on its MAC address. This turned out to be impossible since access to the router setting was not available as the router is under administrative control by the Colombian government. In addition, the RPi was just out of wireless range of the router using the intended USB WiFi adapter. The extra power full backup WiFi adapter brought for such an event was unfortunately damaged in transit. The backup WiFi solution was thus instead used as the primary WiFi connection. This has a more limited range and allows much fewer simultaneous connections. Fig.4 shows one of the team members in the installation process in the refrigeration center.

Fig. 4. Installation Process in the refrigeration center

B. *Web Interface Design*

In this section, the web interface installed in Calle Santa Rosa will be presented. It represents the final design solution after several iterations of the human-centered design process. The interface is in Spanish, since the community members of Calle Santa Rosa speak Spanish as their second language, and none of the community members has English speaking capabilities, but the interface has been translated for the purpose of this text. The web interface was designed to be responsive so it fits on both computer and mobile screen sizes. The index page (front page) of the web interface is shown in Figure 5, and the equivalent page on a smart phone is shown in Figure 6.

The Figure 5 displays the front page of the web interface, and the top red menu bar reflects two main functionalities that the web interface provides the community in Calle Santa Rosa with. The front page (Figure 5) corresponds to the menu option "Refrigerator center", and displays the current status of the refrigerator center that is installed. The JavaScript library Highcharts [2] was used to produce graph to the left in Figure 5, and the graph displays the energy consumed in the refrigerator center and the energy produced by the solar panels, both in kWh, for the last 24 hours. To the right of the graph, the current battery level is shown. At the bottom on each page of the web site, a small description of what the page displays is provided. The rest of the website will be explained with the red menu bar as a starting point.

[2]https://www.highcharts.com/

C. *Prediction Model for the Solar Panel System*

The menu option "Prediction of the refrigerator center", yields a web page where the user can select a number of freezers and refrigerators using drop-down menus to run a prediction for. The user is thereby provided with a loading bar while the energy model is run in order to provide the user with a prediction on the how the battery level will evolve and the energy consumption and production will progress the next 24 hours for the selected number of freezers and refrigerators. First, the user receives a pop-up box that express either "Be careful!1", and the time of which the batteries will exceed the recommended minimum battery level, or "Very good!!", if that is not the case. In Fig.7 is possible to see the result of one of the predictions.

The user has to click this pop-up box away in order to see graphs that report the prediction. That includes one graph that shows the predicted progress of the battery level for the next 24 hours with the red bar indicating the recommended battery level, and a second graph that shows the energy consumption and production of the refrigerator center, similar to the graph in Figure 5, but for the 24 hours ahead.

The page for prediction was altered after conversations with the community. Originally, the prediction page included buttons from one to six that the user could click in order to see how many refrigerators the solar panel system had energy to power. Conversations with the community once in the Calle Santa Rosa revealed that some of the refrigerators were used as freezers by switching the thermostat of the refrigerator to the coldest possible. A freezer use more energy than a refrigerator, so a distinction between the number of freezers and number of refrigerators had to be made. In addition, the salesman of the refrigerator center would prefer to use more of the refrigerators as freezers than the current two, but the lack of any display of the refrigerator center's energy status had made it difficult for him to experiment with anything beyond the recommendations he was given in 2015. A new design for the prediction page was proposed and shown as a paper prototype to the salesman to check whether the new solution would accommodate his needs. The prediction page was thereby changed to give him a tool he could use to evaluate if he could turn on more freezers. This illustrates the importance of user involvement and how new information drives the human-centered design process from one iteration the the next.

The prediction is based on a model created with Matlab's Simulink Simscape Power Systems. The model takes the current battery level and predicted irradiation and temperature levels from NASA as its input. The sub-models consists of models for the PV panels, the DCDC converter, the batteries,

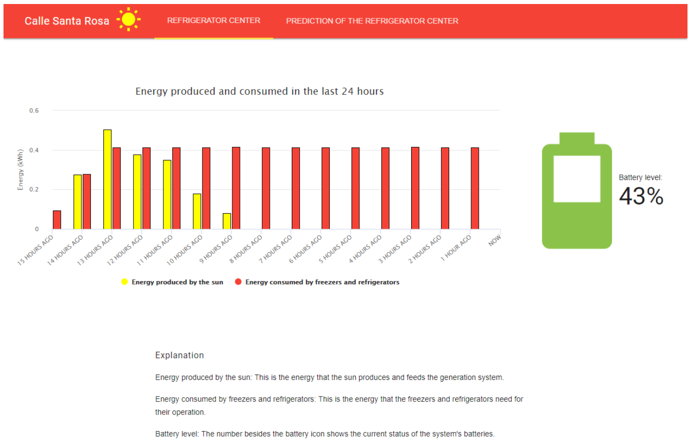

Fig. 5. The index page (front page) of the web site that displays the current status of the refrigerator center. The graph to the left shows energy consumption and production in the last 24 hours, and the icon to the right shows the current battery level.

the refrigerator loads and the Maximum PowerPoint Tracker (MPPT). The prediction model is intended to run on user input request and it is therefore desirable to have the simulation time as low as possible such that the waiting time would be minimal. This was achieved by simulating for 24 seconds and subsequently multiplying all relevant values with 3600 such that the simulation would be valid for 24 hours instead. The consequence of implementing the model in this way is that certain library models included with Simulink, such as those for batteries, can not be used. Thus, the battery model was instead implemented as a Coulomb counter. This simplification is further justified by the fact that more detailed battery modeling would be beyond the scope of our master thesis. The PV panel model was based on a script provided in [13]. Using this script together with current sources in Simulink yielded faster simulations than with the included Simulink block. An averaged DCDC buck converter model was used for stepping down the voltage from the panels to the operating voltage of the batteries and the duty cycle was controlled by a Perturb and Observe (P&O) MPPT control algorithm. C++ code was generated in order to further increase simulation speed and with the added benefit of being able to run on a larger number of platforms.

In order to keep track of the current SoC of the batteries a Coulomb counter is being run in real time by counting the current going to the battery and coming from the battery.

IV. Validation with the community

Usability tests were performed in Calle Santa Rosa with the monitoring system installed to evaluate the final design version against the usability performance and satisfaction criteria put forward in the user requirement specification.

The usability tests had to be performed with the help of Universidad de La Salle students because it has to be performed in Spanish as the community members do not speak English. The usability performance and satisfaction criteria were transformed into check boxes and questions the students could answer instead during the usability test so the results could be easily counted afterwards. In Fig.8 we show the moment when the usability test is applied in one of the community members.

Five community members were engaged in the usability testing according to Jakob Nielsen's theory in [14]. The participants were the following:

- The administrator of the Communication Technology center (CTC). The CTC got granted by the government with computer and Internet.
- The salesman of the refrigerator center.
- One among the most skilled community members in communications technology.
- A woman that worked as a chef in the neighbouring community building.
- The school teacher and the administrator of the solar panel systems.

All tested the interface on a smart phone. There was a big difference between the skills of the participants. The school teacher was undoubtedly more familiar with graphs than the rest and solved the tasks faster than the others. The woman that worked as a chef had very little experience with communications technology, and the usability test turned more into a training session. Close to all satisfaction criteria put forward in the the user requirement specification developed were met. All five participants of the usability test answered ”Yes” to whether they were satisfies with how easy to find the

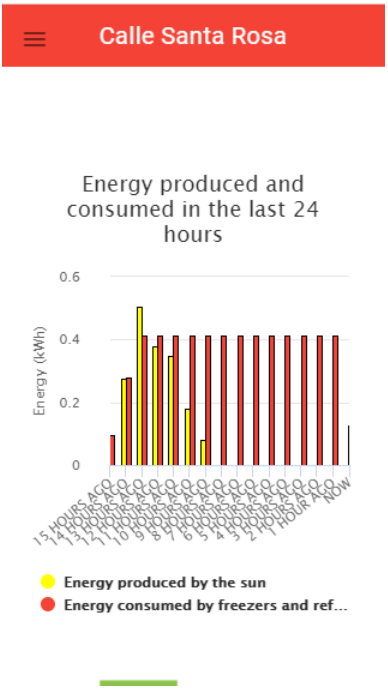

Fig. 6. The equivalent of the index page on a smartphone. The graph shows energy consumption and production in the last 24 hours, and the icon showing the battery level

battery level, to find the web page with the refrigerator center's status, to read the energy consumption and production of the graphs and to run a prediction. The salesman in the refrigerator center expressed that he found the web interface very useful when asked if he would use the web interface in his future work when deciding the number of freezers and refrigerators he could have running, even despite the fact that he had never used a cell phone before. The community's school teacher and administrator of the solar panel systems stated that the interface would be very important because it allows them to know the appropriate level of the batteries, when he was asked whether he thought the web interface should be useful in community meetings when deciding upon the operation of the refrigerator center. However, the satisfaction criteria of how easy it was to access the web interface was not met. The goals were that less than 10 % of the test users would report dissatisfaction, but two of the test participants answered it was difficult to access the web page because it was accessed by typing into the web browser the correct IP-address instead of the human-readable host names (such as www.google.com) they were more used to. Finally, all the information was

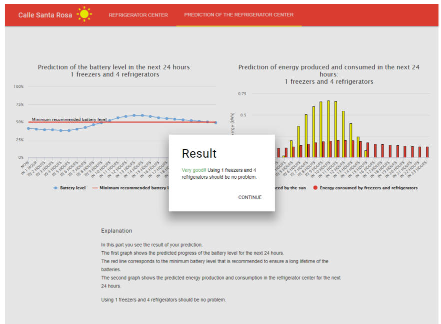

Fig. 7. After the pop-up box is clicked away, two graphs show the result of the prediction. To the left is the graph showing the predicted battery level for the next 24 hours (the red line marks the minimum recommended battery level). To the right, the predicted energy consumption and production for the next 24 hours is given.

Fig. 8. Usability testing in Calle Santa Rosa.

transfer to the community. In Fig.8 we show the moment of a trainning sesion with the community.

V. Conclusions

A monitoring system for a PV solar energy production system was developed and implemented in a rural locality in Colombia, with the main objective of providing decision support to the local community to better exploit their micro-business. The monitoring system was designed and implemented as a joint project between students of the Norwegian University of Science and Technology and Universidad de La Salle.

A Raspberry Pi was used to host the web interface locally in the rural area. It served as a great tool throughout the case study as a lightweight computer that is cheap (contributing to making the overall monitoring system cheap). Also, Raspberry Pi is an educational tool that is used to teach computer science to children in school. Perhaps Raspberry Pi can be used in a

Fig. 9. Meeting with the community.

similar way in rural areas that are new to technology in order to inspire and educate the population.

The fact that the monitoring system was successfully installed and close to all satisfaction criteria was met, shows that development of rural electrification projects need the use of technology in different fields, and alliances between countries (in this case Colombia and Norway) can support this development. This is a promising result because speed of growth of rural electrification projects can be increased when development can happen in collaboration with developed countries where the level of technical knowledge is higher. The human-centered design process from the ISO standard 9241-210 was used to overcome the cultural differences between the developers and the users, and served as a great tool to guide the work process and to keep the community's needs at the center of the case study. However, the case study also shows the importance of including the real users.

During the case study, it was experienced that support for open source communication by the producers of photovoltaic system equipment seems to be rather the exception. The open source communication protocol by Victron Energy was experienced as an necessity in the development of an affordable monitoring system for Calle Santa Rosa, which will be elaborated in the following. In our viewpoint, open source support should be an important concern when designing micrograids and choosing equipment for a photovoltaic solar system. It facilitates the development of alternative, more affordable monitoring solutions that can enable owners of microgrids to utilize the system to its fullest. The JavaScript library Highcharts was experienced as a highly flexible charting library and is recommendable.

The level at which the human-centered design process was followed can be disputed. For example, the ISO standard 9241-210 provides a sample procedure for assessing applicability and conformance with the process, but this was considered outside the scope of the case study. Also, inspection-based evaluation methods in which experts who put themselves in the role of a user to investigate how the interface complies with design heuristics is by ISO 9241-219 considered one of the most widely used approaches to user-centered evaluation was excluded in this research. This case study was an interdisciplinary one in which compromises had to made in order to make sure the time limit of the case study was adhered. Although the authors were novices in the field of interaction design, it was believed that to let usability heuristics guide the design process would only help enhance the quality of the product.

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