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 were 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

[1]https://www.nngroup.com/

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.

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 $SunDanzer DCR165$ 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.

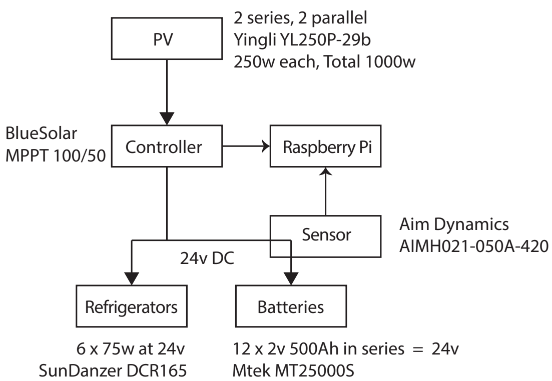

Fig. 2. Schematics of the installed system

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.

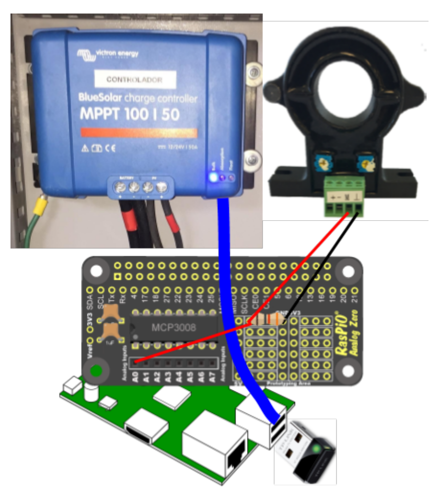

Fig. 3. Hardware setup showing the Aim Dynamics sensor, BlueSolar and WiFi module connected to the RPi

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.

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.

[2]https://www.highcharts.com/

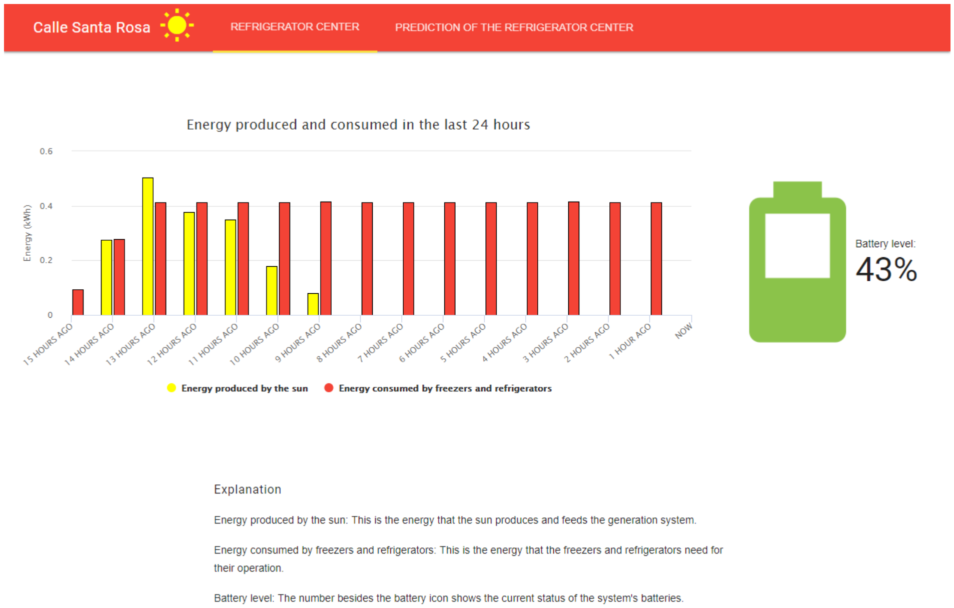

Fig. 5. The index page (front page) of the web site that displays the current status of the refrigerator center. The graph to the left shows energy consumption and production in the last 24 hours, and the icon to the right shows the current battery level.

The 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, 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.

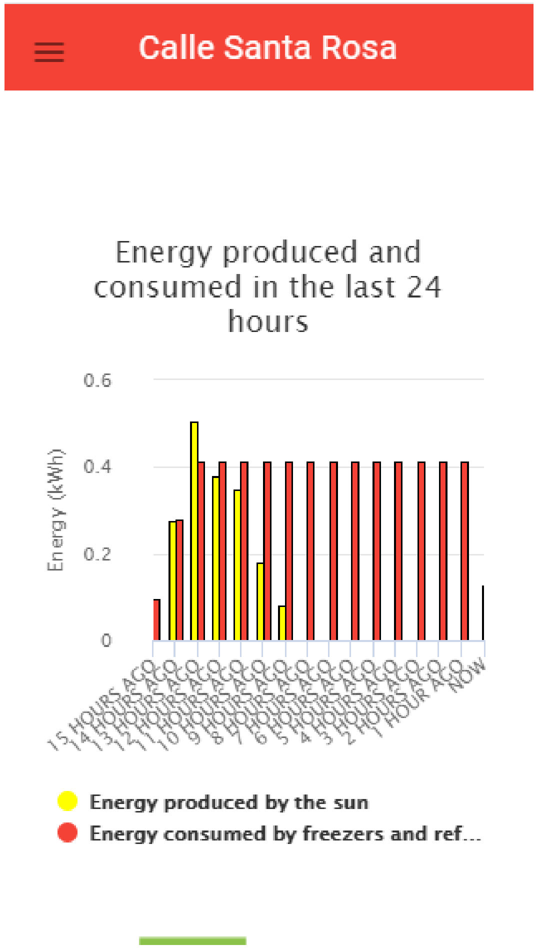

Fig. 6. The equivalent of the index page on a smartphone. The graph shows energy consumption and production in the last 24 hours, and the icon showing the battery level

- 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 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

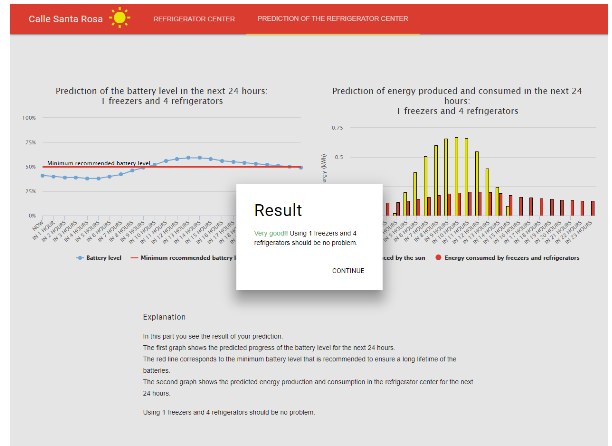

Fig. 7. After the pop-up box is clicked away, two graphs show the result of the prediction. To the left is the graph showing the predicted battery level for the next 24 hours (the red line marks the minimum recommended battery level). To the right, the predicted energy consumption and production for the next 24 hours is given.

Fig. 8. Usability testing in Calle Santa Rosa.

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 transfer to the community. In Fig.8 we show the moment of a trainning sesion with the community.

Fig. 9. Meeting 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 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 microgrids 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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