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Off-grid Energy Monitoring

A thesis submitted in partial fulfilment

of the requirements for the degree

of

Master of Science

in Computer Science

at

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by

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Abstract

A range of circumstances and physical conditions exist in New Zealand that strongly motivates the adoption of off-grid electricity systems. However, there is scant detailed knowledge and understanding of many aspects of their use, including their effectiveness and economics. Moreover, the availability of detailed data on their use, which could produce this knowledge and potentially help to more effectively control these systems, is likewise lacking. Along with an interest in such systems in New Zealand, attention on the developing world, particularly the Pacific region, is also evident.

This research first involves a review of off-grid systems in New Zealand, particularly in terms of scale and form, along with related monitoring work performed within and outside the country, and the monitoring hardware and software used for that task. Second, the installation of precision monitoring equipment and associated communications are evaluated in terms of available off-grid residential systems of genuine off-grid systems, full-time permanently occupied residencies, and non-grid connections. Third, the commissioning and testing of the above-related equipment, and the storing of the data in a database, is conducted. Fourth, the development of real-time monitoring dashboards and data analysis techniques that provide short-, medium-, and long-term information on installation operations is performed. Finally, opportunities for improvement, including controls leading to improvement, are identified.

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Chapter 1: Introduction

This thesis involves the study of off-grid electricity systems. Many homeowners, particularly in remote locations, are concerned about fossil fuel exploration and extraction, which contribute to environmental damage. Motivated by this concern, many homeowners are transitioning to off-grid means of generating energy, despite the initial costs of establishing these systems (Canada Mortgage and Housing Corporation, 2001). To contribute towards the overall success and usability of these renewable energy sources, an awareness of energy usage patterns, efficient energy-saving appliances, and non-electrical forms is required (Wind and Sun, n.d.). As the number of homeowners using solar and other alternative energy sources continues to grow, awareness of the need for energy management strategies has become essential (Banerjee, Rollins, & Moran, n.d.).

To address this need, this thesis focuses on monitoring and gathering detailed data from an off-grid system to develop an understanding of usage patterns and to optimise them.

1.1 Motivation

In the past, a large amount of electricity in New Zealand was produced from renewable resources, which were derived from geothermal and hydro supplies. However, in 2008, a severe drought caused an increase in the use of gas and coal for energy. Although 65% of energy in New Zealand that year came from renewable sources (New Zealand Ministry of Economic Development, 2009), the drought fostered a heightened awareness of the need for additional sources of renewable energy. Since that time, the New Zealand government has commissioned several studies on the viability of transitioning the country's energy consumption to reach a 90% level from renewable sources by 2025 (see Figure 1.1) (New Zealand Ministry of Economic Development, 2009).

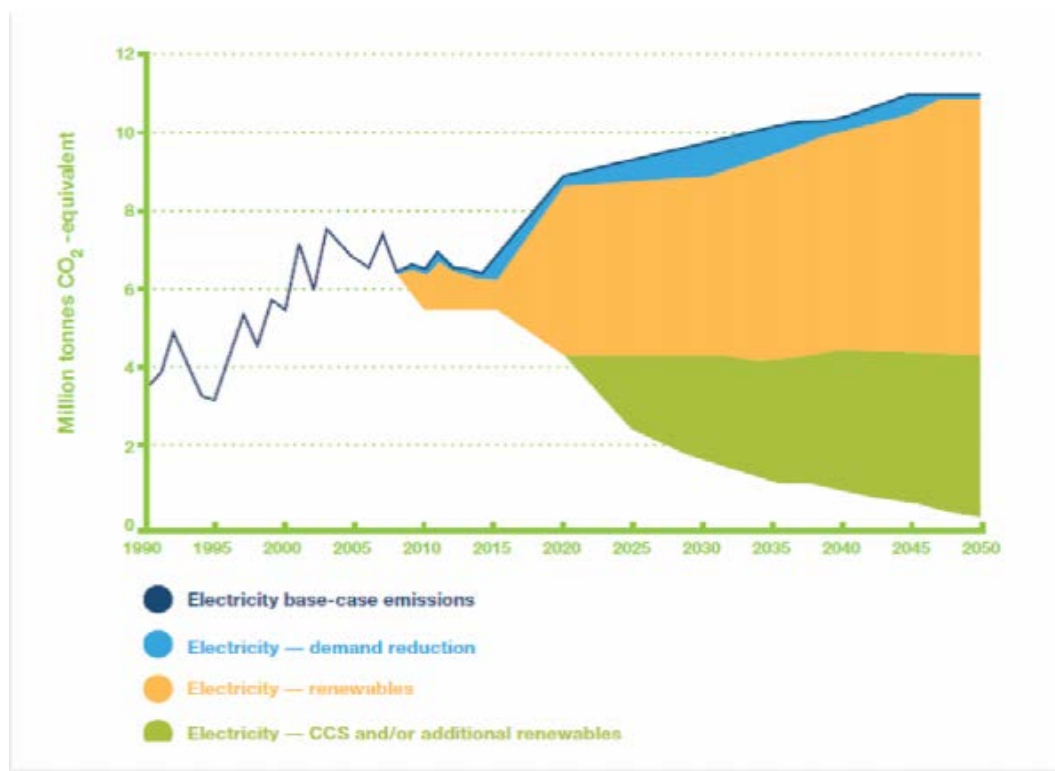


Figure 1.1 : Plan for renewable resource use by 2025 (reproduced from the New Zealand Ministry of Economic Development, 2009)

A steady interest in more sustainable electricity sources has meant an increase in the demand for off-grid photovoltaic (PV) systems and the need for monitoring the amount of power being used and generated. ‘The first rule of off-grid living’, as one researcher notes, ‘is that the electricity you produce must be equal to or greater than the electricity you consume’ (Energy Solutions Centre and Natural Resources Canada, 2005). Therefore, using a monitor can enable users to determine how much power is remaining in the system before the power runs out, which thereby assists them in maintaining a level of available energy sufficient to their needs. Moreover, monitor use can help users manage their PV systems so they run at an optimal level.

Living off-grid involves an increased awareness of what appliances draw the most electricity and when the peak electrical demands are for the system. This awareness can help on-grid users as well; knowing sources of electricity consumption in a household and their timing can enable users to monitor, control, and reduce their electrical power consumption and costs. An understanding of household usage patterns has enabled some users to change their lighting, heating,

communication, and entertainment devices to reduce their energy needs (Energy Solutions Centre and Natural Resources Canada, 2005).

Although there has been a growing interest in electricity-monitoring consumer devices over the past few years, systems that provide the required level of detail—and which are suitable for off-grid environments—are not readily available. Consumer device hardware and software systems must be developed to provide the necessary information.

1.2 Objective

This research focuses on off-grid systems because these systems are critical for their users in the long term, particularly in terms of effectiveness and economic factors. The research results are applicable to the above and to emerging nano-grid systems (small communities, such as in the Pacific region), off-grid farms, and off-grid businesses. In these cases, the economics of power distribution have made off-grid systems an increasingly attractive option, which even electricity providers have promoted.

1.3 Approaches

The proposed research involves the following:

1. A review of (a) existing off-grid systems in New Zealand, particularly in terms of scale and form; (b) related monitoring work being done in New Zealand and internationally; and (c) monitoring hardware and software suitable for the task.
2. The installation of precision monitoring equipment and associated communications in an available off-grid residential system.
3. The commissioning and testing of the above equipment, which includes data entering an off-grid monitoring database.
4. The development of real-time monitoring dashboards and data-analysis techniques for providing short-, medium-, and long-term information on installation operations.
5. The analysis of this data and the initial identification of opportunities for improvement or for controls leading to improvement.

1.4 Research questions

The objective of this research is to describe the monitoring-equipment installation process in a sample off-grid residential system. In addition, the research involves developing software to collect the power monitoring data from the equipment used and to store it in a database. It further includes building a monitoring dashboard to display the real-time data with analysis techniques that provide short-, medium-, and long-term information. This information is intended to enable identification of opportunities for improvement, or controls leading to improvement.

To inform this research, potential questions to be addressed include the following:

- Can scheduling of appliances improve efficiency and reduce the need for back-up generation?
- Is it possible to gain a sound understanding of a battery's state of charge, health, and life expectancy?
- Is it possible to perform 'smart' load dumping with wind, solar or hydro energy generation, which would use surplus energy rather than waste it?
- What are the opportunities for utilising storage capacity in other appliances?
- What are the benefits from installing solar panels, and are they worth the initial costs?

1.5 Thesis structure

In Chapter 2, off-grid systems in New Zealand are presented with a focus on their forms and scales. Related monitoring projects in New Zealand and other countries are then reviewed. Examples of monitoring hardware and software available in New Zealand are outlined. In Chapter 3, the off-grid residential system used for this research and its environment are described. In Chapter 4, installation of precision monitoring equipment, equipment commissioning and testing, and data flow into the database are presented. In Chapter 5, examples of data visualisations, the development of real-time monitoring dashboard designs, and descriptions of their implementation are provided. Battery state-of-charge monitoring is discussed

in Chapter 6. In Chapter 7, the thesis conclusion and suggestions for future research are presented.

Chapter 2: Background

In this chapter, New Zealand off-grid systems, with a focus on their forms and scales, are presented. Related monitoring projects within and outside New Zealand are then reviewed, and examples of monitoring hardware and software available in New Zealand are outlined.

2.1 Off-grid systems in New Zealand

For those who live ‘on-grid’, an awareness of the amount of electrical energy they are consuming, its source, and whether it is being used at peak times is typically not critical information. However, those who live ‘off-grid’ must be acutely aware of all electricity consumption, its source, and when peak usage occurs (Apperley, 2013). For example, using the oven will increase both the energy generated and the power usage, while using the kettle will consume less energy but still require a high amount of power. These types of considerations are important for off-grid energy users. Other factors that off-grid energy users must be aware of include the energy consumption of each appliance, both per use and daily total; this information guides users on the limits of their inverter or battery capacity. In addition, load matching is helpful to the off-grid user when multiple energy sources are used, such as by employing solar energy on sunny days and non-solar sources on cloudy days. This selective approach may also inform issues that off-grid users must consider—with the aim of balancing their energy use with the comforts that appliances add to their daily lives (Apperley, 2013).

Most off-grid residential systems in New Zealand fit in three categories of users: full-time off-grid, part-time off-grid, and grid-tie.

2.1.1 Full-time off-grid users

Users in this category live their lives fully off the grid. Most of them are full-time off-grid users because they live in a remote location where there is no municipal electricity supply. However, in some cases, it may be a lifestyle choice to be disconnected from the grid, even though a connection may be available. For example, one high-country new homeowner made this lifestyle choice when she was quoted that it would cost her between \$24,000 and \$30,000 to have electricity

run to her house being built on a 3.9 acre bush block because of the remote property location (EECA, 2013). She considered other means of obtaining electricity, and ultimately chose to be independent and to never again receive a power bill: she set up a solar system with a gas back-up to save electricity in the long-term. Her home uses the top range of energy-saving appliances, is fully insulated, and has minimal energy requirements, all of which make being off-grid an affordable and manageable option. This option enables her everything that she would have had on a grid-tied system, including comfort and a good standard of living, as well as cost-savings with no monthly power bill. Her off-grid system has a nominal battery storage capacity of 36 kWh, 800 W solar PV panels, and an inverter capable of delivering 230 V AC up to 3 kW (EECA, 2013).

2.1.2 Part-time off-grid users

The users in this category are those, for example, who have an off-grid weekend home or house boat, where they typically stay for short periods. The rest of their lives are lived on the grid. For example, a family with a Motukiekie Island holiday home that is used only for ten to twelve weeks a year find that having a solar power system provides them with all the home comforts. Moreover, the electricity needs in their holiday home remain high because of the number of modern conveniences they have (EECA, 2013). Their system was developed over time to meet their needs and those of a caretaker, who lives full-time on the property in an apartment and who maintains the system. The overall consumption when their home is occupied is approximately 8 kWh per day. The system includes an extensive PV array, micro wind turbine, large battery bank, and small diesel generator that charges the batteries once a day for an hour and a half; additionally, it provides power under high loads, such as for the clothes dryer (EECA, 2013).

2.1.3 Grid-tied users

The users of this category have both a grid connection and their own power-generation system, such as solar PV, which fulfils some of their electricity needs. When additional electricity is required, these users can draw from the grid; or, when their own power generation exceeds their requirements, they can feed the surplus back to the grid. Taurikura Lodge is an example of this system working

well. Renewable energy is generated there, and the surplus is sold back to the grid. The lodge owners receive monthly payments for the surplus (EECA, 2013). For the approximately 2,100 kWh that they exported to the grid one summer month, they received a \$380 credit on their power bill. With their energy generation system and energy-efficient adaption of their lodge, they intend to maintain this exchange dynamic to never again receive another power bill (EECA, 2013).

2.2 Off-grid system technology and characteristics

2.2.1 Electricity generation

Electricity generation in off-grid systems primarily relies on PV systems with a backup source, such as a diesel generator or another renewable source, such as wind or hydro. The effectiveness of these PV systems relies on correct panel placement and system modulation to control energy input and output (Canada Mortgage and Housing Corporation, 2001).

2.2.2 Storage

The energy harnessed from solar panels is typically stored in a series of batteries (Murphy, 2012). However, this storage method has several limitations, such as the requirement of knowing how much electricity is available at a given time. To determine this information, a calculation of amp hours (Ah) is performed by multiplying incoming current by time. The result is the measurement rate on remaining power in the battery. For example, if 100 Ah are entering the battery from the solar panel, fewer Ah will be available as output. It has been reported that battery storage delivers 83% of input (Murphy, 2012). This loss of power can be explained by how the battery stores the energy inputted during the day and then discharges it at night; over time, this erratic charge and discharge causes a loss in battery life (Murphy, 2012).

2.2.3 Inverters

‘A power inverter...is an electrical power converter that changes direct current (DC) to alternating current (AC). The input voltage, output voltage, and frequency are dependent on design’ (Wikipedia, 2013). The inverter changes the energy from DC to AC energy form, which enables it to be used in a domestic

house (Caamaño-Martín, Masa, Gutiérrez, Monasterio, Castillo, Jiménez-Leube, & Porro, 2009). The inverter can be programmed to operate in specific periods in which it is charging from the PV system or discharging into the house to support peak time usage (Caamaño-Martín et al., 2009).

2.2.4 Required information

Knowing about energy management systems is an essential part of successfully running a self-contained off-grid system (Zelazo, Dai, & Mesbahi, 2012). Many complex approaches can be used—including dynamic programming, mixed-integer linear programming (MILP), and direct load control (DLC)—to regulate energy combined with the factors above for completing the balance of system equipment required. However, the user must find an approach that they understand and can effectively manage (Zelazo et al., 2012). The providing of real-time information to users is possibly the most important method for enabling them to understand and independently manage their usage.

2.3 Related monitoring research

The objective of a study based in the US by Rollins and other researchers on off-grid monitoring devices is similar to the present research (Banerjee et al., n.d.). Their system measured both the energy generated by an off-grid house powered by a renewable source and its overall energy consumption. Their monitoring system was comprised of a single device, a MATE¹ remote, which collected data through an RS232 interface from an inverter at a rate of one sample per minute. Instantaneous residual battery life in volts and household energy consumption in kilowatt hours were stored on a Fit PC² through a customized software tool in an append-only log.

The researchers stated that an awareness of the increased need to gauge low and high energy demand times would be helpful to users of these off-grid systems. They observed that users held a reactive stance to energy saving when battery levels became low, rather than an informed stance to conserve energy before

¹ <http://www.outbackpower.com/downloads/documents/1401103031817mate.pdf>

² <http://www.fit-pc.com/web/>

critical levels were reached. The monitoring devices Rollins discussed provide off-grid system users with an increased awareness (Banerjee et al., n.d.).

Another study conducted in Canada on the energy consumption of off-grid houses focused on manually recording data from 12 local houses to determine the energy used as well as the lifestyle the home owners developed to contend with the fluctuating energy supply (Canada Mortgage and Housing Corporation, 2001). Each house in the study was assessed for its energy source, system size, storage system used, and potential electrical load. Many users employed a simple PV setup with a diesel-powered backup generator, while others used a complex hybrid system to obtain their energy from wind, micro-hydro, and PV (Canada Mortgage and Housing Corporation, 2001).

Murphy (2013) discussed two independent data recording systems he built to collect data over two and a half years from PV panels powering his home (Murphy, 2012). One system was used in parallel with a grid connection. The average daily energy used from the grid amounted to 1.8 kWh each day, which contributed to total electricity use of 4.5 kWh per day. Energy storage in his four batteries resulted in 1,686 kWh being available over 30 months, with a de-rated value of 1.5 kWh per battery. The results showed high and low peak times over the given period, various seasons, and each day. However, his research was limited in that he was not able to monitor the accurate amount of power entering the system because the batteries were full over the summer period. Nevertheless, as a research document, his results represent one of the longest periods of consistent recording of this type of data. Moreover, the results presented in his graphs enable the present study to project similar findings as if the research were run for a longer time period (Murphy, 2012).

In addition, Lee and other researchers proposed the use of a smart metering system to access data from a PV renewable energy system. They described their smart meter as an advanced version of a conventional meter with the added ability of detailed measuring. It is equipped with the ability to send/receive data and detect outages, along with a communication device, remote control, power quality reader, meter tampering detector, meter synchronizer, and a large amount of memory to store the data (Lee & Lai, 2009). Their smart meter is very similar to

the one designed by the present researcher for this study. Their research and studies like it are good informational resources for those designing a meter to measure PV energy systems; they provide a sound framework that can be adjusted to suit the researcher (Lee & Lai, 2009).

2.4 Monitoring systems

2.4.1 Available monitoring devices and software

Professor Sami Rollins of the University of San Francisco believes that knowing how much power the grid solar panels in their homes are producing can help homeowners provide a transition to the grid whenever their solar power is depleted (Riddell, 2011). Professor Rollins is developing tools to enable this capability for those living in off-grid homes (Riddell, 2011).

Several devices and related software have been developed to monitor power consumption. They can be categorized in two groups: those that monitor power consumption, and those that collect and display data from the monitoring devices. Both are relevant to the present project, which involves collecting data from different monitoring devices and using software to display the data online.

2.4.2 Monitoring devices

Several commercial solutions have been developed to monitor power consumption. These can be separated into two groups. The first focuses on monitoring DC power consumption; the second focuses on monitoring AC power consumption.

DC monitoring devices

Numerous commercial products in this group are available. These devices can monitor electrical power for homes, motor homes, and boat batteries (Sun Power Plus, 2013), while providing information on energy usage, battery state, and system issues when they occur (Sun Power Plus, 2013). Three of these devices are highlighted in this section. From Bogart Engineering and Sun Power Plus, these devices offer a range of functions (Bogart Engineering, 2010).

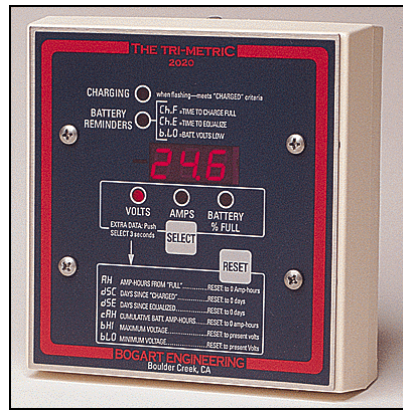


Figure 2.1: TriMetric TM2020 Battery Monitor (reproduced from Sun Power Plus, 2013)

The TriMetric TM2020 Battery Monitor, shown in Figure 2.1, can monitor DC power consumption. It can measure battery voltage, charge percentage, amps, amp hours, and five other data functions (Sun Power Plus, 2013). When the batteries are registered as being charged by the TriMetric monitor, the device resets the amp hours to zero and the battery charge is set to 100% if required by the user. It can also inform the user of charge voltage at any programmed time within the charging process, which helps the user know its efficiency. In addition, when power is not connected to it, the TriMetric monitor retains all information prior to shutdown. When operational, it has a low current draw and clear display.

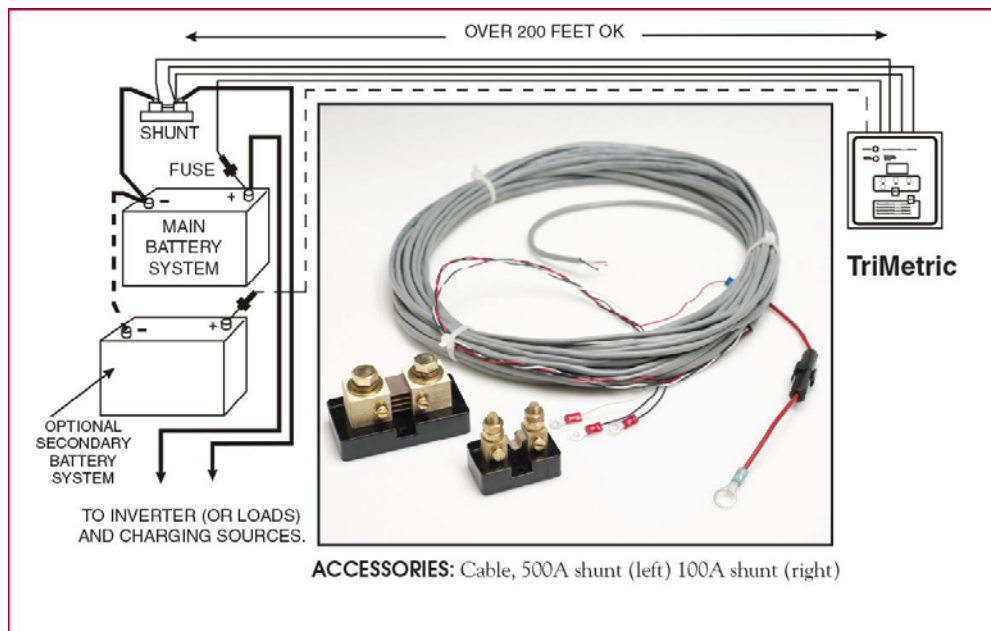


Figure 2.2: TriMetric TM2020 Battery Monitor accessories (reproduced from Sun Power Plus, 2013)

The monitor comes with an adapter that enables the monitor to operate on a 48 V system, as well as lightening protection for systems from 12 to 48 V. Two shunts are available for this monitor, which are required to monitor amps and amp hours, (see Figure 2.2) (Sun Power Plus, 2013).

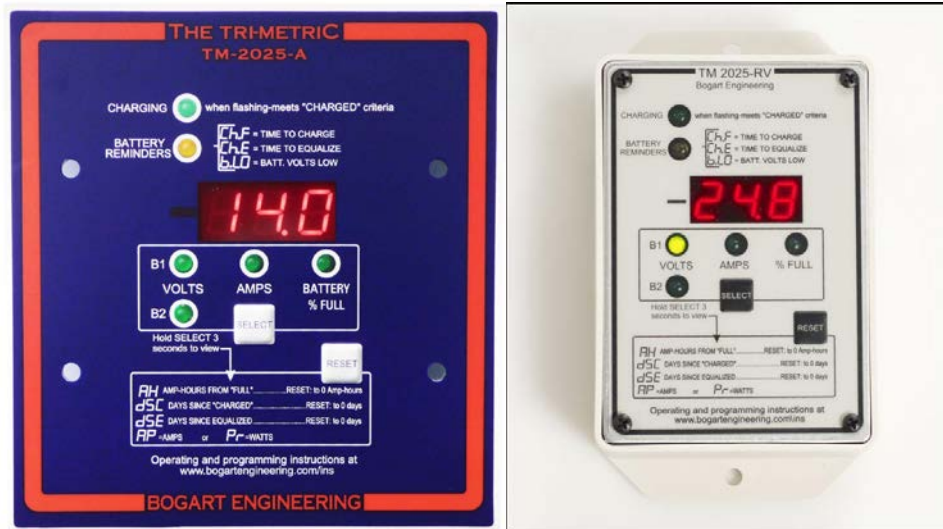


Figure 2.3 : TriMetric TM2025-RV / TM2025-A Battery Monitor (reproduced from Sun Power Plus, 2013)

The TriMetric TM2025-RV / TM2025-A Battery Monitor, shown in Figure 2.3, operates with 12 to 48 V battery systems (Bogart Engineering, 2010). This device can measure the following in the battery:

- **Charge percentage:** To verify level of charge and gauge whether it requires more charge.
- **Voltage:** To determine that the correct voltage is entering the battery.
- **Energy input/output:** Amps and watts can be measured.
- **Days since last full charge:** Information to help maximize the battery life by reminding the user to charge them.
- **Voltage-only data for second battery:** When more than one battery is operating, full data is available for the first battery, while voltage-only data is available for the second.



Figure 2.4: PentaMetric Battery Monitor (reproduced from Sun Power Plus, 2013)

Another device that monitors DC power consumption is the PentaMetric Battery Monitor, shown in Figure 2.4. It can measure two batteries with a common negative and two loads (Bogart Engineering, 2010). This device includes an input unit, display unit, and RS232, USB, and Ethernet/Internet interfaces. The input unit and one of the interfaces are required to collect the data from this device, while the remaining components are optional (Bogart Engineering, 2010). The components used in this project include only the input unit and USB interface. This device can measure the following:

- **Volts:** From 8 to 100 V and two-channel voltage.
- **Amps:** ± 0.01 to 200 A and three-channel amps.
- **Temperature:** -20°C to 65°C .
- **Amp Hour:** Up to $\pm 83,000$ Ah and three channels.
- **Cumulative (Negative) Battery Amp Hours:** Up to $-1,000,000$ Ah and two channels.
- **Smoothed (Time-filtered) Amps:** From ± 0.01 to 200 A (100A/100mV shunt), or from ± 0.1 to 1,000 A (500A/50mV shunt), and three channels with time constants of 0.5, 2, or 8 min.
- **Smoothed (Time-filtered) Volts:** From 0 to 100 V and two channels.
- **Watts:** From ± 0.1 to 20,000 W and two channels.
- **Watts (Hours):** $\pm 21,000$ kWh and two channels.

- **Battery % Full:** From 0 to 100% and two channels.
- **Days Since Charged:** From 0.01 to 250 days and two channels.
- **Days Since Equalised:** From 0.01 to 250 days and two channels (Sun Power Plus, 2013).

AC monitoring devices

In addition, there several available commercial products that can measure AC power consumption.



Figure 2.5: Smart Circuit 20 (reproduced from Watts Up?, n.d.)

One device that can monitor voltage and current and switch loads on/off is the Smart Circuit 20, shown in Figure 2.5 (Inverters R Us, 2013). This device can send data every second. Its specifications include the ability to measure 100 to 250 V, 50/60 Hz, 20 A, and with USB and Ethernet interfaces (Watts Up?, n.d.).

This device measures and records current watts, minimum/maximum watts, power factor, volt amp (apparent PWR), cumulative watt hours, average monthly kWh, elapsed time, duty cycle, frequency (Hz), cumulative cost, average monthly cost, line voltage, minimum/maximum volts, current amps, and minimum/maximum amps (Inverters R Us, 2013).



Figure 2.6: Current Cost ENVI Energy Monitor (reproduced from EnviroGadget, 2010)

Another solution for monitoring AC power consumption is the Current Cost ENVI Energy Monitor, shown in Figure 2.6 (EnviroGadget, 2010). This device provides homeowners with their electricity usage data through a wireless display unit. It includes a sensor, transmitter, and display unit. When installing the device, users must connect the sensor at one end of the transmitter and clamp the other end to the live energy supply (typically the cable exiting the home electricity meter). All electricity usage data is sent from the transmitter to the display unit through a wireless connection up to 30 m from it. The display unit provides homeowners with many details regarding their electricity usage. For example, the cost of the current electricity drain can be communicated. This information can be provided by the display unit in graph form, showing day, evening, and night consumption. In addition, the display unit notifies homeowners how the new information differs from previous consumption, it can use stored information, and the stored information can be used to calculate daily, weekly, and monthly consumption and costs.

The Current Cost ENVI Energy Monitor system can track up to nine individual appliances and show the energy usage of each one. For this function, individual appliance modules are required. The appliance to be monitored must be plugged into the individual appliance module, which in turn must be plugged into the wall socket (EnviroGadget, 2010).

2.4.3 Software

Numerous software have been developed for monitoring AC power consumption. The software is categorized in two groups: web-based and desktop.

Web-based software

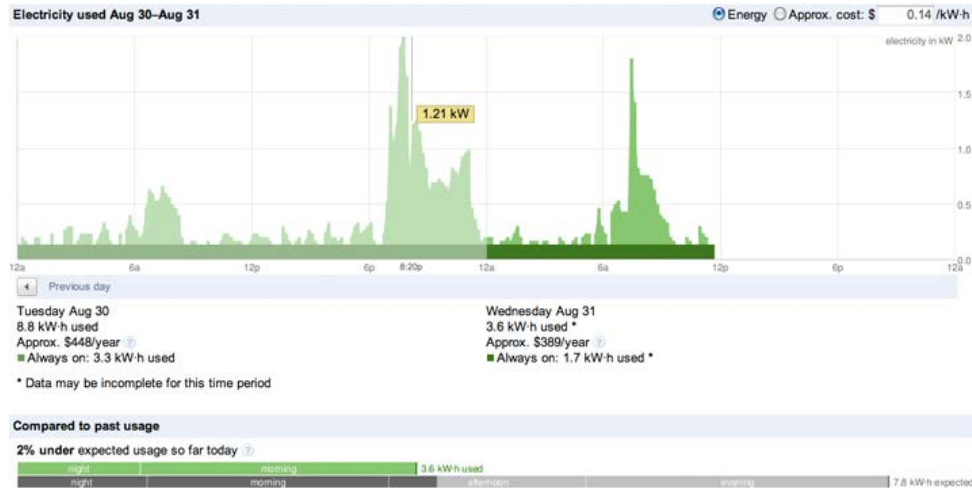


Figure 2.7: Google PowerMeter (reproduced from Google, n.d.)

Google PowerMeter, shown in Figure 2.7, is a free, web-based energy-monitoring tool that was launched to raise awareness about the importance of accessing and being informed about one's energy usage (Google, n.d.). Unfortunately, this software service has not been active since September 16, 2011 (Google, n.d.).



Figure 2.8: Watts Up? software (reproduced from Foster et al., 2010)

The Wattson energy monitor uses the Watts Up? web-based Facebook application to monitor user energy consumption, as shown in Figure 2.8. Users can display their usage data and compare it with their friends' data on Facebook. The data is displayed in bar graphs and tables by weekly consumption. The application fosters energy conservation awareness and support among friends (Foster, Lawson, Blythe & Cairns, 2010).

Desktop software

Numerous software in the desktop category have been developed to help homeowners monitor their energy data. Some users prefer desktop over web-based software so they can locally store their usage data and it is readily available to them.

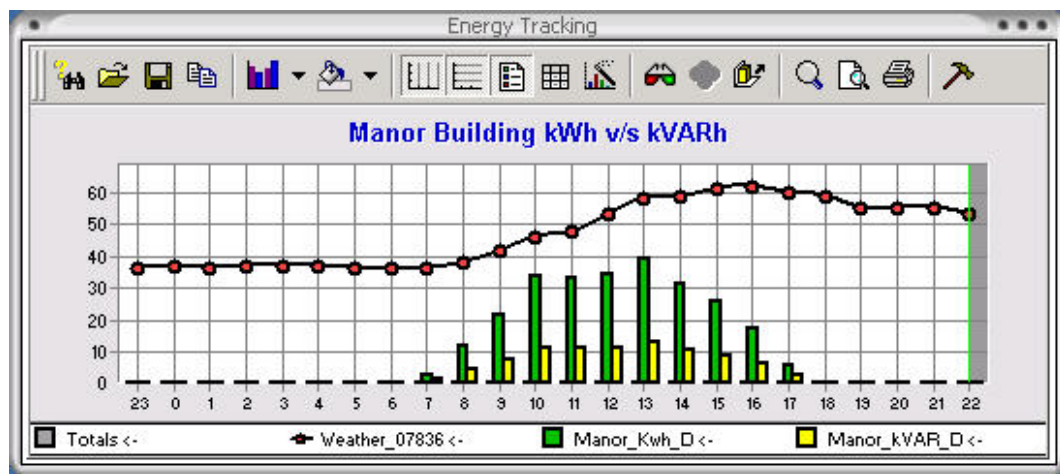


Figure 2.9: Energy@DeskTop software (reproduced from Energy Tracking, 2005-2013)

Figure 2.9 provides an image from Energy@DeskTop software, which is an 'advanced and powerful application that presents real-time energy data from our meters and loggers' (Energy Tracking, 2005-2013). For analysis, data is stored and displayed by Energy@DeskTop software in a local database. To make power management easy, this application enables users to customize a range of features, including the names and colours for grids and charts. Data sharing capability is not a part of this software; it is therefore suitable for people seeking a low-volume solution. Energy consumption, load profile, and energy requirement data can be sent by FTP from each meter, or by emailing the energy measurements to the user. The current monthly energy requirement and consumption data acquired by

energy measurement meters is sent to the user by email, while it can also be sent by FTP or HTTP from the meters. Data from the last 24 hours is available in chart format, and the load profile information is available as a spreadsheet, which includes the data received by FTP or email (Energy Tracking, 2005-2013).

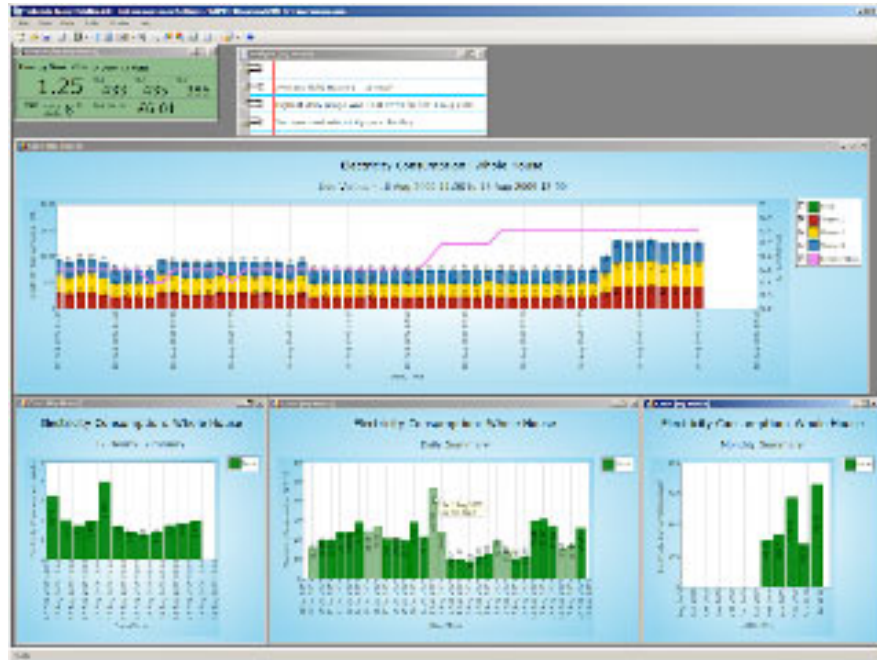


Figure 2.10 : Techtoniq Energy Station software (reproduced from Current Cost, 2013)

Techtoniq Energy Station is another application that presents both historical and real-time information, as shown in Figure 2.10. This application was made by independent software developers who specialize in producing real-time data solutions for Microsoft Windows (Techtoniq, 2009-2013). The application license is currently €9 and enables users to view their information live from any version of a Current Cost device. The application displays historical data charts, live data displays and charts cost, and usage analysis. When specific conditions are met, alerts can be sent to the user about the status of an individual appliance or the entire house (Techtoniq, 2009-2013).

2.5 Battery state-of-charge algorithms

Measuring the state-of-charge of a lead-acid battery is not simple. The charge depends on a range of factors, including history, present load, temperature, and so

on; moreover, many of these parameters are difficult to measure while the battery is in use (Pop, Bergveld, Notten & Regtien, 2005).

Several methods have been developed to predict battery state-of-charge (Scott, Pennington, Schwarz & Rowe, 2011). Some of these methods measure only terminal voltage, while some measure current (charge) conducted or cell impedance. Many of them use a combination of these techniques (Scott et al., 2011). Scott et al. constructed a meter to accurately read and monitor the power level in an electric-powered-vehicle battery. Their objective was to enable the user to correctly gauge how much charge the battery held before using the vehicle. They acknowledged that several types of meters that estimate charge already exist. However, none of the meters that electric-powered vehicle manufacturers were prepared to install at the time of manufacturing could measure the amount of remaining charge to a degree similar to fossil-fuel vehicle gauging of the amount of fuel left. Therefore, Scott et al. developed an algorithm and circuitry for a gauge that they bench-tested. Their research is of interest to the present study because the accurate measurement of electrical current is an issue that many researchers in this area have encountered.

2.6 Summary

In this chapter, some off-grid systems in New Zealand were presented, particularly in terms of scale and form. Related monitoring work within and outside New Zealand were reviewed, and examples of monitoring hardware and software available in New Zealand were presented. The next chapter describes the components and specifications of the off-grid system and outlines off-grid system monitoring requirements.

Chapter 3: Off-grid system environment

To provide an understanding of the overall off-grid system, Section 3.1 describes its components and specifications and Section 3.2 describes its monitoring requirements.

The off-grid system is intended to be the sole electricity source for a small house. The house was designed to be self-sufficient and had originally depended on a generator. The present system delivers approximately 5 kWh of electricity per day. The power is used for lights and the refrigerator, television, and computers; it is generally not used for heating. The house is equipped with gas for cooking, a gas-boosted solar hot water heater, and a wood-burning stove for space heating.

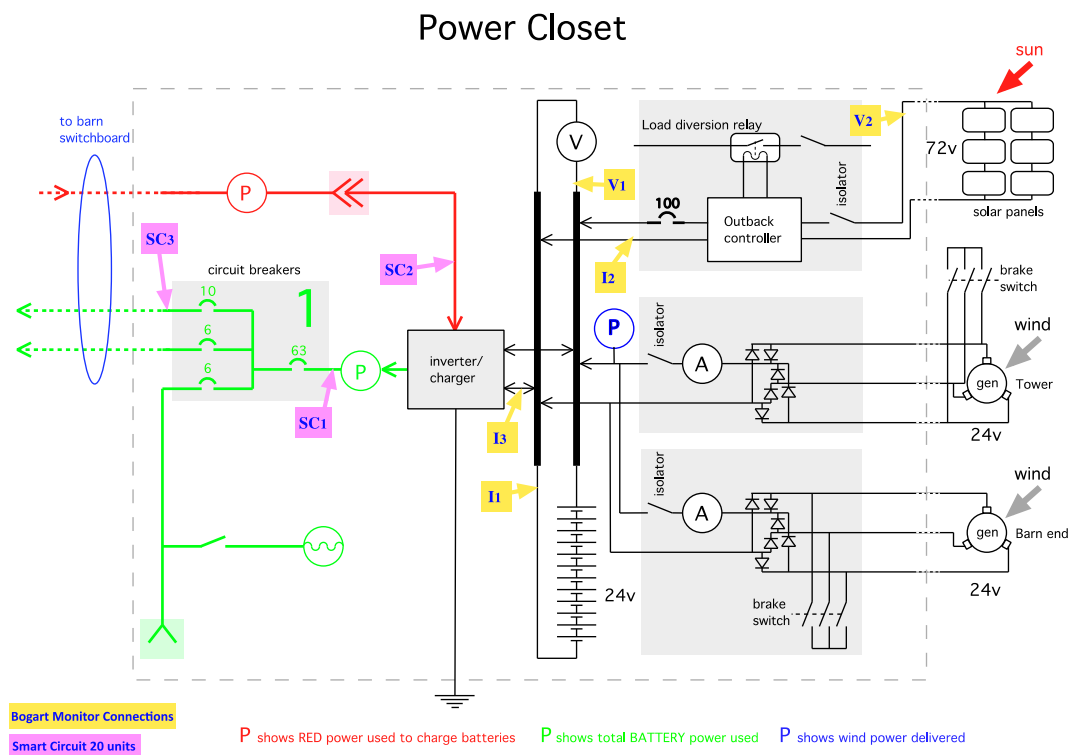


Figure 3.1: Schematic diagram of the overall off-grid power system

3.1 System components and specifications

Figure 3.1 shows a schematic diagram of the overall off-grid power system. The system is centred on a 24 V battery storage system, and a 24 V DC/230 V AC inverter, which provides the main power source for the installation. The batteries

are charged by solar PV panels through a maximum power point tracking (MPPT) controller, two small wind turbines, and a backup petrol generator that is connected to the inverter, and that when the generator is running it is switched through automatically and directly to provide the 230 V AC, and at the same time acts as a battery charger through the inverter

3.1.1 Battery bank

The system includes four batteries (Exide 6RP670T³ purchased in February 2006); each unit contains 3 cells for a total of 12 cells in a series (\Rightarrow 24 V nominal). The battery 'nameplate' rating capacity is for 670 Ah. As of August 2013, this capacity was recorded as being reduced to 190 Ah because of the end-of-use charge cycling affect.

3.1.2 Inverter/charger

The system inverter converts 24 V DC input to 230 V AC output, has a true sine wave, and serves as a charger from the backup generator. Its output frequency is 50 Hz \pm .05%, and its power is 1600 VA continuous and 2200 VA for 30 min maximum. The current setting of the inverter is low 23.2, float 27.0, absorb 28.8, equalise 31.2, low voltage, and auto shutdown. Low refers to shutdown voltage, float and absorb relate to a normal charging cycle, and equalise refers to a periodic (every 30) 'blast'. The system automatically powers down if a low voltage state occurs for more than 2 min. It is a Studer XP Compact 2200-24⁴ purchased in February 2006.

3.1.3 Petrol back-up generator

The petrol back-up generator is connected to the inverter, and that when the generator is running it is switched through automatically and directly to provide the 230V AC, and at the same time acts as a battery charger through the inverter. It has an electric starter and four-stroke, 240 V, 50 Hz, 5500 VA continuous

³ <http://www.allabout12volt.com.au/pdfinfo/ENERGYSTORE%20LEAFLET.PDF>

⁴ http://www.mysolarshop.co.uk/pdf/studer_products_xpc_en.pdf

power, and it is inverter-stabilized. The generator model is 390cc EU65IS⁵ made by Honda Company and purchased in March 2008.

3.1.4 Solar controller

The MPPT controller requires that the PV panels are configured at a significantly higher voltage than the batteries. The recommended panel nameplate input is 2000 W (MPPT). It is an Outback Flexmax 80⁶ solar controller that was purchased in January 2009.

3.1.5 Solar panels

The system has six solar panels; each panel has 50 cells in a series and open circuit power of 30.4 V. They are connected as two sets of 3 panels in a series (=> 91.2 V nominal). The panels are Electric 180W PV-AD180MF5⁷ solar panels made by Mitsubishi Company and purchased in January 2009.

3.1.6 Wind turbines

The energy input for wind turbine A (wind tower) is 24 V. It has three phases of AC output, which can generate 400 W of power at a wind speed of 12.5 meters per second. It has three blades and a rotor diameter of 1,400 mm. This turbine model is an HWG-400⁸ purchased in February 2006.

The energy input for wind turbine B (barn end roof mount) is 24 V. It has three phases of AC output, which can generate 300 W of power at a wind speed of 12.5 meters per second. It has four blades and a rotor diameter of 1,040 mm. This turbine model is a Wintek 300⁹. Installed in January 2007, it is currently decommissioned and scheduled for replacement.

⁵ <http://campaigns.hondampe.com.au/Power%20Equipment/ownersmanuals/generator/eu65isown01.pdf>

⁶ <http://www.outbackpower.com/index.php/outback-products/charge-controllers/item/flexmax-80>

⁷ <http://www.mitsubishi-electric.co.nz/product/nlaproduct.aspx?item=754103>

⁸ <http://ehochedez.free.fr/documents/eole/divers/hwg400.pdf>

⁹ <http://www.naturalenergy.co.nz/wintek.jpg>

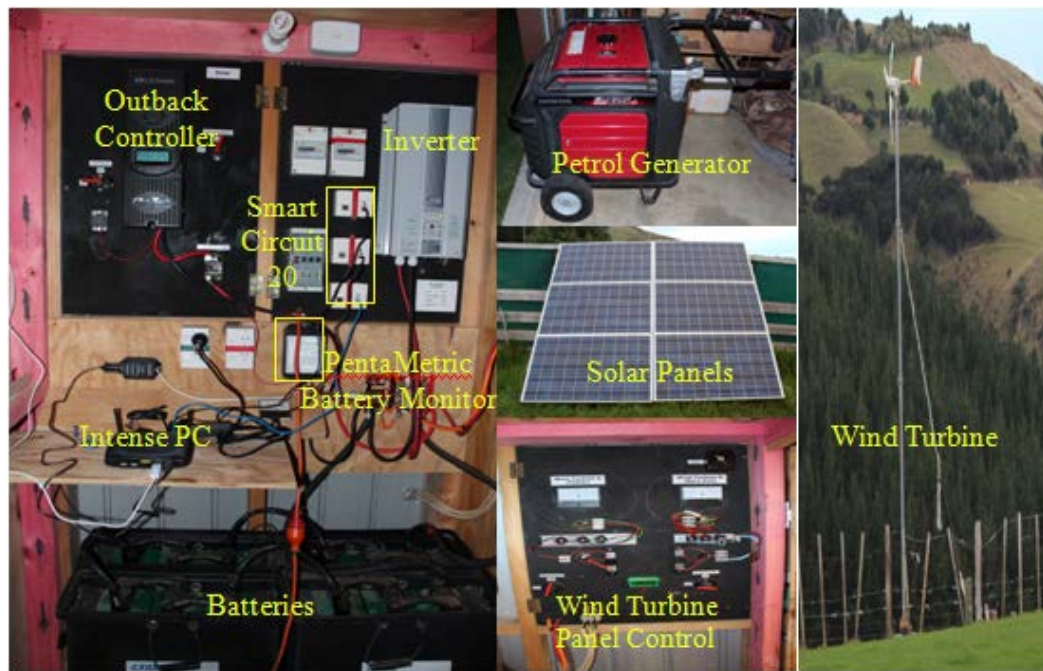


Figure 3.2: Home off-grid system setup

3.2 Off-grid monitoring system requirements

The off-grid monitoring system has several requirements, including determining the battery charge state and the source of the charge. The type of power used and where it flows in the off-grid system should also be known. The Bogart PentaMetric Battery Monitor (explained in Chapter 2) performs the monitoring with two DC voltages and three DC currents, which suits the present purpose because it enables monitoring of the battery voltages, solar PV voltages, and currents of the battery, solar PV, and inverter. It therefore provides a comprehensive view of the DC aspect of the system. Figure 3.1 shows where the Bogart PentaMetric connects to the off-grid system: (V1) battery voltage, (V2) solar PV voltages, (I1) battery current, (I2) solar current, and (I3) inverter current.

In an off-grid system, there is no guarantee that the voltage and frequency will always be the ones specified. Therefore, both voltage and frequency must be monitored. In addition, as power flows within the system, an important aspect of monitoring is having accurate power data with correct power factors. Of the monitoring devices available (described in Chapter 2), the SC20 was determined to be best suited to the present requirements because it provides data on voltage,

current, frequency, and power factor. Figure 3.1 shows the SC20 units connected to the system: (1) inverter AC output, (2) generator input, and (3) house load. Additionally, in an off-grid system, it is necessary to monitor how much power each appliance uses; therefore, an inexpensive device is needed that can report appliance power levels. The Current Cost EnviR monitor (explained in Chapter 2) is suited to the present requirements because it reports the power level of each appliance and is inexpensive. Another important requirement for effective monitoring is having the correct software to collect the data and store it in the database, while using a real-time web page to display it.

3.2.1 Bogart PentaMetric Battery Monitor

The Bogart PentaMetric Battery Monitor measures two voltages and three currents through a USB interface (explained in Chapter 2). It was installed in the system in July 2013.

3.2.2 Smart Circuit 20 Monitors

The Smart Circuit 20 230 V Monitor measures voltage, current, watts, frequency, and power factor through a USB computer interface (explained in Chapter 2). Three of them were installed in the system in July 2013.

3.2.3 Current Cost EnviR Monitor

The Current Cost EnviR 230V appliance monitor uses clamp sensors to measure current and a wireless connection to the display unit through a USB computer interface (explained in Chapter 2). The Current Cost EnviR 230 V appliance monitor and six sensors were installed in the system in July 2013.

3.3 Summary

In this chapter, the requirements, components, and specifications of the off-grid system were described. The following chapter provides an overview of the monitoring system in terms of its design, the laboratory set-up for evaluating and testing its design, and installation and commissioning of the monitor at the off-grid site.

Chapter 4: Monitoring system, installation, and commissioning

The monitoring system described in this chapter was designed to monitor and record operational information about the off-grid electricity system in real time. Monitoring is performed at the DC level of the battery system, solar panels, and inverter input, and at the AC main level of the inverter output and auxiliary generator input followed by the individual appliance level. Section 4.1 provides an overview of the monitoring system and its design, Section 4.2 describes the laboratory setup used to evaluate and test the design, and Section 4.3 describes the installation and commissioning of the monitor at the off-grid site.

4.1 Monitoring system

Details of the monitoring system, including an overview of the system, system architecture, software, and database, are covered in the following sections.

4.1.1 Off-grid power monitoring system overview

The system contains two main parts: hardware and software. The hardware aspect includes three types of monitoring device: a Bogart PentaMetric battery monitor, three Smart Circuit 20 controller monitors, and a Current Cost EnviR appliance monitor. The Bogart PentaMetric measures DC level data of the battery voltage, PV voltage, battery current, PV current, and inverter current. The Smart Circuit 20 and Current Cost EnviR monitors measure the 230 V AC level data. The three Smart Circuit 20 controller monitors measure the inverter, generator, and house voltages, frequency, current, power factor, and watts. The Current Cost EnviR monitor measures the watts for six different appliances using six sensors. Each sensor uses a current clamp attached to the appliance and a wireless connection to the Current Cost EnviR display unit. All of these devices connect to a computer through USB cables. The software component includes the off-grid power monitoring software, which collects the data from all devices every ten seconds and stores it in the off-grid power monitoring database. It includes a web page that displays the data from the off-grid power monitoring database in real time.

4.1.2 System Architecture

A general overview of the architecture of the monitoring system is provided in Figure 4.1. The terms used in this figure are explained below.

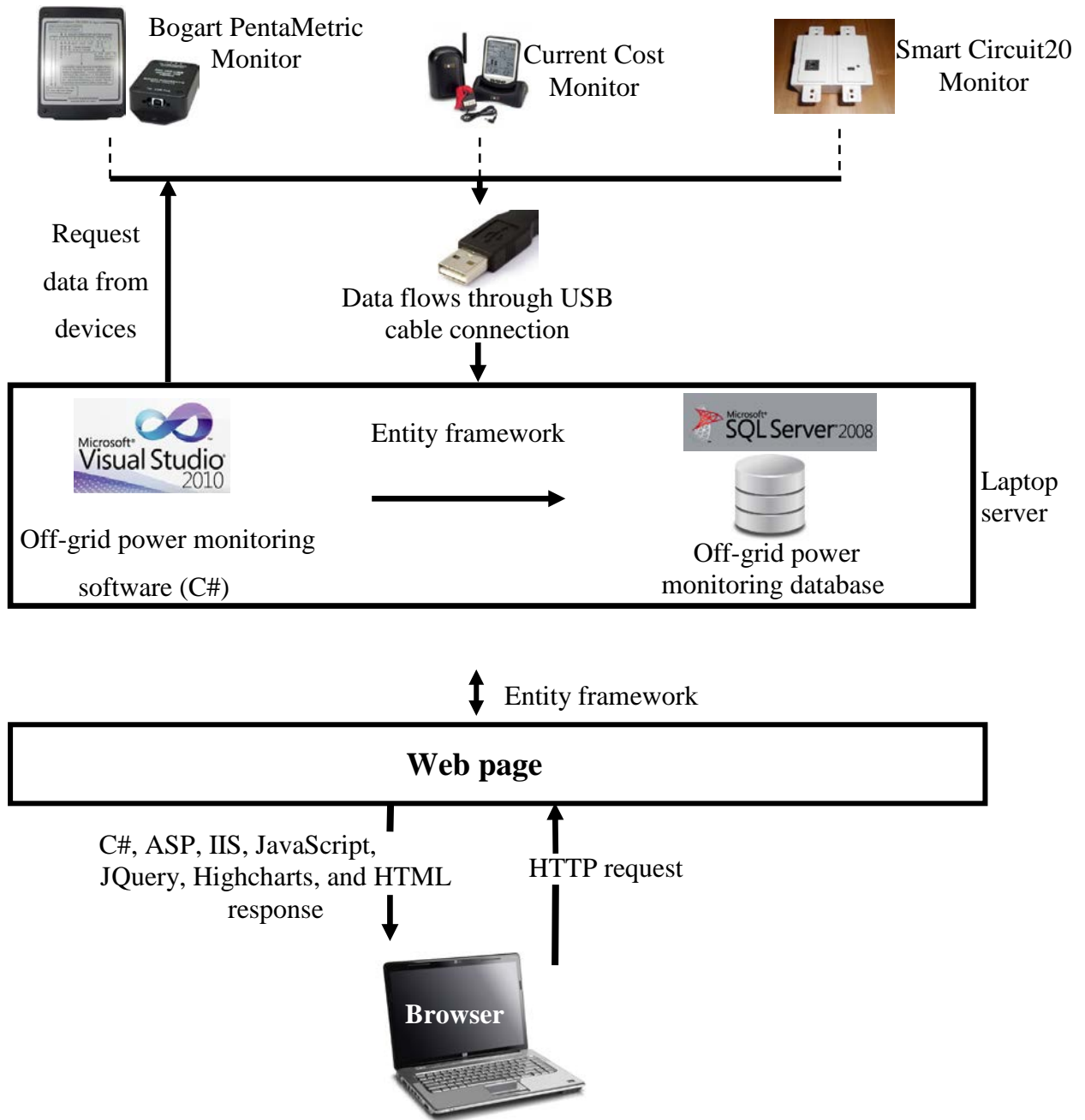


Figure 4.1: Overview of off-grid power monitoring system architecture

C#: C sharp: ‘A new programming language from Microsoft, it was created so that programmers can make a variety of applications’ (ComputerUser, 2013).

HTTP: Hypertext Transfer Protocol: ‘The protocol used to transmit and receive all data over the World Wide Web’ (ComputerUser, 2013).

HTML: Hypertext Markup Language: ‘HTML is a collection of formatting commands that create hypertext documents—Web pages, to be exact’ (ComputerUser, 2013).

IIS: Internet Information Server: ‘Also known as Internet Information Service, IIS is a Microsoft developed system that provides a set of Internet-based services for servers using Microsoft Windows’ (ComputerUser, 2013).

Entity Framework: ‘Entity Framework (EF) is an object-relational mapper that enables .NET developers to work with relational data using domain-specific objects. It eliminates the need for most of the data-access code that developers usually need to write’ (Data Developer Center, 2013).

ASP: Application Service Provider: ‘An Application Service Provider refers to a model where an application is hosted on a central facility’ (ComputerUser, 2013).

JavaScript: ‘JavaScript is a scripting language developed by Netscape to enable Web authors to design interactive sites’ (ComputerUser, 2013).

JQuery: ‘The JQuery library provides a general-purpose abstraction layer for common web scripting, and is therefore useful in almost every scripting situation’ (Chaffer & Swedberg, 2009).

Highstock: ‘Highstock lets you create stock or general timeline charts in pure JavaScript, including sophisticated navigation options like a small navigator series, preset date ranges, date picker, scrolling and panning’ (Highcharts JS, 2013).

The project system has two main processes, which independently operate. The first process involves requesting and storing all device data in the off-grid power monitoring database. The second process involves retrieving and presenting the data in a web page.

In the first process, each device connects to the computer using a USB cable and it then runs the off-grid power monitoring software. The software requests the data needed from each device every ten seconds and then stores it in the off-grid power monitoring database.

In the second process, when the off-grid power monitoring web page is opened, an HTTP request is sent to the computer server. The web page then uses the Entity

Framework to query all data from the off-grid power monitoring database. The database sends all data to the off-grid power monitoring web page. The data is processed by the Entity Framework, which sends the data in C#, ASP, JavaScript, JQuery, Highcharts, and HTML format to the computer server; it is then forwarded by the computer server to the browser. This process is described in Chapter 5.

4.1.3 Off-grid power monitoring software

The off-grid power monitoring software was developed for this study. The steps involved in building this software are detailed below.

Market software installing and testing

Understanding the concepts and features of other software is important to building new software. Several applications related to the devices used in this study were installed and tested prior to building the present software. Requirements for our software included collecting data from all devices every ten seconds and obtaining specific data from all devices. Not all device data could be gathered from the three different devices used in this study with a single application.

Understanding device data format

Each device has a different data format. Several documents are available that describe the data format of each device. Bogart Engineering has provided all documentation necessary to understanding the data format of its PentaMetric monitor (Bogart Engineering, 2010). The Smart Circuit 20 monitor communication protocol documentation provided by Watts Up? can be used to understand the data format and assist programmers (Watts Up?, n.d.). The Current Cost data format documentation provided by Current Cost is likewise very useful and easy for programmers to understand (Current Cost, 2009).

Programming language and developer tool

There are many programming languages, such as Java, C++, and C#, that can be used to build software. C# was selected for building the present software because of the researcher's knowledge of the language, and Microsoft Visual Studio 2010 was the developer tool used.

Writing the software code

The informative device data format documents provided by each device company made writing the software code easier. The objective at the start of writing the software code was to write each device code in separate Visual Studio applications, which would make it easier to test the devices and ultimately combine all device code in a single application.

Initialization

Before each device could be accessed from the code, their interface parameters (data format, baud rate) had to be defined.

First, in each device code, the device was defined to enable communication with it. The device definition is different for each device. The few lines of code below show how to define each device.

The Serial Port Constructor was used to set up the property values to open the port to receive the data from it.

```
#region Constructor
public Pentametric(string port)
{
    mInBuffer = new List<byte>();

    mSp = new SerialPort(port, BAUD_RATE, PARITY, DATA_BITS);
    mSp.Open();
    mSp.DataReceived += new SerialDataReceivedEventHandler(mSp_DataReceived);
}
#endregion
```

The Serial Port Number was set up for each device in the app.config file. The code below shows one of the device serial port numbers.

```
<setting name="PentametricPort" serializeAs="String">
    <value>COM4</value>
</setting>
```

One of the requirements of this software is to set up a ten-second interval to collect data from each device. A few lines of code, shown below, were written to establish this interval.

```
System.Timers.Timer tmrSmart Circuit1 = new System.Timers.Timer(); tmrSmart
Circuit1.Interval = 10000; // 10000 = 10 seconds

tmrSmart Circuit1.Elapsed += new System.Timers.ElapsedEventHandler(tmrSmart
Circuit1_Elapsed); tmrSmart Circuit1.SynchronizingObject = this; //Synchronize
with the current form...
tmrSmart Circuit1.Start();
```

Reading the data

The devices read numerous parameters; however, in this study, only some of these parameters are required. In the code for each device, two methods were written: `DataReceived` and `ReadValue`. The `DataReceived` method is used to receive all data from the device; the `ReadValue` method reads from the device the specific required parameters. For example, the Smart Circuit 20 device can read 18 parameters; however, only 5 of them are needed for this study.

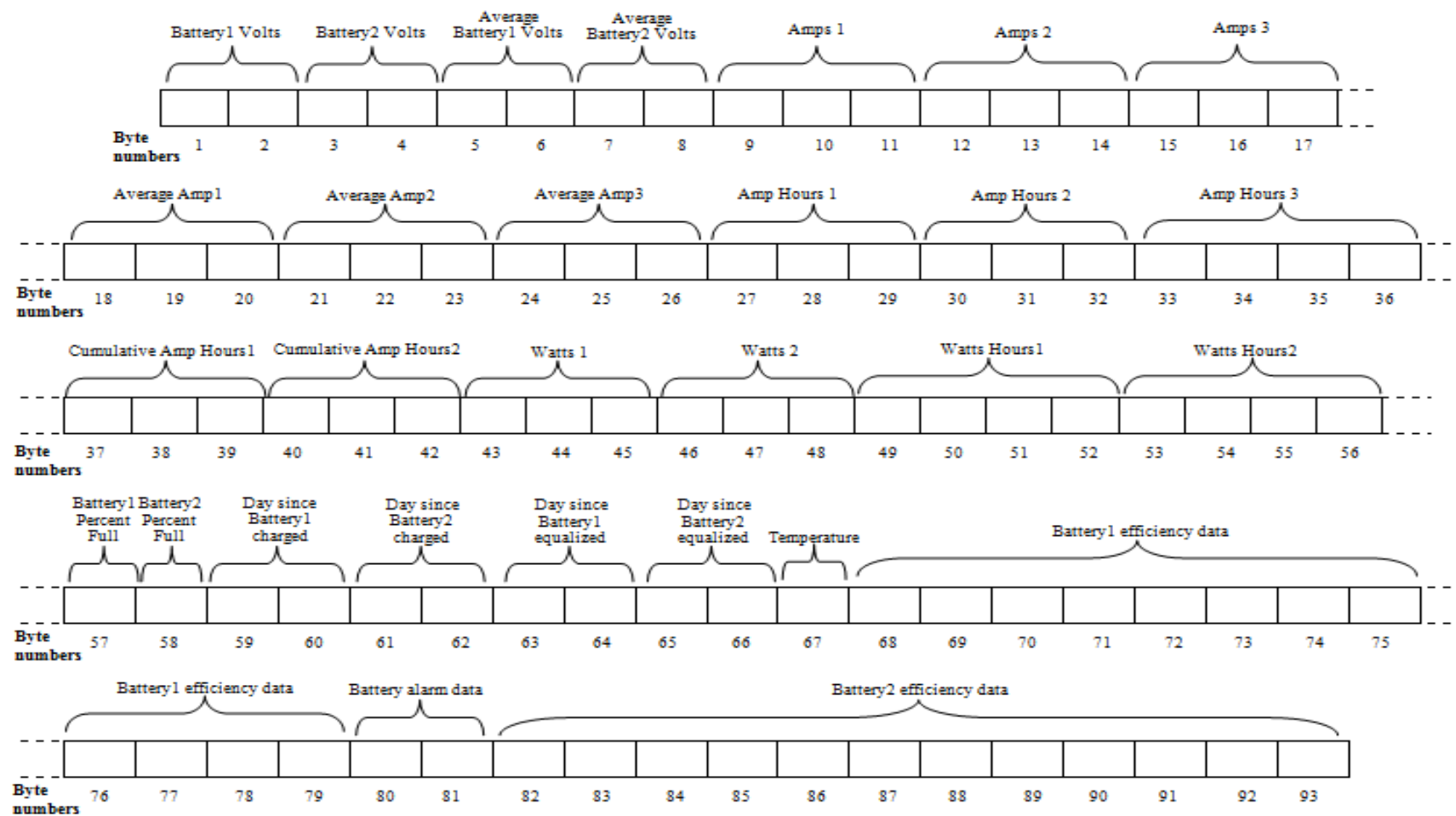


Figure 4.2: Bogart PentaMetric parameter

Figure 4.2 outlines all parameters received from the Bogart PentaMetric device. As mentioned above, only five of these parameters are required for this study. The code below shows how to read these parameters.

```
public int ReadValue(byte address, byte bytes)
{
    byte[] toSend = new byte[] { 0x81, address, bytes, 0 };
    byte checksum = 0;
    foreach (byte b in toSend)
        checksum += b;
    toSend[toSend.Length - 1] = (byte)(255 - checksum);
    mInBuffer.Clear();
    mSp.Write(toSend, 0, toSend.Length);
    for (int i = 0; i < TIMEOUT * 100; i++)
    {
        int toRead = mSp.BytesToRead;
        byte[] received = new byte[toRead];
        mSp.Read(received, 0, received.Length);
        mInBuffer.AddRange(received);
        if (mInBuffer.Count == bytes + 1)
        {
            //Make sure the checksum is correct
            byte cs = 0;
            foreach (byte b in mInBuffer)
                cs += b;
            if (cs == 0xff)
            {
                int result = 0;
                for (i = bytes - 1; i >= 0; i--)
                {
                    result <<= 8;
                    result |= mInBuffer[i];
                }
                return result;
            }
            throw new TimeoutException();
        }
        Thread.Sleep(10);
    }
    throw new TimeoutException();
}
```

ReadFormat1 is used to read volt parameters.

```
public double ReadFormat1(byte address)
{
    return ReadValue(address, 2) / 20.0;
}
```

ReadFormat2 is used to read amp parameters.

```
public double ReadFormat2(byte address)
{
    uint amp1 = (uint)ReadValue(address, 3);
    uint sign = amp1 >> 23;
    amp1 &= 0x7fffff;
    if (sign != 0)
        amp1 |= 0xff800000;
    return -((int)amp1) / 1000.0;
}
```

The code below shows how to read the 5 required parameters of the 18 parameters that the Smart Circuit 20 device receives.

```
public string ReadValue()
{
    string data=string.Empty;
    try
    {
        if (inBuf.IndexOf("#d") >= 0)
        {
            inBuf = inBuf.Substring(inBuf.IndexOf("#d"));
        }
        if (inBuf.StartsWith("#d") && inBuf.Contains(";"))
        {
            inBuf = inBuf.Substring(0, inBuf.IndexOf(";") + 1);
            data = inBuf;
            inBuf = "";
            mSp.DiscardInBuffer();
            mSp.Write("#R,W,0;");
        }
    }
    catch
```

```

{
    data = "";
}
return data;
}

```

Similarly, the Current Cost device receives several parameters; however, only six of them are required for this study. The code below shows how to read these parameters.

```

public void ReadValue()
{
    if(!mSp.IsOpen)
        mSp.Open();
    dt[0] = "";
    dt[1] = "";
    dt[2] = "";
    dt[3] = "";
    dt[4] = "";
    dt[5] = "";
    for (int i = 0; i < 6; i++)
    {
        dt[i] = mSp.ReadLine();
    }
    mSp.DiscardInBuffer();
    var ccObject = new CurrentCostObject();
    foreach (var item in dt)
    {
        CurrentCostUpdate cc;
        try
        {
            cc = new CurrentCostUpdate(item);
        }
        catch
        {
            continue;
        }
        switch (cc.Sensor)
        {
            case 1:
                mSensor1 = cc.ChPower;

```

```

        break;
    case 2:
        mSensor2 = cc.ChPower;
        break;
    case 3:
        mSensor3 = cc.ChPower;
        break;
    case 4:
        mSensor4 = cc.ChPower;
        break;
    case 5:
        mSensor5 = cc.ChPower;
        break;
    case 6:
        mSensor6 = cc.ChPower;
        break;
    }
}

ccObject.Timestamp = System.DateTime.Now;
ccObject.HouseLighting = mSensor1;
ccObject.WaterPump = mSensor2;
ccObject.Refrigerator = mSensor3;
ccObject.Entertainment = mSensor4;
ccObject.Portable1 = mSensor5;
ccObject.Portable2 = mSensor6;
}

```

The Smart Circuit 20 device has a buffer that must be cleared after receiving each sample from it.

```
mSp.Write("#R,W,0;");
```

Storing the data in the database

The Entity Framework is very important for accessing the database and entering the data received for each device into it. Therefore, each device must use the Entity Framework. The code excerpt below shows how one of the devices uses the framework.

```

using (PowerMonitoringEntities ctx = new PowerMonitoringEntities())
{
    Monitor.Enter(ctx);
}

```



```

PowerMonitoringEF.CurrentCost bmEntity = new
PowerMonitoringEF.CurrentCost();
bmEntity.Timestamp = ccObject.Timestamp;
bmEntity.Entertainment = ccObject.Entertainment;
bmEntity.HouseLighting = ccObject.HouseLighting;
bmEntity.Portable1 = ccObject.Portable1;
bmEntity.Portable2 = ccObject.Portable2;
bmEntity.Refrigerator = ccObject.Refrigerator;
bmEntity.WaterPump = ccObject.WaterPump;
try
{
    ctx.CurrentCosts.AddObject(bmEntity);
    ctx.SaveChanges();
}
catch (Exception ex)
{
    MessageBox.Show(ex.ToString(), "An error occurred!",
        MessageBoxButtons.OKCancel, MessageBoxIcon.Exclamation);
}
finally
{
    Monitor.Exit(ctx);
}
}
}

```

4.1.4 Off-grid power monitoring database description

The off-grid power monitoring database designed and created for this study is described below. The database was created with Microsoft SQL Server 2008.

Off-grid power monitoring database entity relationships

The entity relationship diagram in Figure 4.3 outlines the entities and attributes required for the database. There are four entities in the off-grid power monitoring database: BogartMonitor, SmartCircuitMachines, SmartCircuit20, and Current Cost tables.

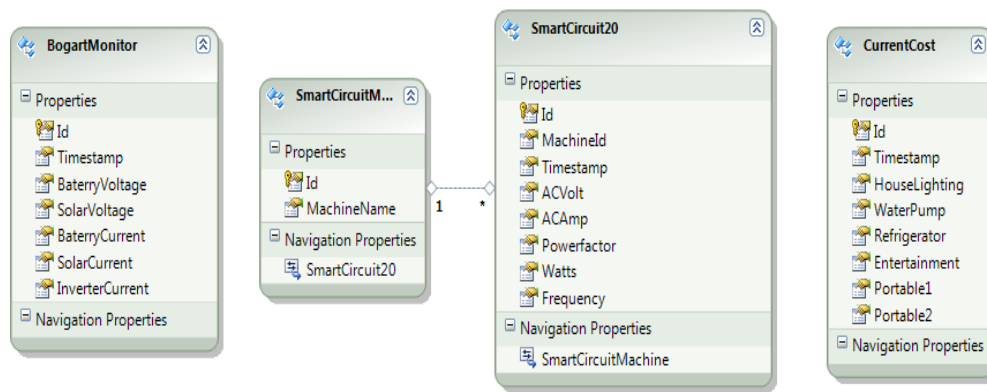


Figure 4.3: Off-grid power monitoring database entity relationships

The BogartMonitor table has seven attributes: Id, Timestamp, BatteryVoltage, BatteryCurrent, SolarCurrent, and InverterCurrent. These attributes are described below.

Id: Primary key of this table and auto increase number of the record. The data type of this attribute is INT (4).

Timestamp: Date and time of data recording. The data type of this attribute is DATETIME.

BatteryVoltage: Recorded battery voltage. The data type of this attribute is FLOAT (8).

SolarVoltage: Recorded solar voltage. The data type of this attribute is FLOAT (8).

BatteryCurrent: Recorded battery current. The data type of this attribute is FLOAT (8).

SolarCurrent: Recorded solar current. The data type of this attribute is FLOAT (8).

InverterCurrent: Recorded inverter current. The data type of this attribute is FLOAT (8).

The SmartCircuitMachines table has two attributes: Id and MachineName. This table was created to avoid data redundancy in the SmartCircuit20 table. These attributes described below.

Id: Primary key of this table and unique number for each device; it is used in the SmartCircuit20 table as MachineId. The data type of this attribute is INT (4).

MachineName: Name of each device. The data type of this attribute is VARCHAR (100).

The SmartCircuit20 table has a number of attributes, including Id, MachineId, Timestamp, ACVolt, ACamp, Powerfactor, Watts, and Frequency. The descriptions of these attributes are below.

Id: Primary key of this table; it is the auto increase number of the record. The data type of this attribute is INT (4).

MachineId: Identification unique number from the SmartCircuitMachines table. The data type of this attribute is INT (4).

Timestamp: Date and time of data recording. The data type of this attribute is DATETIME.

ACVolt: Recorded AC voltage. The data type of this attribute is FLOAT (8).

ACamp: Recorded AC amps. The data type of this attribute is FLOAT (8).

Powerfactor: Recorded power factor. The data type of this attribute is INT (4).

Watts: Recorded watts. The data type of this attribute is FLOAT (8).

Frequency: Recorded frequency. The data type of this attribute is FLOAT (8).

The CurrentCost table has eight attributes: Id, Timestamp, HouseLighting, WaterPump, Refrigerator, Entertainment, Portable1, and Portable2. These attributes are described below.

Id: Primary key of this table; it is the auto increase number of the record. The data type of this attribute is INT (4).

Timestamp: Date and time of data recording. The data type of this attribute is DATETIME.

HouseLighting: House lighting consumption in watts. The data type of this attribute is FLOAT (8).

WaterPump: Water pump consumption in watts. The data type of this attribute is FLOAT (8).

Refrigerator: Refrigerator consumption in watts. The data type of this attribute is FLOAT (8).

Entertainment: Entertainment consumption in watts. The data type of this attribute is FLOAT (8).

Portable1: Portable 1 consumption in watts. The data type of this attribute is FLOAT (8).

Portable2: Portable 2 consumption in watts. The data type of this attribute is FLOAT (8).

The tables below show the collected data stored in the off-grid power monitoring database.

Table 4.1: Bogart Monitor sample data

| | Id | Timestamp | BatteryVoltage | SolarVoltage | BatteryCurrent | SolarCurrent | InverterCurrent |
|---|--------|-------------------------|----------------|--------------|----------------|--------------|-----------------|
| 1 | 212901 | 2013-08-06 22:02:14.390 | 23.9 | 13.5 | -10.43 | -0.037 | -10.381 |
| 2 | 212900 | 2013-08-06 22:02:04.390 | 23.9 | 13.5 | -10.438 | -0.037 | -10.372 |
| 3 | 212899 | 2013-08-06 22:01:54.383 | 23.9 | 13.5 | -10.466 | -0.037 | -10.387 |
| 4 | 212898 | 2013-08-06 22:01:44.377 | 23.9 | 13.5 | -10.428 | -0.038 | -10.375 |
| 5 | 212897 | 2013-08-06 22:01:34.370 | 23.9 | 13.5 | -10.449 | -0.038 | -10.404 |
| 6 | 212896 | 2013-08-06 22:01:24.377 | 24 | 13.5 | -10.439 | -0.036 | -10.418 |

Table 4.2: Smart Circuit 20 machines

| Id | MachineName |
|----|-----------------------|
| 1 | Inverter AC Output |
| 2 | Generator Power Input |
| 3 | House (back) Load |

Table 4.3: Smart Circuit 20 sample data

| | Id | Machinelid | Timestamp | ACVolt | ACamp | Powerfactor | Watts | Frequency |
|---|--------|------------|-------------------------|--------|-------|-------------|-------|-----------|
| 1 | 638966 | 3 | 2013-08-06 21:56:24.693 | 228.7 | 1.304 | 87 | 261.8 | 50 |
| 2 | 638965 | 2 | 2013-08-06 21:56:24.687 | 0 | 0 | 0 | 0 | 0 |
| 3 | 638964 | 1 | 2013-08-06 21:56:24.683 | 228.8 | 1.427 | 86 | 289.3 | 50 |
| 4 | 638963 | 3 | 2013-08-06 21:56:14.627 | 228.7 | 1.305 | 87 | 262.2 | 50 |
| 5 | 638962 | 2 | 2013-08-06 21:56:14.617 | 0 | 0 | 0 | 0 | 0 |
| 6 | 638961 | 1 | 2013-08-06 21:56:14.613 | 228.9 | 1.428 | 86 | 290.3 | 50 |

Table 4.4: Current Cost sample data

| Id | Timestamp | HouseLighting | WaterPump | Refrigerator | Entertainment | Portable1 | Portable2 |
|-------|-------------------------|---------------|-----------|--------------|---------------|-----------|-----------|
| 21586 | 2013-04-29 14:38:59.543 | 85 | 77 | 26 | 30 | 68 | 34 |
| 21585 | 2013-04-29 14:38:49.590 | 85 | 79 | 29 | 29 | 70 | 33 |
| 21584 | 2013-04-29 14:38:39.500 | 86 | 77 | 26 | 29 | 66 | 33 |
| 21583 | 2013-04-29 14:38:29.447 | 85 | 77 | 27 | 31 | 66 | 34 |
| 21582 | 2013-04-29 14:38:19.540 | 85 | 77 | 27 | 30 | 65 | 33 |

4.2 Testing

To save time while testing the monitor at the off-grid site, a laboratory was built so that all aspects of the system could be tested before the equipment was installed. This section describes the laboratory setup, problems encountered and solved, and the schematic diagram of the laboratory setup.

4.2.1 Laboratory setup

Before using the software, we tested it in a laboratory situation to resolve any problems before actual use. Figure 4.4 shows the laboratory setup, which included three devices: the Bogart PentaMetric, Smart Circuit 20, and Current Cost. The Bogart Pentametric and Smart Circuit 20 lab tests schematic diagrams are shown in Figures 4.5 and 4.6. The software was tested on each of these devices.



Figure 4.4: Laboratory setup

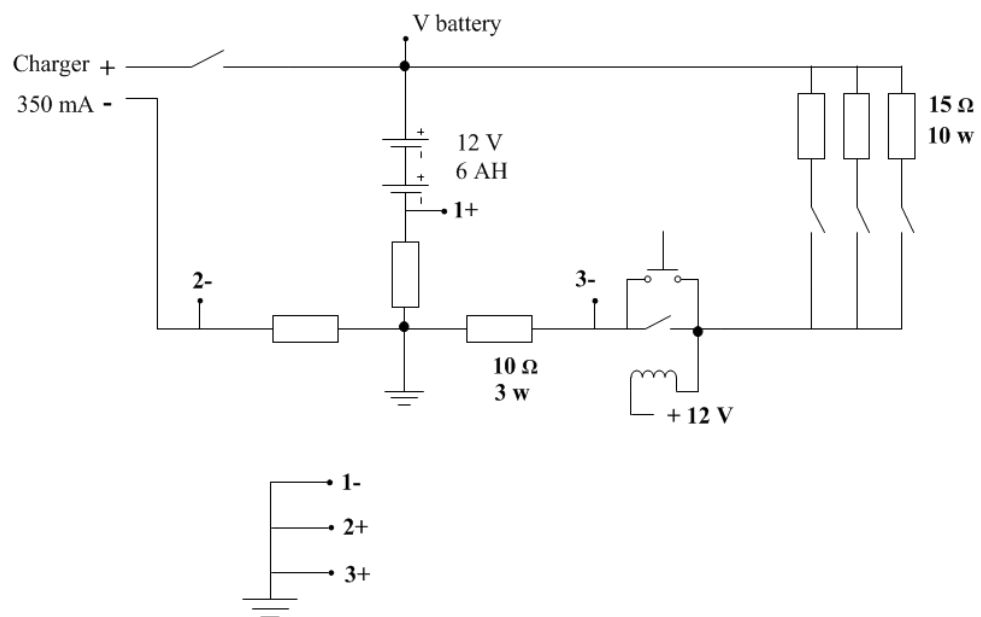


Figure 4.5: Bogart Pentametric lab test

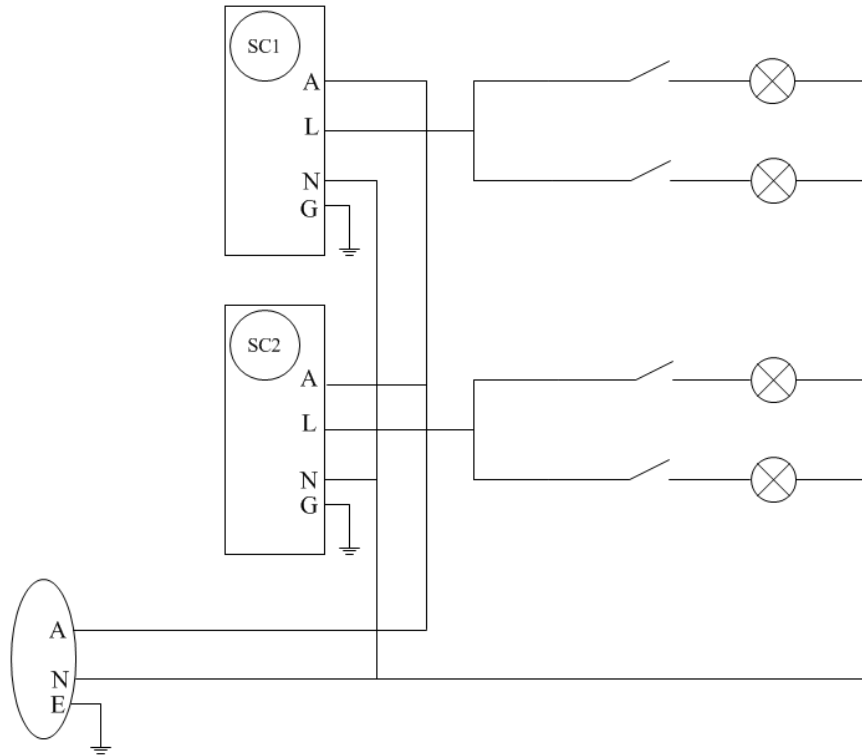


Figure 4.6: Smart Circuit 20 lab test

4.2.2 Problems and solutions

While testing the devices, some issues were found when the software was running and storing the data in the database. For one, the software stopped running when the computer was updated and then restarted. To solve this problem, we added the software to the start-up folder so the software would run automatically when the computer restarts. Obtaining the correct time right was another issue; there were a few milliseconds of delay when the time was recorded in the database for each device. This issue was caused when the data was read from the devices; it was not in the same order for each sample. To address this issue, the manual correction of time after each download from the database was needed. In addition, when one of the devices was turned off, the software stopped running. This issue was resolved by programming the software to enter zero in the database and continue operating if one of the devices was turned off.

4.3 Installation and commissioning

After the monitoring software was fully tested in the laboratory environment, it was installed at the off-grid site. An important requirement for installing the software in the field is having the optimal PC. Intense PC from Fit PC Company had all the specifications that were required to run our software on it: low power consumption, the correct number of USB ports, and the specific features for running the software (Fit PC, 2013).

4.3.1 Device installation

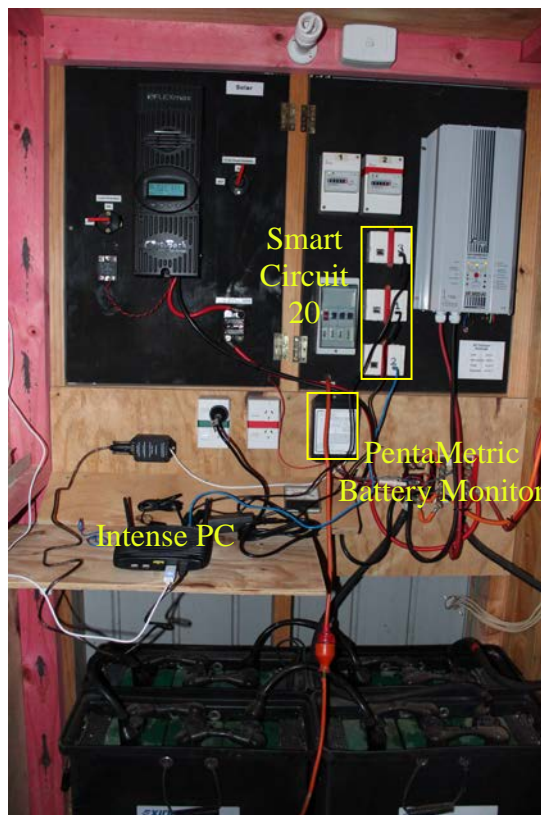


Figure 4.7: Off-grid system device installation

The Intense PC and devices installed in the field are shown in Figure 4.7. After the PC was set up in the field and our software was installed on it, drivers for all the devices were then installed to enable communication with the PC.

4.3.2 Remote desktop and Internet connections

The Intense PC was accessed from outside the field to verify that it was continuing to receive and download the data. A remote desktop connection was

established to communicate with the Intense PC. The Intense PC was given a dynamic IP address; therefore, it was necessary to maintain an updated IP address to retain the remote desktop connection. To address this need, the No-IP Dynamic Update Client (DUC)¹⁰ was installed on the Intense PC, and a No-IP hosting account was created. The No-IP Dynamic Update Client (DUC) maintained the most current IP address of the Intense PC and automatically updated it at the No-IP.com host (No IP, 2013). In addition, the Intense PC had to be connected to the Internet by a wired connection, as opposed to a wireless one, because when the PC was accessed through the remote desktop connection, it would log off, which would cause a wireless Internet connection—and remote desktop connection—to disconnect.

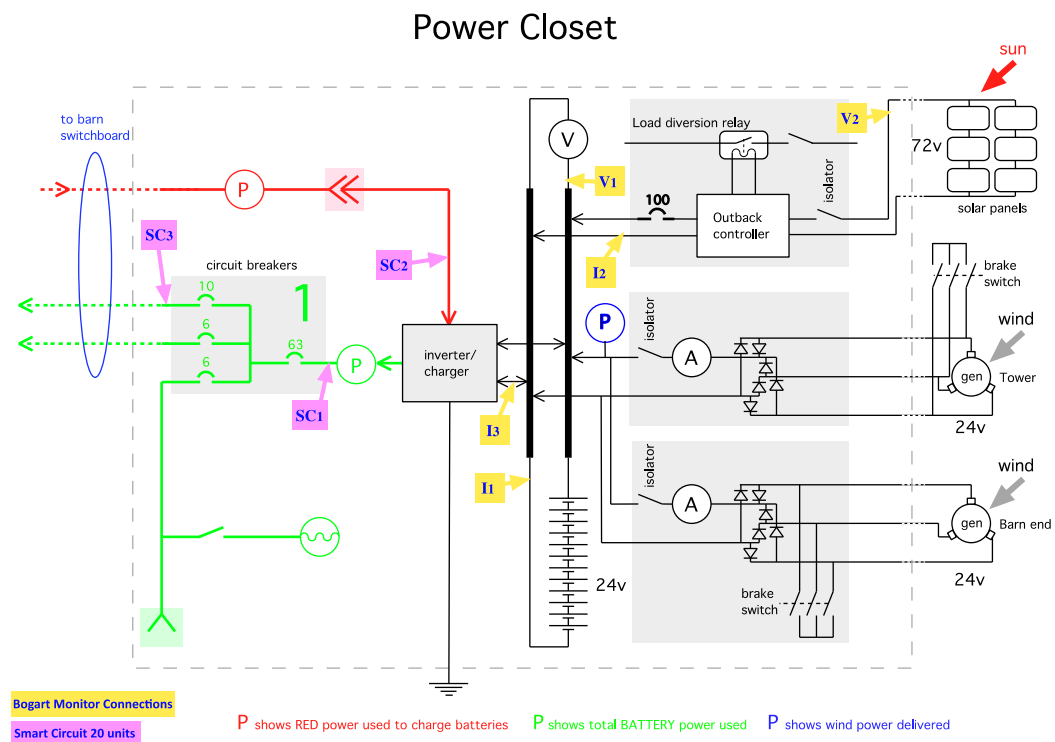


Figure 4.8: Schematic diagram of system-installed devices

¹⁰ <http://www.noip.com/>

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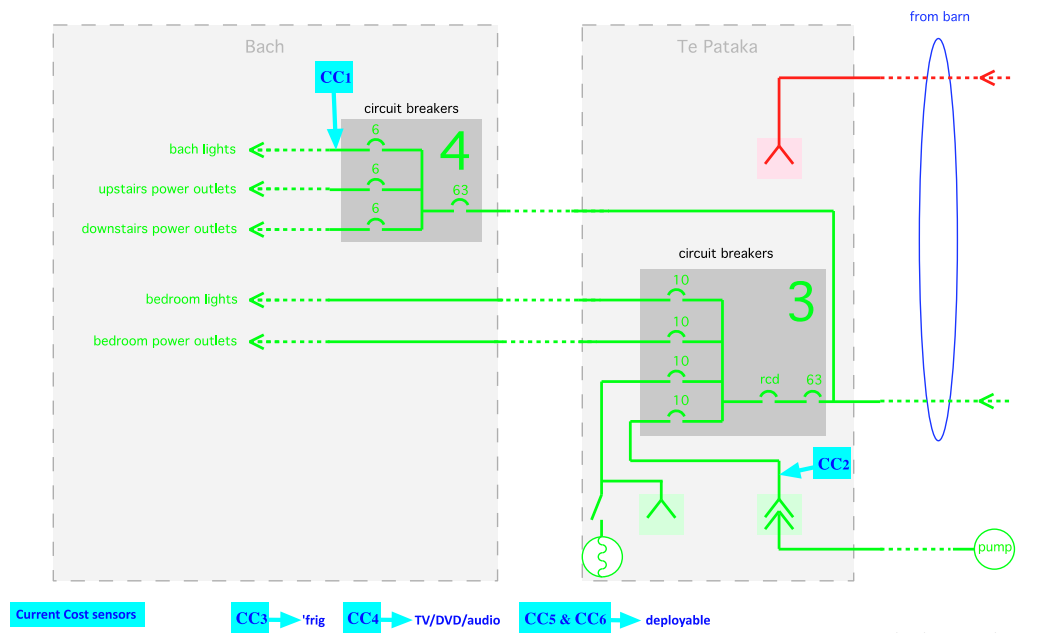


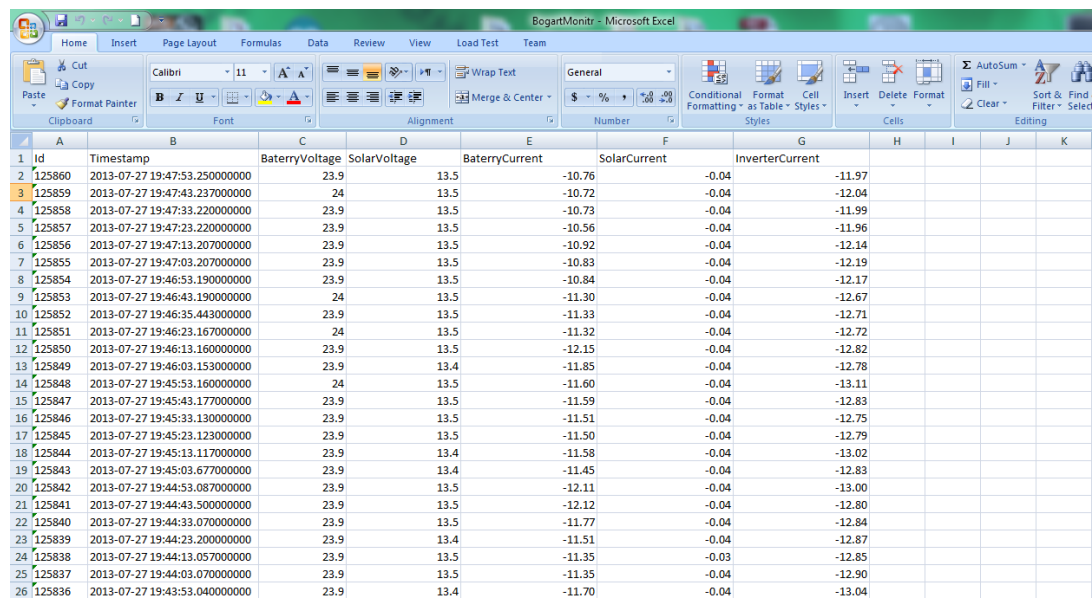
Figure 4.9: Schematic diagram of system-installed devices

The devices installed in the system are shown in the schematic diagrams in Figures 4.8 and 4.9. Yellow denotes the Bogart PentaMetric device, pink represents the Smart Circuit 20 devices, and bright blue represents the Current Cost devices.

4.3.3 Downloading data

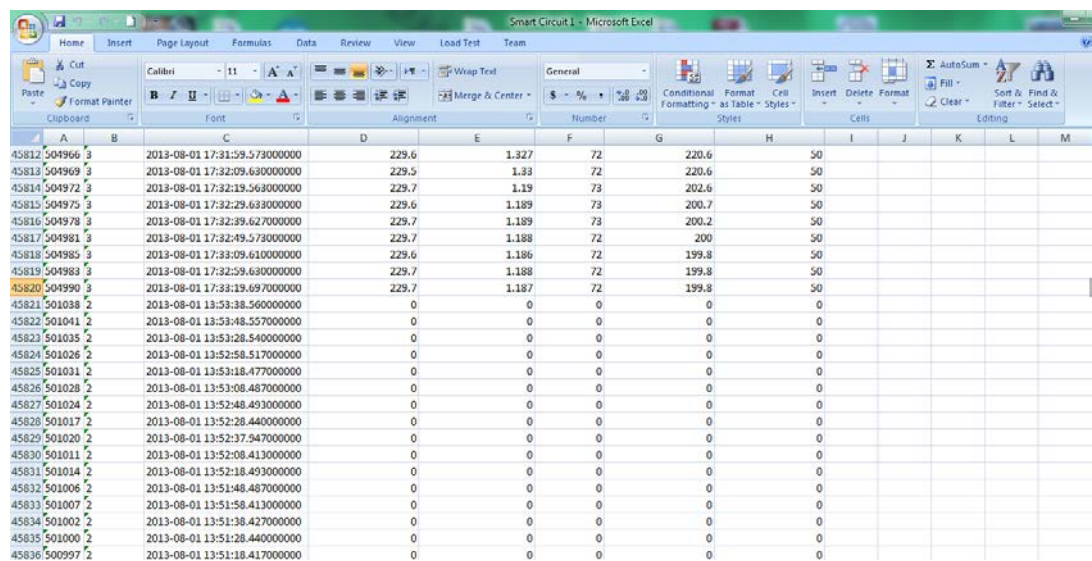
To download the data, the Intense PC was accessed through the remote desktop connection. The data was then exported from the database to the Intense PC in an Excel spreadsheet. The spreadsheet could then be copied from the Intense PC to another PC through the remote desktop connection.

4.3.4 Sample data



| | A | B | C | D | E | F | G | H | I | J | K |
|----|--------|-------------------------------|----------------|--------------|----------------|--------------|-----------------|---|---|---|---|
| | Id | Timestamp | BatteryVoltage | SolarVoltage | BatteryCurrent | SolarCurrent | InverterCurrent | | | | |
| 1 | 125860 | 2013-07-27 19:47:53.250000000 | 23.9 | 13.5 | -10.76 | -0.04 | -11.97 | | | | |
| 2 | 125859 | 2013-07-27 19:47:43.237000000 | 24 | 13.5 | -10.72 | -0.04 | -12.04 | | | | |
| 3 | 125858 | 2013-07-27 19:47:33.220000000 | 23.9 | 13.5 | -10.73 | -0.04 | -11.99 | | | | |
| 4 | 125857 | 2013-07-27 19:47:23.220000000 | 23.9 | 13.5 | -10.56 | -0.04 | -11.96 | | | | |
| 5 | 125856 | 2013-07-27 19:47:13.207000000 | 23.9 | 13.5 | -10.92 | -0.04 | -12.14 | | | | |
| 6 | 125855 | 2013-07-27 19:47:03.207000000 | 23.9 | 13.5 | -10.83 | -0.04 | -12.19 | | | | |
| 7 | 125854 | 2013-07-27 19:46:53.190000000 | 23.9 | 13.5 | -10.84 | -0.04 | -12.17 | | | | |
| 8 | 125853 | 2013-07-27 19:46:43.190000000 | 24 | 13.5 | -11.30 | -0.04 | -12.67 | | | | |
| 9 | 125852 | 2013-07-27 19:46:35.443000000 | 23.9 | 13.5 | -11.33 | -0.04 | -12.71 | | | | |
| 10 | 125851 | 2013-07-27 19:46:23.167000000 | 24 | 13.5 | -11.32 | -0.04 | -12.72 | | | | |
| 11 | 125850 | 2013-07-27 19:46:13.160000000 | 23.9 | 13.5 | -12.15 | -0.04 | -12.82 | | | | |
| 12 | 125849 | 2013-07-27 19:46:03.153000000 | 23.9 | 13.4 | -11.85 | -0.04 | -12.78 | | | | |
| 13 | 125848 | 2013-07-27 19:45:53.160000000 | 24 | 13.5 | -11.60 | -0.04 | -13.11 | | | | |
| 14 | 125847 | 2013-07-27 19:45:43.177000000 | 23.9 | 13.5 | -11.59 | -0.04 | -12.83 | | | | |
| 15 | 125846 | 2013-07-27 19:45:33.130000000 | 23.9 | 13.5 | -11.51 | -0.04 | -12.75 | | | | |
| 16 | 125845 | 2013-07-27 19:45:23.123000000 | 23.9 | 13.5 | -11.50 | -0.04 | -12.79 | | | | |
| 17 | 125844 | 2013-07-27 19:45:13.117000000 | 23.9 | 13.4 | -11.58 | -0.04 | -13.02 | | | | |
| 18 | 125843 | 2013-07-27 19:45:03.677000000 | 23.9 | 13.4 | -11.45 | -0.04 | -12.83 | | | | |
| 19 | 125842 | 2013-07-27 19:44:53.087000000 | 23.9 | 13.5 | -12.11 | -0.04 | -13.00 | | | | |
| 20 | 125841 | 2013-07-27 19:44:43.500000000 | 23.9 | 13.5 | -12.12 | -0.04 | -12.80 | | | | |
| 21 | 125840 | 2013-07-27 19:44:33.070000000 | 23.9 | 13.5 | -11.77 | -0.04 | -12.84 | | | | |
| 22 | 125839 | 2013-07-27 19:44:23.200000000 | 23.9 | 13.4 | -11.51 | -0.04 | -12.87 | | | | |
| 23 | 125838 | 2013-07-27 19:44:13.057000000 | 23.9 | 13.5 | -11.35 | -0.03 | -12.85 | | | | |
| 24 | 125837 | 2013-07-27 19:44:03.070000000 | 23.9 | 13.5 | -11.35 | -0.04 | -12.90 | | | | |
| 25 | 125836 | 2013-07-27 19:43:53.040000000 | 23.9 | 13.4 | -11.70 | -0.04 | -13.04 | | | | |

Figure 4.10: Excel spreadsheet of Bogart PentaMetric device data



| | A | B | C | D | E | F | G | H | I | J | K | L | M |
|-------|--------|-------------------------------|----------------|--------------|----------------|--------------|-----------------|---|---|---|---|---|---|
| | Id | Timestamp | BatteryVoltage | SolarVoltage | BatteryCurrent | SolarCurrent | InverterCurrent | | | | | | |
| 45812 | 504966 | 2013-08-01 17:31:59.573000000 | 229.6 | 1.327 | 72 | 220.6 | 50 | | | | | | |
| 45813 | 504969 | 2013-08-01 17:32:09.630000000 | 229.5 | 1.33 | 72 | 220.6 | 50 | | | | | | |
| 45814 | 504972 | 2013-08-01 17:32:19.563000000 | 229.7 | 1.19 | 73 | 202.6 | 50 | | | | | | |
| 45815 | 504975 | 2013-08-01 17:32:29.633000000 | 229.6 | 1.189 | 73 | 200.7 | 50 | | | | | | |
| 45816 | 504978 | 2013-08-01 17:32:39.670000000 | 229.7 | 1.189 | 73 | 200.2 | 50 | | | | | | |
| 45817 | 504981 | 2013-08-01 17:32:49.573000000 | 229.7 | 1.188 | 72 | 200 | 50 | | | | | | |
| 45818 | 504985 | 2013-08-01 17:32:59.610000000 | 229.6 | 1.186 | 72 | 199.8 | 50 | | | | | | |
| 45819 | 504988 | 2013-08-01 17:32:59.630000000 | 229.7 | 1.188 | 72 | 199.8 | 50 | | | | | | |
| 45820 | 504990 | 2013-08-01 17:33:19.697000000 | 229.7 | 1.187 | 72 | 199.8 | 50 | | | | | | |
| 45821 | 501038 | 2013-08-01 13:53:38.560000000 | 0 | 0 | 0 | 0 | 0 | | | | | | |
| 45822 | 501041 | 2013-08-01 13:53:48.557000000 | 0 | 0 | 0 | 0 | 0 | | | | | | |
| 45823 | 501035 | 2013-08-01 13:53:28.540000000 | 0 | 0 | 0 | 0 | 0 | | | | | | |
| 45824 | 501026 | 2013-08-01 13:52:58.517000000 | 0 | 0 | 0 | 0 | 0 | | | | | | |
| 45825 | 501031 | 2013-08-01 13:53:18.477000000 | 0 | 0 | 0 | 0 | 0 | | | | | | |
| 45826 | 501028 | 2013-08-01 13:53:08.493000000 | 0 | 0 | 0 | 0 | 0 | | | | | | |
| 45827 | 501024 | 2013-08-01 13:52:48.493000000 | 0 | 0 | 0 | 0 | 0 | | | | | | |
| 45828 | 501017 | 2013-08-01 13:52:28.440000000 | 0 | 0 | 0 | 0 | 0 | | | | | | |
| 45829 | 501020 | 2013-08-01 13:52:17.947000000 | 0 | 0 | 0 | 0 | 0 | | | | | | |
| 45830 | 501011 | 2013-08-01 13:52:08.413000000 | 0 | 0 | 0 | 0 | 0 | | | | | | |
| 45831 | 501014 | 2013-08-01 13:52:18.493000000 | 0 | 0 | 0 | 0 | 0 | | | | | | |
| 45832 | 501006 | 2013-08-01 13:51:48.487000000 | 0 | 0 | 0 | 0 | 0 | | | | | | |
| 45833 | 501007 | 2013-08-01 13:51:58.413000000 | 0 | 0 | 0 | 0 | 0 | | | | | | |
| 45834 | 501002 | 2013-08-01 13:51:38.427000000 | 0 | 0 | 0 | 0 | 0 | | | | | | |
| 45835 | 501000 | 2013-08-01 13:51:28.440000000 | 0 | 0 | 0 | 0 | 0 | | | | | | |
| 45836 | 500997 | 2013-08-01 13:51:18.417000000 | 0 | 0 | 0 | 0 | 0 | | | | | | |

Figure 4.11: Excel spreadsheet of Smart Circuit 20 device data

4.4 Summary

In this chapter, an overview of the monitoring system and its design were provided, the laboratory setup for evaluating and testing the design was described, and the installation and commissioning of the monitor at the off-grid site were described. In the next chapter, examples of energy-use visualisations are provided,

the dashboard design is described, the implementation and tools used are outlined, and the processes involving the web page and sections are explained.

Chapter 5: Data visualisation, dashboard design, and implementation

The function of the off-grid dashboard is to present a real-time visualisation for the off-grid power monitoring. The dashboard was designed to provide information on real-time power input and consumption, the real-time battery charge state, battery power input/output, power consumption history, power input history, and battery charge state history. In Section 5.1, samples of energy use visualisations are provided. The dashboard design is described in Section 5.2. Section 5.3 explains the implementation, tools employed, and web page processes. A summary of this chapter is provided in Section 5.4.

5.1 Energy use visualisation examples

Numerous examples of domestic energy consumption dashboards are available. However, the particular requirements of off-grid monitoring, such as battery state and energy source information, are not always accommodated by these dashboards. The following paragraphs present a few examples of existing dashboards, which have partly informed the present dashboard design.



Figure 5.1: University of California, Merced, campus energy dashboard
(reproduced from the University of California, Merced, 2012)

Varick Erickson of the University of California, Merced, has developed an online energy dashboard and corresponding software package that monitor and present real-time energy usage on the campus (University of California, Merced, 2012). Images from the system are shown in Figure 5.1 Each room has a series of wireless cameras that count the people in the room. That data informs the system of the rooms to be heated and the given times and days. The information is shown on the dashboard. Overall, the system enables campus staff to monitor, reduce, and save electricity (University of California, Merced, 2012).



Figure 5.2: University of Louisville, Kentucky, building dashboard (reproduced from Mog, 2013)

To minimise environmental impact while maximising opportunities for energy efficiency on campus, the University of Louisville Office of University Planning, Design and Construction (UPDC) in Louisville, Kentucky, has produced a dashboard design that displays the campus sustainability effort (Mog, 2013). A screenshot from the campus building dashboard is shown in Figure 5.2. As part of the energy efficiency program, energy monitors were installed in four residence halls in 2012. These monitors collect data on real-time energy use in each hall, which helps the residents receive feedback on what energy they are using and how their conservation measures are helping. Having the rate of energy displayed on the dashboard helped the university to be one of the leading ten energy savers for the spring of 2012 (Mog, 2013).



Figure 5.3 : University of Massachusetts, Amherst, energy dashboard (reproduced from the University of Massachusetts, Amherst, 2013)

To reduce its overall impact on the environment and to save money, the University of Massachusetts, Amherst, conducted a pilot program using an energy dashboard to help students become more aware of their energy consumption (University of Massachusetts, Amherst, 2013). The dashboard, shown in Figure 5.3, plots energy usage over a two-week period to show students the impact of their efforts to save energy during that period. The pilot program led to the installation of 7 touch-screen 42-inch monitors, which display in real time the energy usage data for 82 campus buildings (University of Massachusetts, Amherst, 2013).



Figure 5.4: Kwantlen Polytechnic University, British Columbia, campus energy dashboard (reproduced from Kwantlen Polytechnic University, 2013)

Kwantlen Polytechnic University in British Columbia has installed Internet-accessible dashboards to display its campus real-time energy consumption, as shown in Figure 5.4 (Kwantlen Polytechnic University, 2013). The dashboards provide data 24 hours a day. The system can display daily, weekly, monthly, and annual rates of use. It serves as a tool for analysing the data received and encouraging continued electricity savings. The university currently has two separate dashboard systems, one for the campuses and one for the horticultural facilities (Kwantlen Polytechnic University, 2013).

5.2 Dashboard design

A requirement of the monitoring system is to provide real-time information on the use and status of the system. For this reason, we intended to develop a dashboard display that is suitable for mobile devices and that can be updated in real time and viewed from any location.

When users open the real-time off-grid monitoring system web page in any device and web browser, they are directed to the main page (see Figure 5.5). On this page, users can see the real-time power consumption and input meters, real-time battery charge status meter, and power input/output of the battery history. In the following paragraphs, each feature of the display is described in detail.

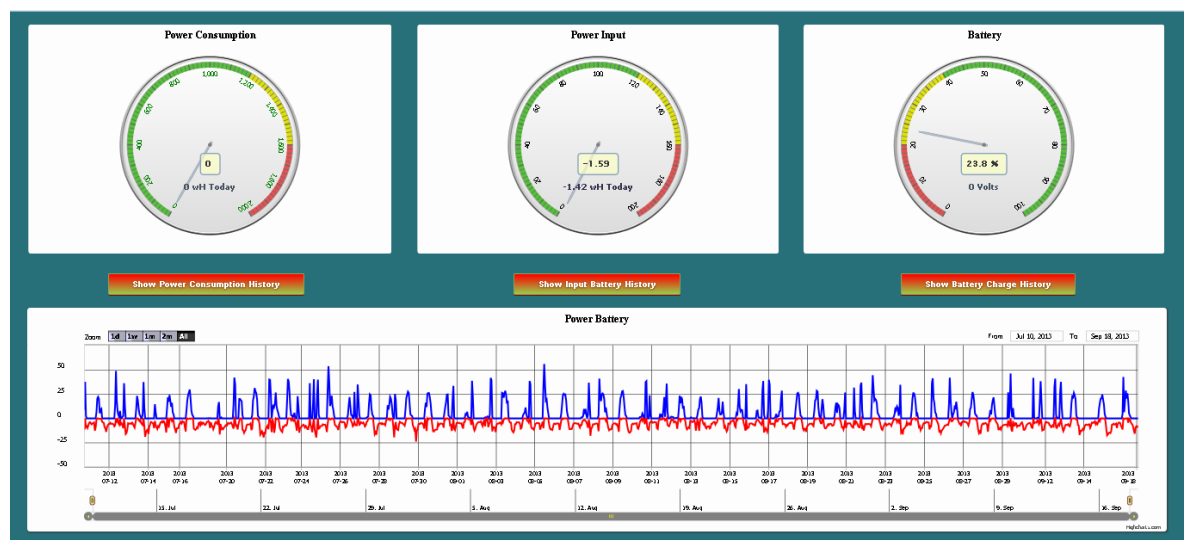


Figure 5.5: Main page of off-grid monitoring system dashboard

The power consumption meter displays the present power consumption using a pointer and counter in the centre of the meter. The daily total of power

consumption in watt hours is shown below the counter depicting the present power consumption, as shown in Figure 5.6.

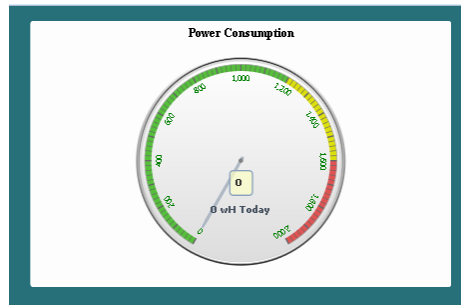


Figure 5.6: Power consumption meter

The power input meter displays the present power input using a pointer and counter in the centre of the meter. The daily total of power input in watt hours is shown below the counter depicting the present power input, as shown in Figure 5.7.

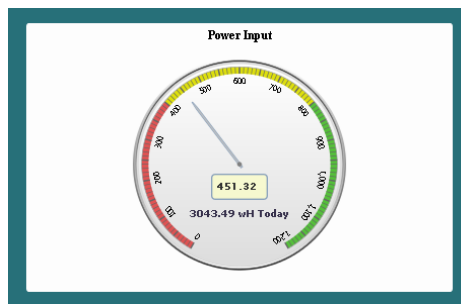


Figure 5.7: Power input meter

The battery meter displays the present battery state of charge using a pointer and counter in the centre of the meter. The present battery voltages are shown below the counter of the present battery state of charge, as shown in Figure 5.8. An algorithm for calculating the battery charge status employs data from the monitoring system, including the history. This algorithm is described in Chapter 6.

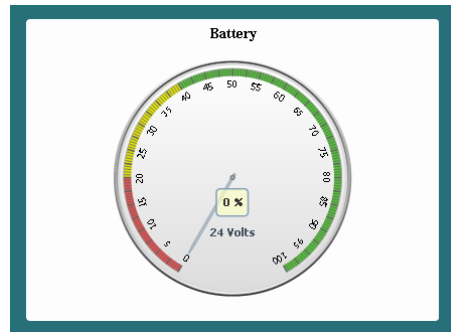


Figure 5.8: Battery meter



Figure 5.9: Power consumption history button

When users press the ‘show power consumption history’ button, shown in Figure 5.9, the chart at the bottom of the page changes and displays the power consumption history in a new chart, as shown in Figure 5.10. The same button then changes to a default button, shown in Figure 5.11. When users press this button, it returns them to the main page of the off-grid mentoring system dashboard.

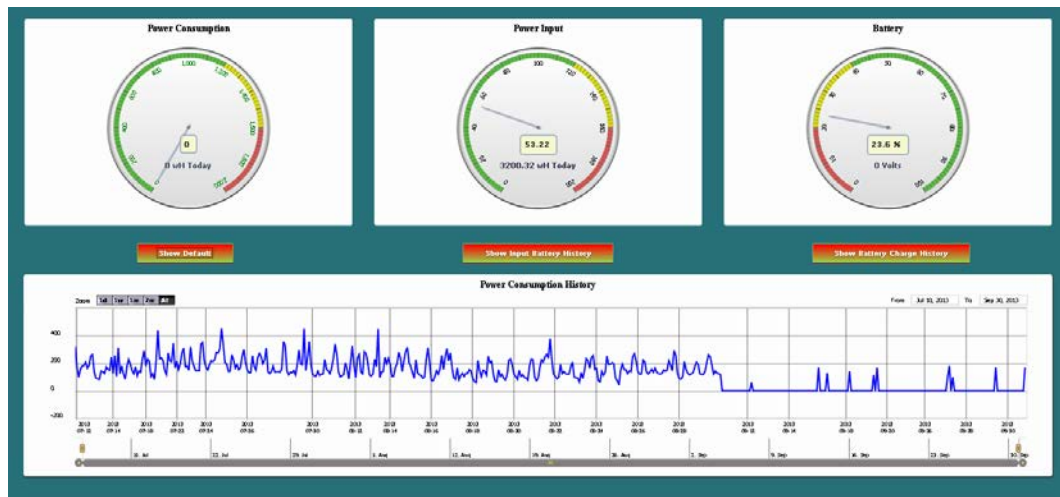


Figure 5.10: Power consumption history chart



Figure 5.11: Default page button

The same process occurs with the ‘show input battery history’ and ‘show battery charge history’ buttons, shown in Figures 5.12 and 5.13, respectively.



Figure 5.12: Power input history button

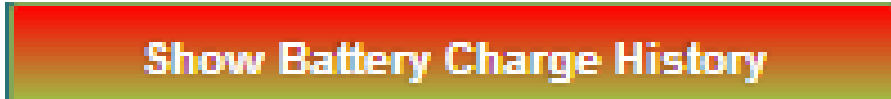


Figure 5.13: Battery charge history button

5.3 Implementation

In this section, the process of implementing our system is described, including the implementation environment, visualisation tools, and user interface.

5.3.1 Implementation environment

The first implementation environment of this study was for the development stage. It was implemented on a Dell laptop with a 500 GB hard disk, 4 GB RAM, and an Intel Core i5 CPU. The second implementation environment was for the production stage. It was implemented on an Intense PC with an 80 GB hard disk, 4 GB RAM, and an Intel Celeron CPU. In the implementation, Microsoft Visual Studio 2010 and Microsoft SQL Server 2008 were used. The implementation was written in C#, ASP, JavaScript, JQuery, Highcharts, Highstock, and HTML.

5.3.2 Visualisation tools

Several visualisation tools from the Highcharts/Highstock library were implemented in our web page, including data range selector buttons, data time scale, text boxes that display time, and zooming and tooltip functionalities (see Figure 5.14).



Figure 5.14: Visualisation tool items

Data range selector buttons

As shown in Figure 5.14, Item 1, this tool provides options for selecting ranges of data for time periods of one day, one week, one month, two months, and all available history.



Figure 5.15: Time selection buttons

Data time scale

The data time scale tool, shown in Figure 5.14, Item 2, enables users to manually select the data time period. It provides additional customisation capabilities for selecting data.

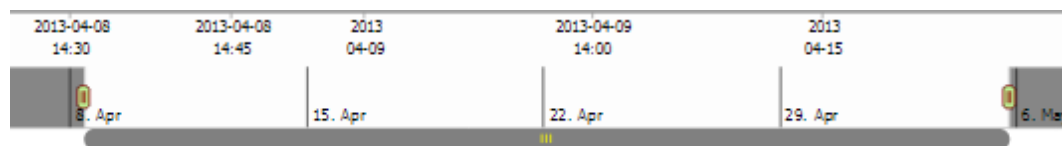


Figure 5.16: Time scale

Text boxes displaying time

Presented in Figure 5.14, Item 3, this tool displays the time after the user selects that option from the available buttons or manually selects it from the time scale.

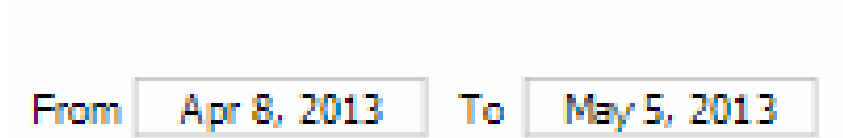


Figure 5.17: Text boxes displaying time

Zooming

As depicted in Figure 5.14, Item 4, this tool enables users to zoom the displayed data by selecting the mouse and finger zooming option.

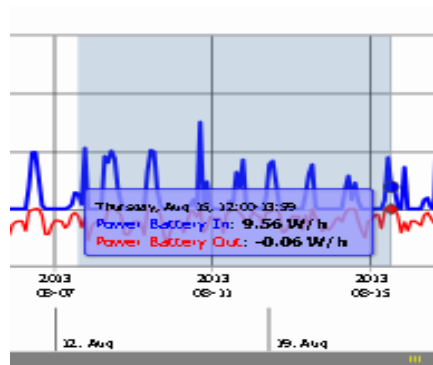


Figure 5.18: Data zooming

Tooltip

Shown in Figure 5.14, Item 5, the tooltip provides information, such as date, data, time, and so on, when the mouse rolls over the given data line on the chart.

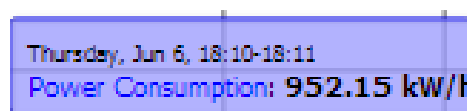


Figure 5.19: Tooltip functionality

5.3.3 Available Libraries

The off-grid power monitoring web page was developed using C# and ASP languages in addition to several free libraries.

Highcharts/Highstock library

The Highcharts charting library is written in HTML5 and JavaScript. It offers interactive charts for any website. The library supports the creation of many chart types, including line, spline, area, area spline, column, bar, pie, scatter, angular gauges, area range, area spline range, column range, bubble, box plot, error bars,

funnel, waterfall, and polar. Highstock is included in the library. It is written in JavaScript and is used to create stock or general timeline charts (Highcharts JS, 2013).

To use Highcharts, the following code excerpt must be included in the web page:

```
<script src="http://code.highcharts.com/stock/highstock.js"
type="text/javascript"></script>
<script src="http://code.highcharts.com/highcharts-more.js"
type="text/javascript"></script>
```

JQuery library

The JQuery library is suitable to almost any scripting situation because it provides a general abstraction layer for common web scripting. Without a JavaScript library, many lines of code must be written to find specific parts of an HTML document structure and to span the Document Object Model tree. JQuery provides a “robust and efficient selector mechanism for retrieving exactly the piece of the document that is to be inspected or manipulated” (Chaffer & Swedberg, 2010).

To use JQuery, the following code excerpt must be included in the web page:

```
<link rel="stylesheet"
href="http://ajax.googleapis.com/ajax/libs/jqueryui/1.8.9/themes/base/jquery-
ui.css" type="text/css" media="all" />
<script src="http://ajax.aspnetcdn.com/ajax/jQuery/jquery-1.5.min.js"
type="text/javascript"></script>
<script
src="http://ajax.googleapis.com/ajax/libs/jqueryui/1.8.9/jquery-ui.min.js"
type="text/javascript"></script>
```

5.3.4 Web page process

The web page process began with two Visual Studio 2010 class libraries: the off-grid energy monitoring web page class, and off-grid energy monitoring entity model class. The web page model contained a server side and client side (see Figure 5.20). To map the relational model from SQL Server to the C# object model, the entity model was required. Use of the Entity Framework included in Visual Studio dramatically simplified the mapping process. An entity data model (EDM) was used to map the object model in the object data, which was then delivered to ASP file format using C#. In the first step of the web page process,

the server side information was transferred to the client side. A combination of Highcharts and Highstock, based on HTML, JavaScript, and JQuery, were used to generate graphical views in the browser of power consumption, power input, and the battery charge status.

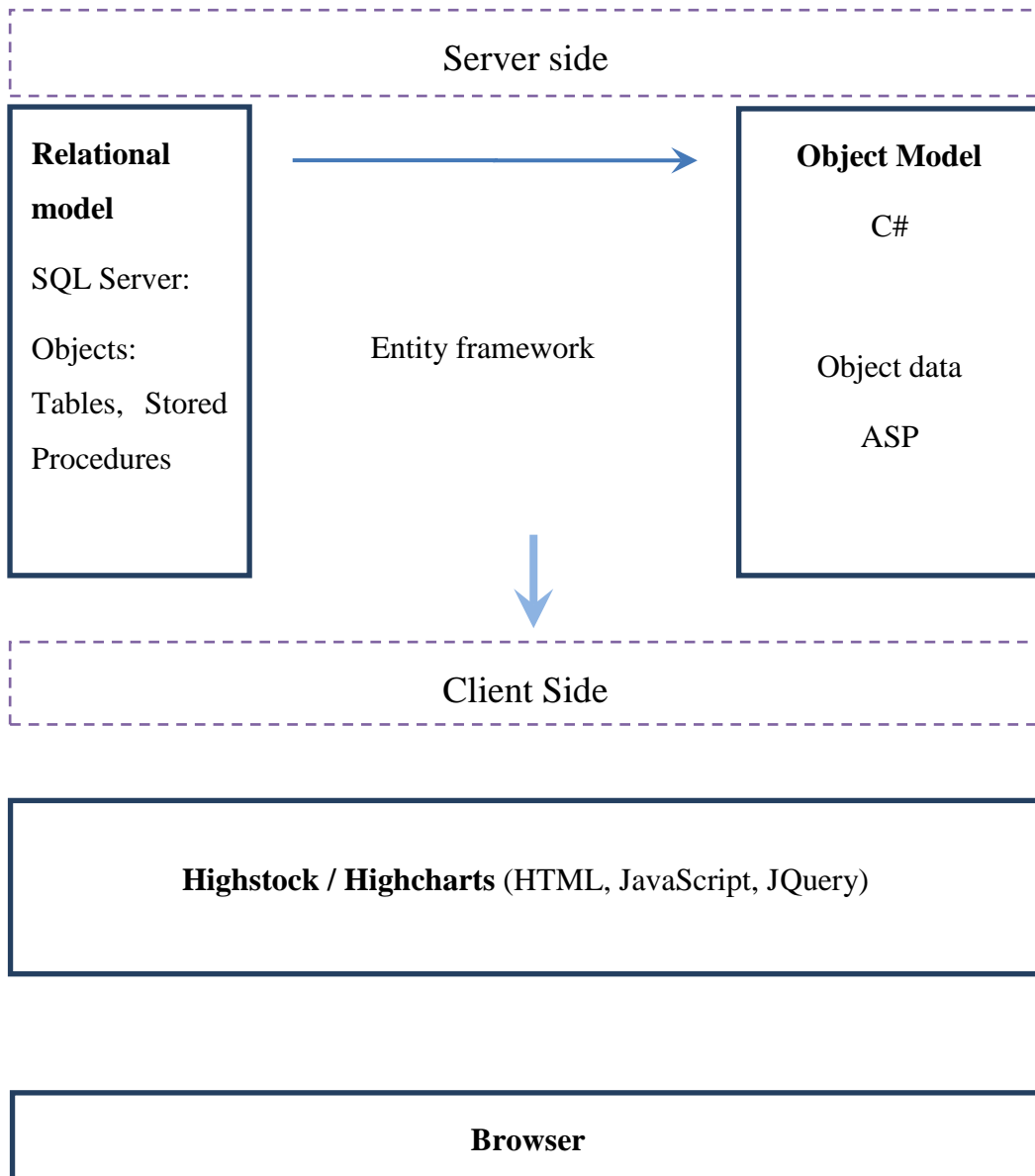


Figure 5.20: Web page model process

5.4 Summary

In this chapter, examples of energy use visualisation were provided, the present dashboard design was described, and the implementation, development tools, and

process of the web page were explained. The next chapter explains state-of-charge (SoC) challenges, describes measuring known information and analysing data collected, and describes the battery SoC algorithm.

Chapter 6: Battery state-of-charge monitoring

The objective of this research was to produce battery state-of-charge (SoC) indications based solely on continuous monitoring of battery voltage and current, as well as on low-voltage shutdown event information. An indication of the battery charge percentage (to at least the nearest quarter) at any given time was desired for the off-grid power system. Section 6.1 explains the challenge of this SoC goal. In Section 6.2, the measuring of collected information is described, while the analysis of data collected is described in Section 6.3. In Section 6.4, the battery SoC algorithm is outlined, and the chapter summary is provided in Section 6.5.

6.1 State-of-charge challenge

To accurately measure battery SoC, measurements must be taken after the battery has been resting for a period of time. This resting state is not a typical one for off-grid energy systems, which are constantly in use (Apperley & Alahmari, 2013). Actions can trigger the equipment that measures battery level and those that record battery SoC; these actions may cause a conflict due to a drop in voltage, and an accurate reading might not be taken (Apperley & Alahmari, 2013). For example, the Pauaeke installation uses a Studer inverter/charger that ceases operation when the battery voltage drops below 23.2 V for 2 min (Studder Innotec, n.d.).

When a heavy load is applied to the battery, the proxy charge level, which normally reads at 0%, can occur above this percentage. The Pauaeke installation, for example, uses an Outback solar controller with a Studer inverter/charger that automatically changes to absorption mode when the battery approaches its capacity to hold a charge, which is shown by a combination of current and voltage (Battery University, 2013).

The load current and total battery current are recognized by the solar controller, while the inverter recognizes the battery current level. However, neither of these is a dependable and accurate reflection of a fully charged battery. The battery voltage during charging depends on the rate of the charge input; it can

occasionally produce a false reading at a level lower than the 100% charge capacity (Pop et al., 2005). An awareness of the history of the battery can enhance an understanding of the SoC; however, it cannot prevent battery shutdown due to low voltage (above 0%) caused by a heavy load, or if the charger backs off under 100% charge. In addition, a drop or other change in battery capacity can be expected as the battery ages (Pop et al., 2005).

Changes in temperature can additionally influence the behaviour of the battery. Some monitors can read these changes with the inclusion of a temperature sensor (Perez, 1993). The behaviour of the charging battery is affected by the rate of charge. For example, a battery will appear to be 100% full when it is actually less than fully charged because of a high rate of charge. This behaviour supports the theory that a slower input charge rate will enable the battery to fully charge itself (Pop et al., 2005). Moreover, the behaviour of the discharging battery varies with the load placed on it. The battery voltage declines as the current load rises. This is not solely due to internal resistance. Time is required to recover the voltage after the load is removed. Additionally, a certain amount of energy is released as heat from the battery rather than being stored in it (Battery University, 2013). Because this energy can be lost because of the temperature and charge rate, which can vary and are occasionally unclear, gauging the battery ‘charge efficiency’ is difficult. Batteries in an off-grid system do not fully charge and discharge over the period of a day; therefore, these batteries may receive many sources of charge, such as from the sun or other energy input. Moreover, the discharge rate also varies due to peak usage; the batteries may not ever be completely full or empty. For example, this behaviour can occur when there is direct sunlight at a high usage time; the load may come directly from the source, not the battery (Apperley & Alahmari, 2013).

6.2 Measuring known data

When monitoring battery energy input/output, voltage and current values can be precisely measured. The charge and discharge rates can also be calculated from these values, and the battery temperature can be observed. However, this latter capability is not yet available at the Pauaeke installation. The inverter low voltage

shut down events (LVSDs) can be easily detected. Nevertheless, the charger back-off events are more difficult to detect, which makes them unreliable as an accurate reflection of the SoC. The battery charge state cannot be accurately known prior to charging because it can vary depending on many factors; however, it can be estimated using the above information (Apperley & Alahmari, 2013).

6.3 Data analysis

Figure 6.1 depicts analysis of actual data from the 23 July to 4 August period. Each vertical line indicates a separate day; however, the lines do not correspond with midnight. The algorithm was initiated without knowledge of the SoC or battery capacity; the assumption that the charge efficiency would be at 80%, with the beginning charge level at 0%, was made. For the first three days, the maximum charge value (C100), having begun at zero, was achieved; the SoC values were considered accurate from that point. Errors in charge efficiency (CE) value are shown in the figure as a general upward (CE too high) or downward (CE too low) drift in the CT and SoC values. The impact of any drift of this value would have been minimal provided that the maximum (C100) value was calculated within five days.

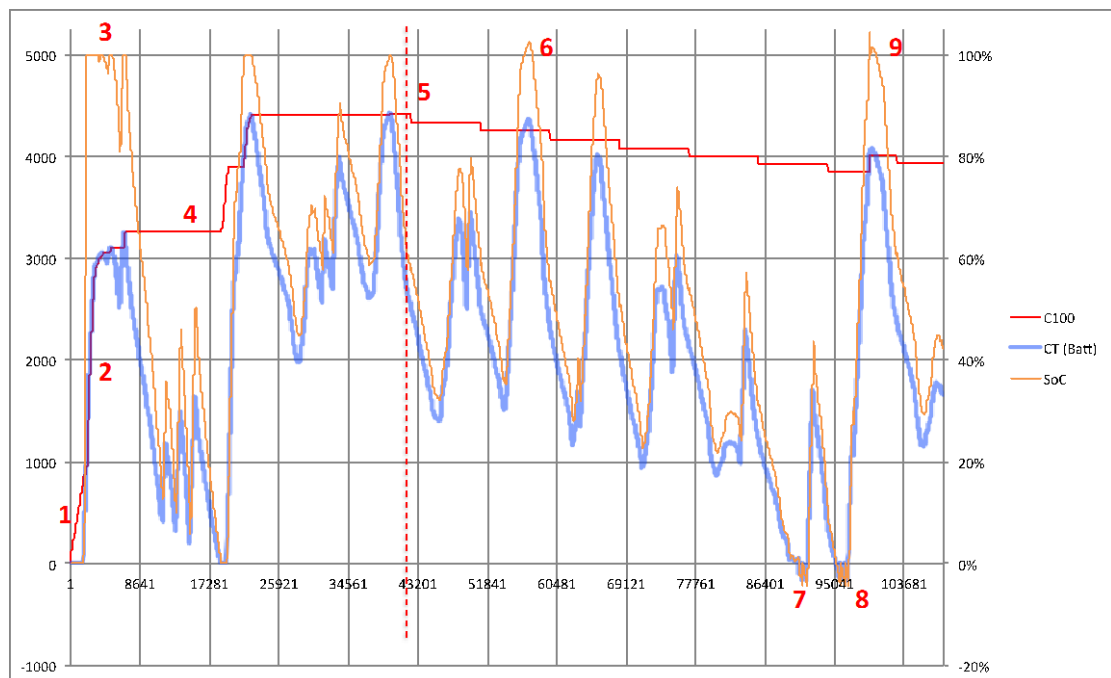


Figure 6.1: Data from the Pauaeke electricity system from 23 July 2013 to 4 August, 2013 (reproduced from Apperley & Alahmari, 2013)

The red numbers shown in Figure 6.1 are described below.

1. C100 increased because the CT was assumed to have an initial value of zero. However, it decreased (i.e., showed a negative tendency); therefore, C100 was increased so that it did not decrease below zero. At this stage, C100 represented the highest value of CT to date.
2. C100 continued to increase in this region, and it followed the rise of CT as charging commenced.
3. Because the true C100 value had not yet been established, the SoC value was 100% for the highest charge level to date.
4. C100 continued to track the maximum value of CT to date; however, it also increased if CT became negative.
5. Five days had passed; therefore, we froze C100 at this point and introduced a daily 2% drop in its value.
6. SoC exceeded 100%. However, it was not as high as 105%; therefore, no action was taken.
7. SoC decreased to -5% with no LVSD event occurring; therefore, the CE was assumed to be too low. A new value of CE was calculated from the battery power input/output over the previous seven days (81%), and CT was reset to zero. Although CT (and therefore SoC) continued to decrease for a period, CT did not reach as far as -5%; therefore, no further action occurred here.
8. SoC again decreased to -5% with no LVSD event; therefore, CE was recalculated to 82%. It again decreased shortly thereafter to -5%, and CE was recalculated to 82.5%. This process was repeated once again, thereby producing a value for CE of 83.2%. An LVSD event occurred soon thereafter; however, because SoC was at 0%, no action from the algorithm was required.
9. The SoC increased to 105%; therefore, C100 was increased to decrease the former value to 100%. Although the SoC continued to increase, it reached to only 101%; therefore, no further action was required.

After the first five days, any perceived errors with the CE value were adjusted by observing the low voltage shutdown alert in the following manner. An LVSD alert occurred when the inverter output voltage dropped to zero and when the battery voltage was low (approximately < 23.2 V) for two minutes or more. Assuming that the tolerance band of $\pm 5\%$ was around the zero level of charge, the actual value of zero (LVSD occurrence) over the SoC level of 5% indicated an error, which required adjusting once more to 0%. If the zero level became too low (under -5%), it required readjustment towards 0%.

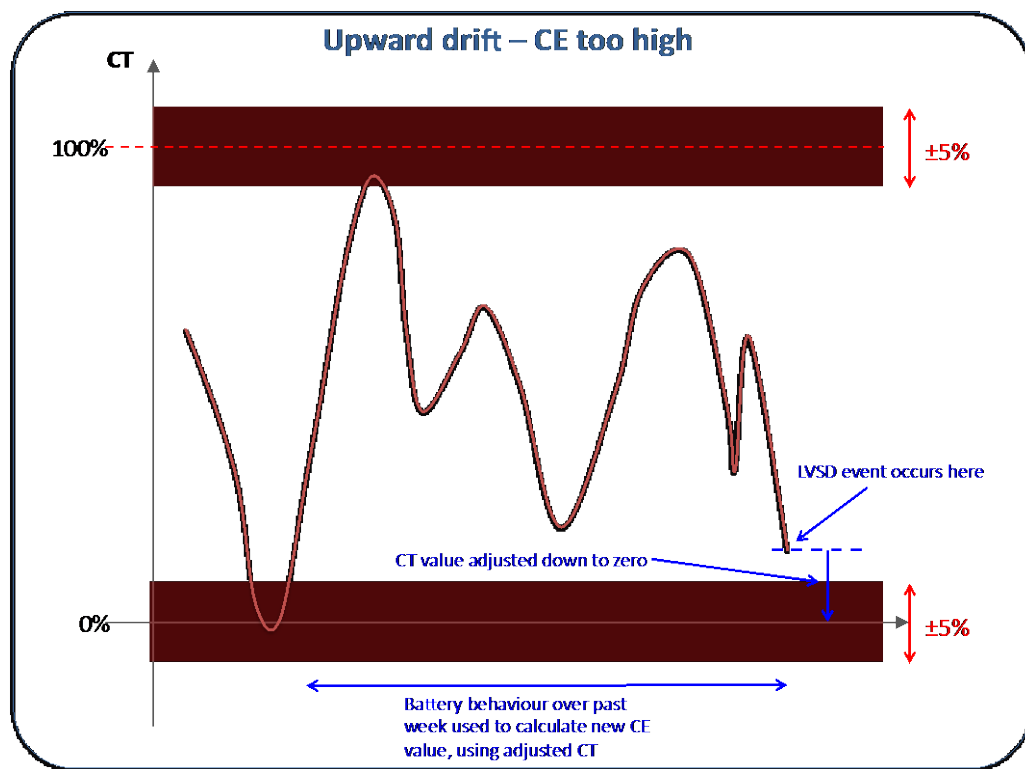


Figure 6.2: Upward drift in the estimated charge level because the assumed charge efficiency value (CE) is too high (reproduced from Apperley & Alahmari, 2013)

An upward drift meant that the CE was excessively high. This behaviour was shown by the LVSD when the SoC increased above 5% and the power draw had not been extreme for the last two minutes. If the power draw was excessive for two minutes or more—for example, more than 500 W—then this value was averaged over the time monitored, and the event was ignored. In addition, if the SOC increased by 20% or more, this too was ignored to prevent errors. The alert

value was typically set to zero for the value equalling CT and to 0% for the SoC; the CE was then adjusted down. During the past week, if information was needed that an SoC occurred, then no adjustments to C100 were required.

To set the CT to 0, we take the Pout, Pin, and CT values from the previous week and subtract them from the current values, thereby giving ΔP_{out} , ΔP_{in} and ΔCT .

$$\text{SoC} = 0\%$$

$$\text{new CE} = (\Delta CT + \Delta P_{out}) / \Delta P_{in}$$

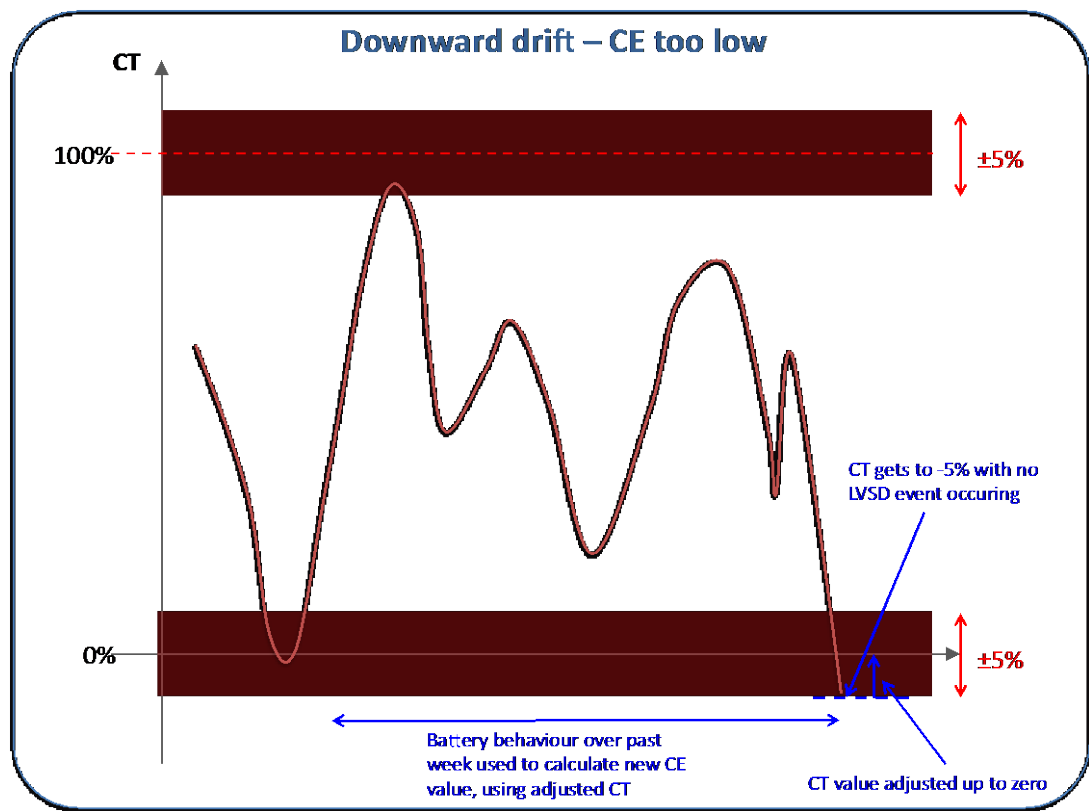


Figure 6.3: Downward drift in the estimated charge level because the assumed charge efficiency value (CE) is too low (reproduced from Apperley & Alahmari, 2013)

As illustrated by Figure 6.3, a downward drift shows that the CE was excessively low (SoC below -5%) without an LVSD event. The adjustments of the CT to zero were required to help move the CE upwards. The same technique and formula were used to achieve a past weekly value with the SoC set to 0%. As shown in the figure, a continuous sequence of drifts occurred until an LVSD event followed or

the battery discharge ceased. The assumption previously mentioned that all CE errors cause drift issues was realized by the two LVSD processes because the LVSD was more consistent than the alerts indicating a full battery.

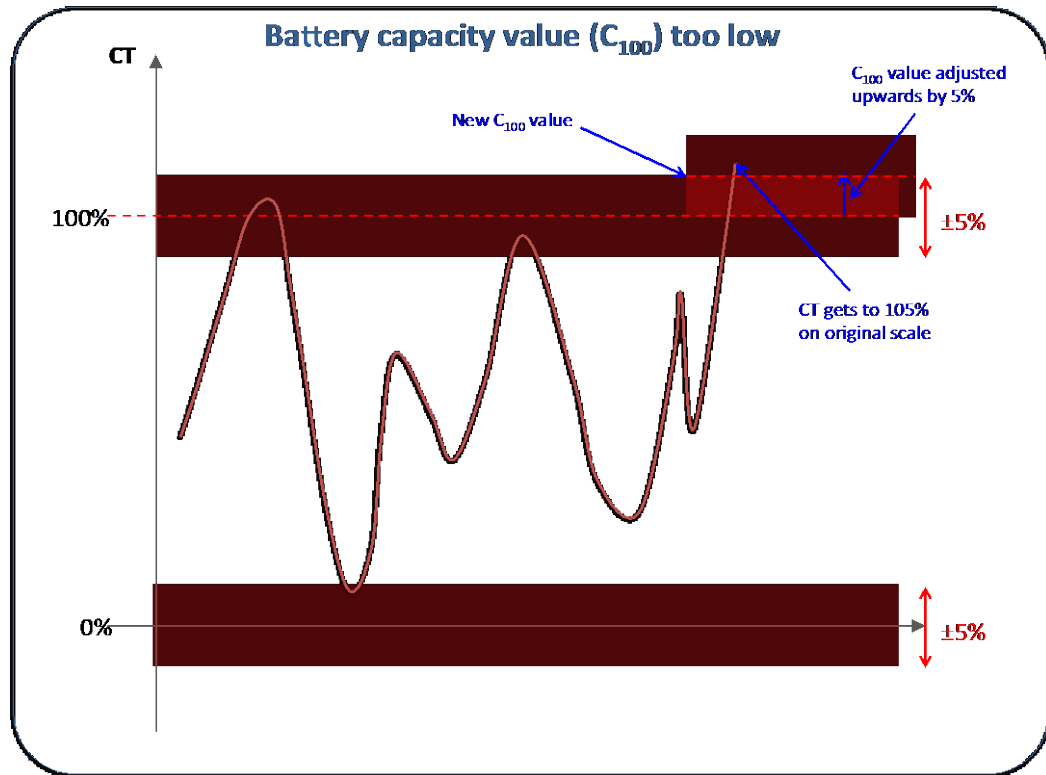


Figure 6.4: The effect of under-estimating the battery charge capacity (C100)
(reproduced from Apperley & Alahmari, 2013)

Issues with the total charge capacity shown by the C100 were occasionally observed. By watching the C100, an error could be observed by the following: When the SoC rose to 105%, a C100 low event occurred (C100LO). Given the assumption that this state resulted from the value being excessively low, for example, rather than the CE value being excessively high, verification was already made for that condition using the LVSD. Therefore, the required adjustments set the C100 to equal the CT.

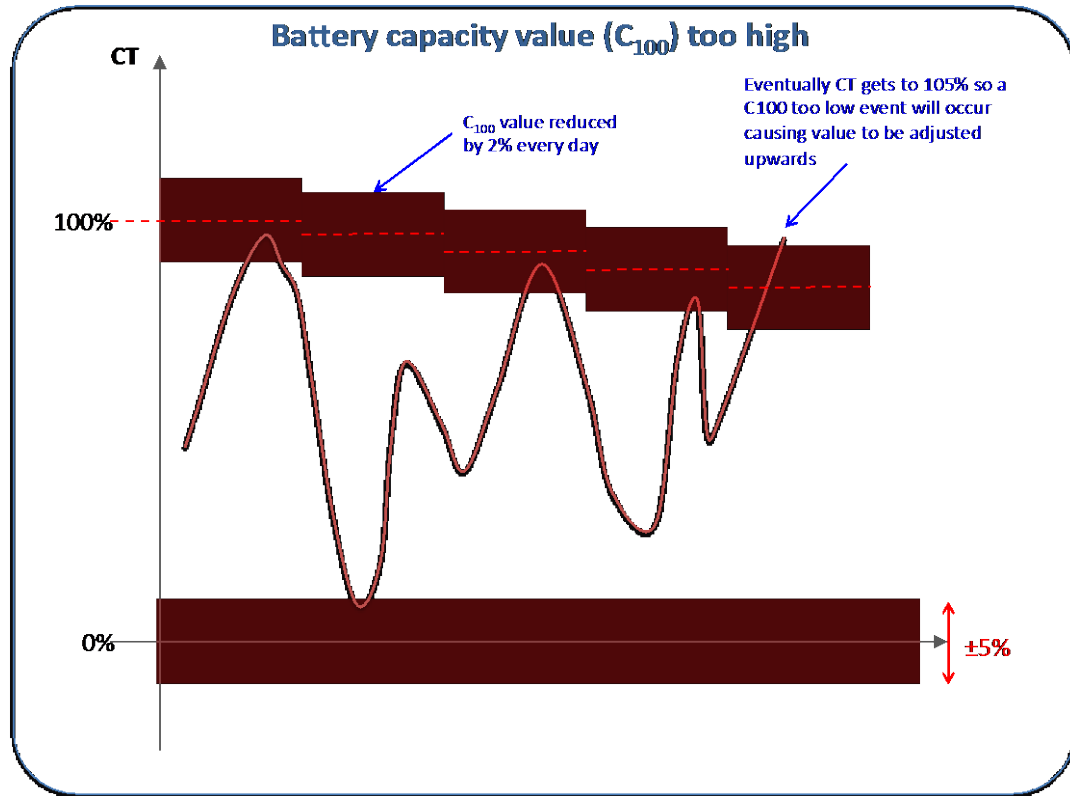


Figure 6.5: The effect of over-estimating the battery charge capacity (C100)
(reproduced from Apperley & Alahmari, 2013)

The cause of the C100 being excessively high could be aging of the battery, the initial settings being incorrect, or the value of the C100 being too high because there is no reliable way to accurately gauge if the battery is full. These possible causes should be evaluated. To identify the problem when the C100 was excessively high, we reduced the setting by 2% every day until a low event was triggered, which would provide information on what the issue was. The end of each day would therefore yield: $C100 = 0.98 \times C100$.

6.4 Battery state-of-charge algorithm

The battery SoC algorithm developed for the present study is described in this section.

| | |
|---------------|---|
| $P_{in} = 0$ | P_{in} is the power input to the battery. |
| $P_{out} = 0$ | P_{out} is the power output from the battery. |
| $CT = 0$ | |
| $C100 = 0$ | C100 is the maximum charge value. |

$CE = 0.8$ CE is the charge efficiency.

For the first five days, this algorithm was used to establish the value for $C100$:

Take next data record

Calculate Power increment $P_{inc} = V_B * I_B * \text{time increment}$, battery increment B_{inc} and update P_{in} and P_{out} :

If $P_{inc} > 0$ then

$P_{in} = P_{in} + P_{inc}$

$B_{inc} = CE * P_{inc}$

else

$P_{out} = P_{out} - P_{inc}$ / P_{out} is maintained as a positive value

$B_{inc} = P_{inc}$

If CT attempts to go below zero, $C100$ must be adjusted upwards

If $(CT + B_{inc}) < 0$ then

$C100 = C100 - (CT + B_{inc})$

$CT = 0$

and if CT exceeds $C100$, $C100$ must be adjusted upwards

else

$CT = CT + B_{inc}$

If $CT > C100$ then

$C100 = CT$

$SoC = CT / C100$

continue looping

From that point, follow this algorithm to maintain CE and keep $C100$ honest:

Take next data record

Take next data record

Calculate power increment $P_{inc} = V_B * I_B * \text{time increment}$, and update P_{in} and P_{out} :

If $P_{inc} > 0$ then

$P_{in} = P_{in} + P_{inc}$

$CT = CT + CE * P_{inc}$

else

$P_{out} = P_{out} - P_{inc}$ / P_{out} is maintained as a positive value

$CT = CT + P_{inc}$

$SoC = CT / C100$

1. Check for upward drift:

If (LVSD) and ($SoC \geq 5\%$) and (2 minute load > 500 W) then

$CT = 0$

$SoC = 0\%$

Calculate ΔCT , ΔP_{out} and ΔP_{in} using values from 7 days prior

$CE = (\Delta CT + \Delta P_{out}) / \Delta P_{in}$

2. Check for downward drift:

If (not LVSD) and ($SoC \leq -5\%$) then

$CT = 0$

$SoC = 0\%$

Calculate ΔCT , ΔP_{out} and ΔP_{in} using values from 7 days prior

$CE = (\Delta CT + \Delta P_{out}) / \Delta P_{in}$

3. Check if C100 is excessively low:

If ($SoC \geq 105\%$) then

$C100 = CT$

$SoC = 100\%$

4. Check if C100 is excessively high:

If (end of day) then

$C100 = 0.98 * C100$

continue looping

6.5 Summary

In this chapter, challenges posed by the state-of-charge (SoC) were explained, measuring known data was described, the data collected was analysed, and the battery state-of-charge algorithm was described.

Chapter 7: Conclusion and future work

In summary, this research aimed to describe the implementation of monitoring equipment in an off-grid residential system. Software was developed to collect the data from the equipment and to store it in a power monitoring database. A monitoring dashboard was built to display the real-time data in combination with analysis techniques to provide short-, medium-, and long-term information.

7.1 Conclusion

In the initial sections of this thesis, the motivation of this research was outlined to address the questions: Why must subjects living off-grid monitor and control their electricity systems more than subjects who live on-grid? Why is understanding off-grid usage patterns useful for developing approaches to regulating on-grid energy usage?

In addition, available monitoring devices and software, off-grid system technology and characteristics, battery state-of-charge (SoC) algorithms, and related work were reviewed. This information was applied to develop the hardware and software used to provide the required information for the present off-grid system. After the off-grid system environment and its components were fully described, the requirements and processes of performing the measurements were addressed.

Once the monitoring software for this research was built, it was tested to identify and solve any issues before actual installation in the field.

To build the dashboard, examples of energy use visualisations were reviewed. The dashboard design and its implementation environment were described in detail in Chapter five. The challenges presented by the battery SoC, variables that can be measured, and data analysis used to produce the SoC algorithm, were described in Chapter six.

During this study, several limitations were identified that require further work. The off-grid monitoring database should be implemented into the IDSLM database at the university of Waikato. Because of security concerns with data entering the university network from outside it, the database was implemented in a Fit PC with

software in the field. To publish the web page, a Windows server was required. However, this server was not available and the web page was not published. As an option, if the University of Waikato can provide a domain in the university server, the web page could then be published.

The study results were used to develop the battery SoC algorithm. The purpose of this algorithm is to help users of off-grid systems learn at any given time the percentage of charge in their off-grid system batteries.

7.2 Future work

The next step in this research is to collect data from more than one off-grid system. Appliance scheduling will then be undertaken to determine the energy-use impact of these appliances. The present power consumption of each appliance will be displayed in the developed dashboard, and the history record of each appliance will be available (see Figure 7.1).

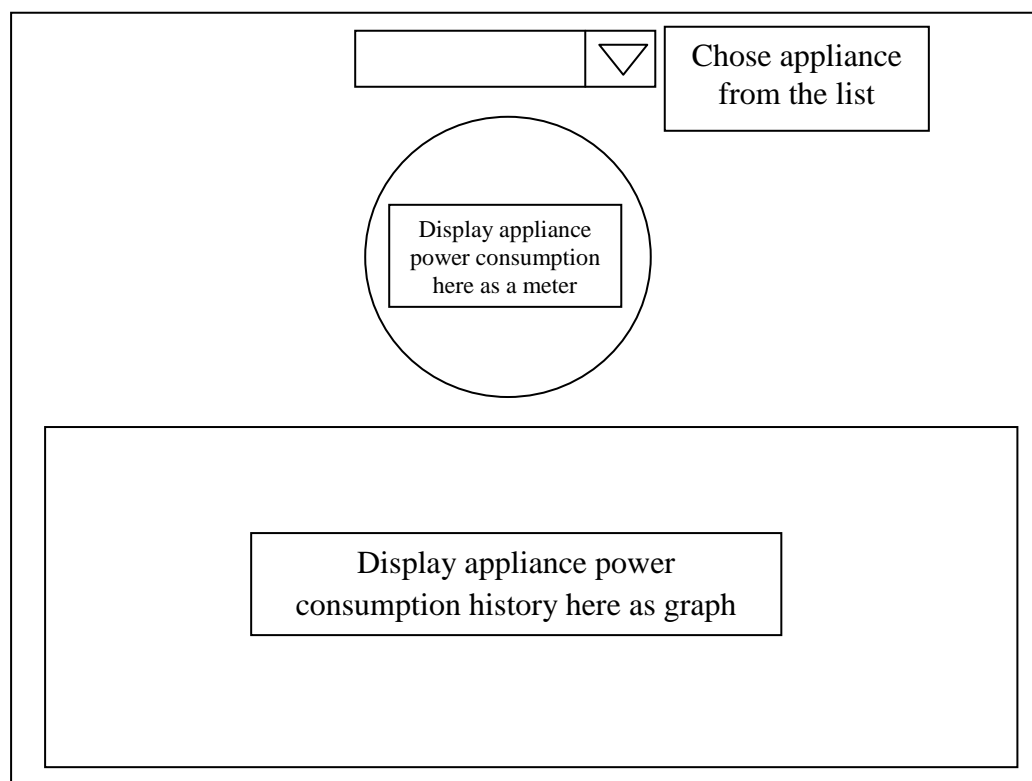


Figure 7.1: Developed off-grid system dashboard of appliance power consumption

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