INSTITUTO POLITÉCNICO DE BRAGANÇA Escola Superior de Tecnologia e Gestão

UNIVERSIDADE TECNOLÓGICA FEDERAL DO PARANÁ

Implementation of a smart microgrid in a small museum

Luís Guilherme Aguiar Figueiredo

Thesis presented in the School of Technology and Management of the Polytechnic Institute of Bragança to fulfill the requirements of a Master of Science Degree in Industrial Engineering (Electrical Engineering branch).

Supervised by:
Prof. Dr. Américo Vicente Teixeira Leite
Prof. Dr. Murilo da Silva

This work does not include the appointments and suggestions of the Juri

Bragança
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Resumo

A crescente demanda por energia associada a questões ambientais contribui para a implementação de diversas tecnologias na geração de energia a partir de fontes renováveis. Dentre essas fontes renováveis, tem-se a geração distribuida composta por fotovoltaica e pico-hídrica. As microrredes são uma abordagem alternativa para atender essa demanda por energia, integrando a geração distribuida, geralmente obtida através de fontes renováveis, com cargas elétricas de uma rede local, e sistema de armazenamento e gerenciamento de energia. Além disso, podem ser conectadas a rede pública (on-grid), com a possibilidade de importar ou exportar energia, ou em modo ilha (off-grid).

As microrredes também possuem a capacidade de controle de produção, cosumo e gestão de energia usando rede uma de comunicações entre todos dispositivos. Os sistemas que possuem essas capacidades são classificados como microrredes inteligentes. Neste trabalho é abordado a implementação de uma microrrede inteligente na Casa da Seda, um museu dedicado à disseminação de ciência localizado em Bragança, Portugal. O intuito deste sistema é tornal o local energeticamente autossustentável em termos médios anuais e contribuir para a disseminação de novas tecnologias baseadas na integração de fontes renováveis em microrredes.

Este trabalho apresenta o contexto e requisitos da microrrede inteligente da Casa da Seda, a sua instalação e colocação em serviço. A microrrede é baseada no Sistema Flexível de Armazenamento da SMA, com integração de geração de energia baseada nas fontes renováveis presentes no local, nomeadamente fotovoltaica e hídrica, e um banco de baterias para incremento do autoconsumo.

O início da operação, em contexto real, e os primeiros dados de geração fotovoltaica evidenciam a satisfação dos requisitos inicialmente identificados.

Palavras-chave: Microrredes, energia renovável, fotovoltaico, pico-hídrico.

Abstract

The growing demand for energy associated with environmental issues contributes to the implementation of several technologies for the generation of energy from renewable sources. Among these renewable sources, there is the distributed generation that can be composed of photovoltaic and pico-hydro. Microdrids are an alternative approach to meeting this demand for energy integrating distributed generation, usually obtained from renewable sources, with loads in a local grid, storage system, and power management. In addition, they can be connected to the utility grid (on-grid), with the possibility of injecting (or not) energy, or on isolated mode (off-grid).

Microgrids also have the capability to control generation, consumption, and energy management using communications' network between all devices. Systems with these capabilities are classified as smart microgrids. This thesis discusses the implementation of a smart microgrid at Silk House, a museum dedicated to the dissemination of science located in Bragança, Portugal. The smart microgrid aims to transform in a self-sustainable museum, in annual average terms, and to contribute to the dissemination of new technologies based on renewable sources integration for microgrids.

This paper presents the context and requirements of the Silk Houses's smart microgrid, its installation and commissioning. The system is based on the SMA Flexible Storage System with battery-backup and increased of self-consumption integrating power generation based on on-site renewable sources, photovoltaic and hydro, and a battery-bank for increased of self-consumption.

The start of operation, in real context, and the first photovoltaic generation data show the satisfaction of the initially identified requirements.

Keywords: Microgrids, renewable energy, photovoltaic, pico-hydro.

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Acronyms

AC Alternating Current.

DC Direct Current.

DG Distributed Generation.

ESTiG Escola Superior de Tecnologia e Gestão.

IPB Instituto Politécnico de Bragança.

PV Photovoltaic.

SB Sunny Boy.

SHM Sunny Home Manager.

SI Sunny Island.

SOC State of Charge.

SOH State of Health.

SRC Sunny Remote Control.

VRLA Valve-regulated lead-acid.

Chapter 1

Introduction

Energy demand worldwide grew at a rate 2.9% in 2018, the fastest growth since 2010, with China, USA, and India responsible for more than two-thirds of the demand global increase [1]. The demand meet the electricity generation by fossil fuels as the primary sources of energy [2]. Despite the growth, the use of fossil fuels has been discussed continuously nowadays for its consequences, for example, the growth of carbon emissions for 2% - the fastest growth in seven years [1].

The need for more energy and, at the same time, questions about the use of fossil fuels and the environmental concerns have contributed, more and more, to the use of renewable sources to generate electrical energy and supply the increasing demand. Renewable sources lead the increasing of world power generation with a growth by 14.5%, followed by coal and natural gas [1]. Positive impacts can be mentioned, as a reason for the growing integration of renewable energy sources, such as the capability to meet the increasing demand for energy, low operation and maintenance costs, beyond the environmental issue [2].

The main primary sources to renewable energy, among the many available, are solar, wind, and hydro, which can integrate the distributed generation (DG), a small scale power generation close to the consumers' loads [2] [3]. These renewable DGs can be integrated to microgrids system improving power reliability and greater consumer independence. In addition, it contributes to meeting the growing demand for energy by harnessing the use of renewable energy sources. Thus, the basic concept of microgrids are the interconnection of DG technologies, integrating renewable sources (or not), connected to loads, with energy storage capacity, and with a management system [2]. It may (or not) be connected to the utility grid.

Microgrids allows the consumer to interact with the energy system to manage the use of energy and reduce energy costs. Besides that, some microgrids can be considered intelligent.

Distinguishing from the conventional one is the presence of intelligence incorporated into load management, optimum efficiency, minimum cost, and maximum reliability [4]. Also, microgrids integrating distributed generation brings environmental, technical, and economic benefits to the consumers and the distributions systems.

1.1 Microgrid: economical, environmental, and societal issues

Several studies and projects have been conducted in microgrids' field for years to find their potential benefits related to economic, environmental, and social issues. Microgrids' projects can provide knowledge dissemination and allow better understanding lessons to individuals that may be applicable and select the optimal system configuration for their contexts [4].

Development of microgrids' projects should take into account some requirements, as cited in [5]: economic feasibility, environmental impact, benefits for society, demand estimation, energy technology generation, storage capability, energy efficiency, demand management, etc. The results of using microgrids can be different depending on local conditions, end consumer requirements, geographic location, climate, and others [4].

1.1.1 Economical issues

The economical issues are related to the investment in infrastructure, operation, and the pay back of the investment. Through microgrids, it is obtained reduction of physical and electrical distance, because the source is located at or near the loads. As a result, microgrids have no costs with distribution and transmission lines, customers services, and other expenses related to conventional power systems [4][6].

On-site renewable DG allows to have clean energy with a minimum cost. On the one hand, the costs for renewable generation equipment and installation still have a high cost to the consumers. On the other hand, the consumer has an economy in energy bill that is supplied by the local concessionaire and gets great independence from it. It is worth mentioning that the economy and independence depends on several points of the microgrid configuration, such as generation capability, load demand, and if it is connected to the utility grid or not. With the great independence from the dominate of the classical market, it is possible to say that it will contribute to a decrease in fees in the energy market. Thus, the microgrid permit a market opening and an increased competition [4].

1.1.2 Environmental issues

Any form of energy production can have some level of environmental impact even being a renewable source, whether during generation or in manufacture. If it considers the manufacturing of solar modules, it will have an associated environmental impact during the process. Such as the extraction of materials and use of fossil fuels to manufacture [4]. However, the generation can differentiate the renewable source from a conventional one that use fossil fuels. Even so, the renewable source has a lower environmental impact.

The penetration of renewable DG enables an optimal inclusion of cleaner and greener energy technologies into the utility grid or even in an independent use via microgrids. Also, it can significantly reduce the intensity of carbon emissions when compared with conventional power plants in power sector [3] [7].

Monitoring environmental impacts generated by conventional sources permits to verify clearly the effects caused by them. For example, in the United States (US), 64% of the total electrical energy generated in 2017 was based on fossil fuels (coal, natural gas, and petroleum), biomass and industrial/municipal wastes. They are the cause of about 34% of total US energy-related CO_2 emissions, that is one of the gases responsible for the greenhouse effect [8]. *Renewable Energy Prospects for the European Union* published in 2018 [9], shows that fossil fuels represent about 71% of the European Union's (EU) primary energy supply. However, a series of current and further work, such as agreements as Horizon 2020 and 2030 Energy Strategy among the EU's countries, have been accomplished in the field of energy and climate. The objective is to improve the EU's economic competitiveness, energy security, as well as reducing emissions.

Such initiatives produced positive results. The EU's carbon emission decrease 25% between

2005 and 2016 and electricity generated by renewable sources increased 2.3% between 2017 (30%) and 2018 (32.3%). These are results of increased efficiency and the transition from fossil fuels to renewable fuels in electricity generation [10] [11].

1.1.3 Social issues

Microgrid usage gives some benefits in economic and environmental field, as discussed in the last topics. Still, the biggest beneficiary are the individuals. A great advantage of microgrids is the use for electrification of remote or underdeveloped areas. The primary grid is incapable of attending these places, due to the infrastructure complexity and cost of transmission lines to reach isolated areas. Usually, the electrification in these areas is given by oil generators. Converting this type of generation to use renewable DGs, taking advantage of local resources and using microgrids, it will provide a greater user independence and promotes an increase socio-cultural impact on the population. Moreover, it contributes for new developments in productive, community, and individual/collective quality of life [12].

1.2 Objectives

This work presents the implementation and commissioning of a smart microgrid in the Silk House Museum, located in Bragança, Portugal. This smart microgrid was developed under the SilkHouse Project and aims to ensure self-sustainability in annual average terms. It will also be a showcase to spread to the society the use of local resources to produce renewable energy and the new technologies of microgrids for smart cities.

The implementation consists of the installation of the microgrid devices at the House of Silk. The second step is the parameterization of the equipment and the system. After, validation of the operation by data analysis of generation and tests of operation are presented.

1.3 Thesis structure

- Chapter 1: Presents an introduction and motivation to this work;

- Chapter 2: Contains a review of renewable sources that will be applied in the SilkHouse Project;
- Chapter 3: Contains an explanation on theoretical components, which are a baseline of this thesis, such as initiatives and projects developed, definition of microgrids and smart microgrids, and presents a generic microgrid structure;
- Chapter 4: Explains the microgrid developed according to SMA technology and details the equipment used in the solution, the final schematic of the microgrid, and the parameterizations of the main components and monitoring system (Sunny Island inverters and Sunny Portal);
- Chapter 5: Provides the analysis and discussion of the microgrid, providing information about the operation, based on generated data and operation tests;
- Chapter 6: Presents the main conclusions and future work.

Chapter 2

Renewable sources: photovoltaic and pico-hydro

The initiatives on renewable energy sources and the environmental issues of fossil fuels used to generate electricity have led to an increasing interest in clean energy technologies. Distributed Generations offers the potential to penetrate these renewable technologies to the distribution system supplying loads with several benefits in the environment, society, and economy. Distributed generation incorporates small-to-medium scale power generation, such as photovoltaic (PV) and pico-hydro, near the consumers, and it is integrated in distributions systems [13].

This chapter begins with an introduction of photovoltaic and pico-hydro generation technology to be applied in the context of this work. It explores the technical considerations and projects involved in the integration of solar PV and pico-hydro systems within DGs to be used in microgrids.

2.1 Photovoltaic system

Photovoltaic systems are based on the integration of PV modules and PV inverters to generate electricity from the solar insolation. Solar energy is the solar insolation converted into useful work as electrical and thermal energy [4] [13]. For electrical power, it can be applied in large solar power plants with the grid at the transmission level; and medium solar plants at the distribution level or small rooftop PVs integrated with the customer, both within microgrids [4].

PV cells are the solar technology manufactured by semiconductor materials, with the most common being silicon. The cells receive the sun's radiation and convert it into electricity through the photovoltaic effect, which creates a flow of electric charge by the movement of electrons in the semiconductor material. The electrical charge can be collected in the form of direct current (DC) electricity. The set of cells form the photovoltaic modules, which must be mounted on a structure. It may be fixed on the rooftop, on the ground, or on a solar tracker [13].

PV inverter is the key element of on-grid PV power systems. It is employed to convert the DC electricity output of PV modules into alternating current (AC) electricity [14]. The AC is suitable for the grid connection or is distributed to support the local grid.

The solar market, using PV systems to electricity generation, had the highest growth when compared to other technologies between 2017 to 2018. The total installed PV power capacity increased 25% to 509.3 GW by the end of 2018, as shown in Figure 2.4, and a medium scenario anticipates demand to rise over 1 TW by 2022 [15]. The reason for a preference in the PV system is a cost significantly lower than for nuclear and coal plants, besides the environmental issues.

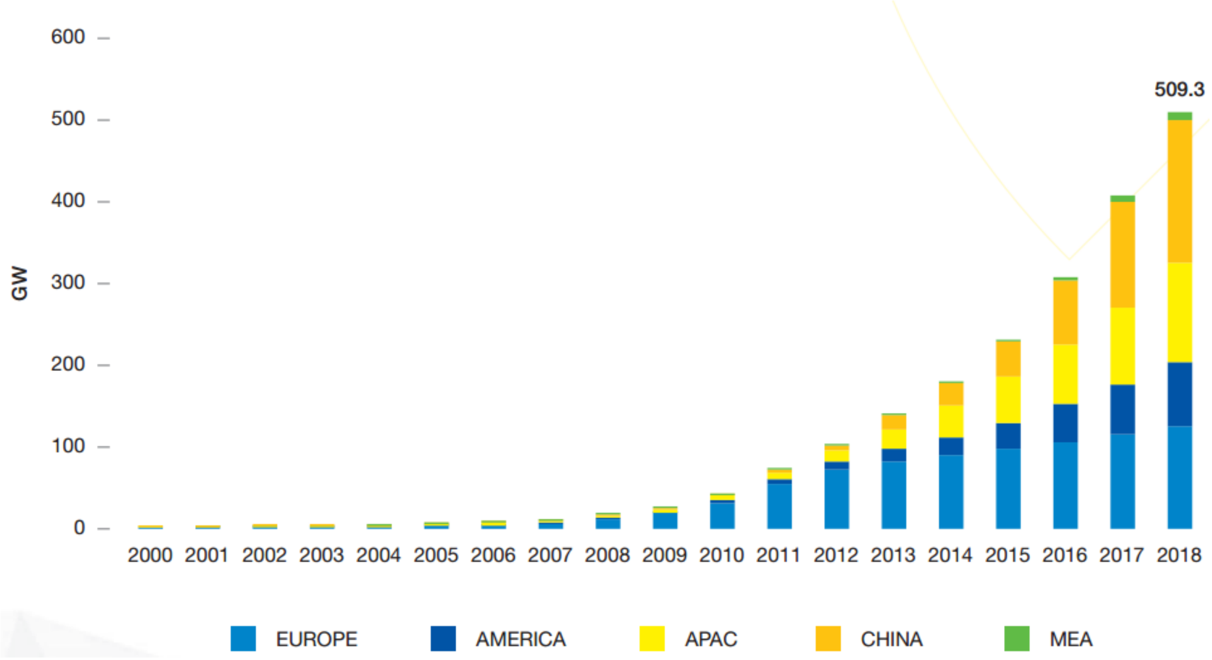


Figure 2.1: Evolution of total power photovoltaic installed 2000 - 2018 [15].

China dominates the solar world with four times more generation than the second-largest market in the world, the US, and more than the remaining top 10 combined [15]. Despite this, China has a decrease of 16% compared with the year before. Europe lead by the EU is one of the new solar growth regions due to 2020 targets. It rises 21% with added of 11.3 GW in 2018, over than the 9.3 GW installed the year before. Portugal is in the forecast list of the twenty markets' solar PV additions between 2019 - 2023 with 9.7 GW in the high scenario.

A photovoltaic system can be applied for these countries as a versatile clean power source that can be used in consumer, distributed, and utility-scale. It has been employed in several projects around the world with support from governments, private initiatives, and research centers. The Polytechnic Institute of Bragança (IPB) located in Bragança, Portugal, has photovoltaic systems installed on the rooftop of three schools of the campus [16]. Each school has twenty-eight PV modules with a peak power of 17.22 kWp. Figure 2.2 shows the PV modules installed at the Education School (ESE) in 2009. The installation was founded by the IPB and the Portuguese Government and integrates into the ambit of the VERCampus Project - Live Campus of Renewable Energy.

Figure 2.2: Photovoltaic modules installed at the ESE rooftop.

2.2 Pico-hydro system

Hydropower is derived from the potential energy of water flow in rivers, oceans, streams, water channels, etc [17]. The movement from higher to lower elevations allows the process for electricity production. It delivers a range of power and non-power benefits to society and the environment. Besides the electricity generation, the benefits include reduced dependence on fossil fuels and flexible production. Hydropower is the world's largest source of renewable electricity generation representing 15,9% of the total global produced with 4200 TWh installed capacity [18]. China and Brazil led the installed and new installed capacity worldwide, Portugal is the tenth place in Europe.

Hydroelectric power is found around the world, mostly, on a large scale. However, it is available in other categories according to the size of electrical energy produced, as shown in Table 2.1. Pico and micro-hydro appear not to be relevant when compared to hydropower classes of mini to large. But, they have a significant contribution to remote and off-grid places, providing many benefits in terms of capacity, cost-effective, size, design, and installation [17] [19]. These low power hydroelectric plants provide small generation enough for communities, and no significant installation site changes are required.

Table 2.1: Classification of hydropower [17].

Class	Power
Pico	<5 kW
Micro	<100 kW
Mini	<1 MW
Small	<10 MW
Large	>10 MW

Pico-hydro system is a subset of a hydropower generation classified based on its capability of producing electricity up to 5 kW, through vertical fall and small water flow from river, water channel, stream, or water reservoirs [17] [19]. This system is usually located in developing countries for the use in rural/remote electrification supplying low consumption domestic loads, such as lighting and radio. The technologies for the pico-hydro system are simple, reliable, a versatile power source, and accessible to the technologically less developed countries [20].

Many reports are found in the literature about the implementation of pico-hydro systems for electrical generation. For instance, [21] describes a pico-hydro plant using a "pump-as-turbine" implemented as part of a program from the Nottingham Trent University to demonstrate this technology in Sub Saharan Africa. This system was installed in Kerugoya, Kenya, with 110 households being connected to the generation by a single-phase distribution system. In [22] a project is presented to establish this type of development within Ecuador, by undertaking a market assessment for pico-hydro, developing technical capacity to install and maintain the systems at demonstration sites. In Malaysia, the government is aware on the impact and importance of pico-hydro and set a target that small hydro (mini, micro, and pico) will contribute up to 500 MW to the national power supply until 2020 [17].

The application of pico-hydro by other means, without the use of river or stream, can be found in the literature. Reference [23] presents the use of pico-hydro generation taking advantage of water supply at University Malaysia Pahang. The water is supplied from a head-water reservoir via pressure pipes and it was installed at a turbine at the end of the pipe to convert the lost energy to electricity. In [24] the authors describe the pico-hydro generation using consuming water distributed to houses. The electricity is generated at the same time as usual activities, as bathe and laundry, by the water flow in the pipes which rotates a small scale hydro turbine to drive a generator.

Figure 2.3 presents an example of a pico-hydro application with a low-head turbine, in falls up to 5 m [25]. The low-head turbine is placed vertically in the water, and the generator is placed on top of the turbine. The draft tube underneath creates the necessary pressure drop to drive the propeller. The turbine will rotate the alternator and produce electricity.

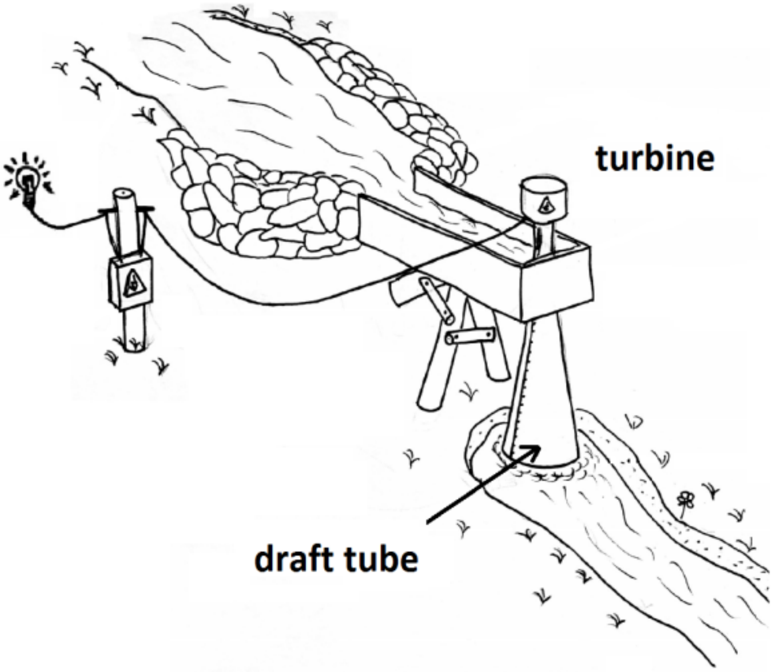


Figure 2.3: Example of pico-hydro application with low-head turbine [25].

The electricity from the pico-hydro generation can be applied in grid-connected systems. Many approaches have been conducted to connect the pico-hydro system to the grid with flexibly and efficiently. Recent works [26] [27] [28] present that it is possible to integrate a permanent magnet synchronous generator working at variable speed to a grid, with variable speed, depending on the flow rate and head. The innovative results show that the energy produced can be harnessed using PV inverters and PV micro-inverters. Furthermore, PV technology is consolidated in the market with widely available components.

2.3 Hybrid renewable energy

The photovoltaic system provides opportunities for sustainable, cost-free, and pollution-free energy. However, the daily solar radiation varies a lot throughout the year with low sunlight available during the winter period. It can be seen from Figure 2.4 the variation of solar power output throughout 2016 - 2017 at Victoria University, Australia [2]. During the winter (in this case June to August in the Southern hemisphere), the solar radiation is low and consequently, the output power will be lower. To compensate for this variation and be more attractive in economical operation and abundance of resources, it could be utilized the combination of DGs.

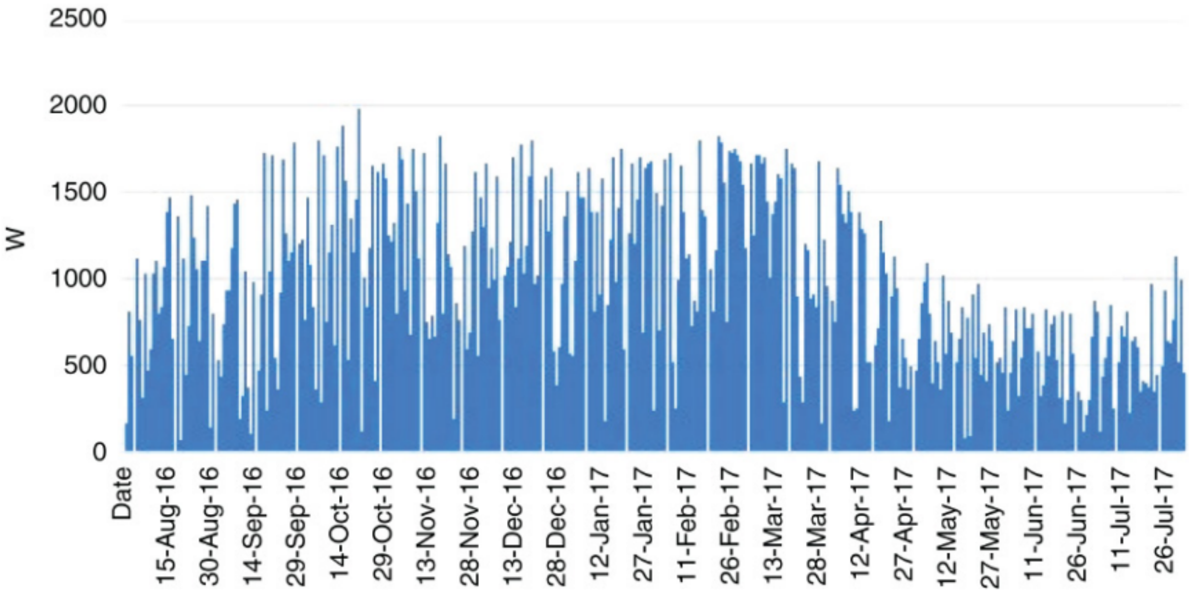


Figure 2.4: Solar power output throughout a year [2].

The set of renewable DGs as a unit can form a hybrid system. It is a combination of renewable energy sources depending on the availability of resources in an individual area and load demand, connected (or not) to the utility grid [2]. The combination of PV and pico-hydro system contribute to the intermittency nature of each other throughout the year. This combination allows an extended generation during the summer (PV system) and winter (pico-hydro), producing energy 24 hours a day, unlike photovoltaic systems. It is thereby improving the reliability of the hybrid system. Also, it can be added a storage system to this configuration to ensure the quality and power capacity of the microgrid. These combinations of DGs in hybrid systems can be applied to microgrid systems.

Chapter 3

Microgrids

This chapter presents relevant theoretical background of microgrids for better understanding of the developed work. It describes their various definition in literature, basic configuration and operation, and concepts of smart microgrid.

3.1 Initiatives and projects

Several initiatives and projects have been conducted in the past years to push forward the integration of renewable sources and the development of new technologies for intelligent grids. They have backing of from universities, government, and private sector.

In Europe, many research efforts are devoted to promote microgrids that are considered a fundamental feature of current and future active distribution networks. In 2007, it was published an overview of ongoing research, development, and demonstration projects, which presented two projects [29], as follows. *Microgrids: Large scale integration of micro-generation to low voltage grids* was the first developed led by the National Technical University of Athens (NTUA), included 14 utilities partners; manufacturers, such as SMA and EmForce; and research institutions and universities, as INESC Porto and University of Manchester. The objectives of this project were study the operation of microgrids to increase the penetration of renewable sources based on the on-grid and off-grid systems, develop control strategies, and others. The studies provided several innovative technical solutions. *More Microgrids: Advanced Architectures and Control Concepts for More Microgrids* was also led by NTUA with support of manufacturers, as Siemens and ABB; power utilities from Denmark, Portugal, Germany, the Netherlands, and Poland; and researchers from Greece, Spain, Portugal, and others. The objectives were: investigation of new renewable DG, development of alternative control strategies, study of the impact on power operation, etc. The project finished in 2009, reaching the objectives in the development of new hardware prototypes, models, algorithms, and processes.

In Brazil, a similar microgrid, as developed in this work, was implemented to offer research and deepening environment in the area in the Federal University of Ceará [30]. The structure includes three PV systems with single-phase inverters, with different characteristics, two loads, and energy storage system. Despite initiatives and projects, there are no specific policies and regulations to smartgrids or microgrids in Brazil [31].

A laboratory prototype microgrid was developed as research and demonstration purposes in the Polytechnic Institute of Bragança, at the laboratory of the School of Technology and Management (ESTIG) [32]. The prototype is in operation since 2012 with 5 kW nominal power installed. Combine a small distributed renewable generators, as solar tracker, wind turbine, and PV modules, and a battery bank as the main storage device. It is a single-phase system which utilizes a bidirectional inverter to form the grid and to take control of the power flow. The Figure 3.1 presents the IPB microgrid.

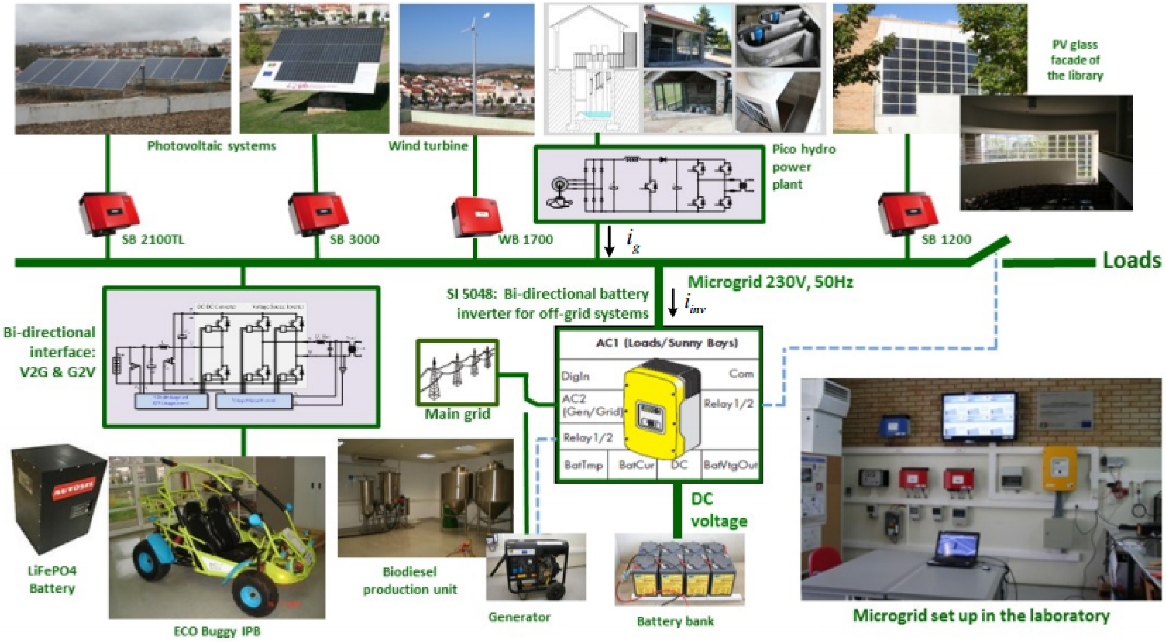


Figure 3.1: Microgrid of the IPB [32].

3.2 Microgrids definition

When electricity was first made available in the late nineteenth century, the generation and distribution were localized close to the consumers. Sometime later, with the higher demand for the service, arise the system as we know today, large power plants interconnected to the customers by distribution and transmission lines [7]. However, these conventional electrical grid systems are in the significant transition from passive distribution networks to active distribution networks [6]. The passive networks are unidirectional, the transport and distribution power goes from where it is generated (mainly far from loads) to the load centers [4]. It becomes active with the penetration of DG units leading to bidirectional, which means that the power can flow in the grid from the customers electrical generation.

In order to achieve clean energy from renewable DG, active distribution networks should employ future network technologies, such as smartgrid [6]. Smartgrid is an intelligent grid to handle load and distributed resources using information and communication technology [33]. Also, it is used for improving power reliability and quality, increasing system energy efficiency, and providing the possibility of grid-independence to the end-users sites [34].

Integrating DG and storage devices in a smart grid scenario results in the microgrids concepts [35]. The basic idea of the microgrid is not new. However, the use of this term is more modern, and it is possible to find several definitions in the literature. According to the concept presented in [36], microgrid is a cluster of loads and microsources, normally microturbines, PV cells, and fuell cells, operating as a single controllable system that provides power and heat to its local area.

In [37], microgrid is a network of small distributed electrical power generators operated as a collective unit, forming a system of energy system. It can run in grid-connected or islanded mode.

In [38], microgrid is an aggregation of electric and thermal generators, storage units, and loads. It has characteristics to take advantage of the opportunities that may arise in this liberalized market and contribute in a more rational and optimum electric network.

In short, from a review of the literature, the microgrid can be described as follows. It is a distributed generation network, integrating renewable sources (or not), connected to loads, with energy storage capacity, and with a management system (with higher or lower intelligence level). That can supply the electrical demand of a house, a building, or a region. It may (or not) be connected to the conventional grid. In the next section, it will be presented the basic structure and operation of a microgrid.

3.3 Microgrid structure and operation

Figure 3.2 presents a generic microgrid which is connected by the utility grid and is constituted of common components, such as load and electrical generation. It is a single-phase electrical system which integrates renewable sources (PV and wind generation), loads, energy storage system, and communication infrastructure.

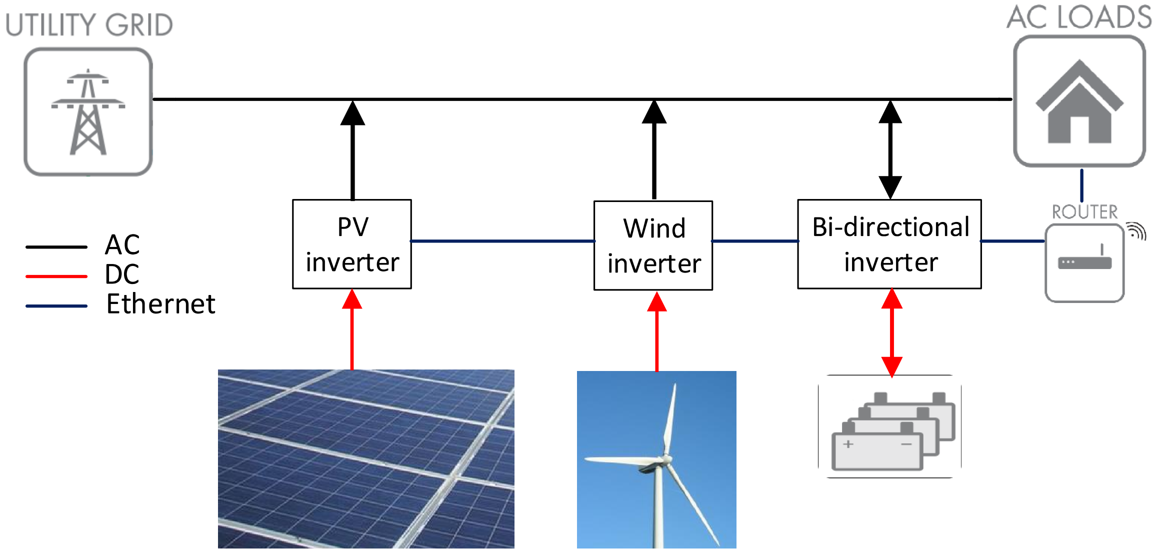


Figure 3.2: Generic on-grid microgrid.

This structure can operate as a bidirectional system. The basic operation is described as follows. The PV and wind turbine can supply the loads with their energy production. When this production is higher than the consumption, the excess can be used to recharge the storage system. If the batteries are charged, the overproduction can flow to the utility grid. Also, when the consumption is higher than the generation, the system can be supplied from the utility grid.

The electrical energy generated from the PV and wind generation are converted by a PV and wind inverter, respectively, and also allows connection to the local grid. The bidirectional inverter is responsible for connecting the battery bank to the local grid and flow the energy in both directions. All these inverters can form a network communication when linked to a router. Intelligent loads can be connected to it, and be commanded through a smart device to operate (or not) in determined periods, i.e., when has a higher energy production. This network communication enables some intelligent level for the microgrid.

3.3.1 On-grid and Off-grid system

Microgrid can operate in two different modes, grid-connected or isolated. On-grid systems are connected to the utility grid. They can draw power from the grid when the power generated by the microgrid is less than the load demand, and in case of excess of generated power, they can fed energy back to the grid [2]. Also, this type can be classified as Urban Microgrid, because it has various applications for urban use [4].

On-grid mode needs certain restrictions and requirements to operate and should meet all codes, standards, and interconnection requirements to protect the larger grid and preserve the power quality [4]. The islanding mode, in on-grid microgrid, can improve the reliability of power supply. The microgrid can shift to islanded operation, in case of faults, external disturbances, or disasters [39] [40]. After the isolation, the DG or the storage system will supply power energy to the loads. However, islanding has great harmfulness: unstable voltage and frequency values, and danger for workers which could not judge if there is any microgrid feed-in to the utility grid (or not) when islanding happened [39].

Off-grid microgrid work independently of the utility grid and do not need to comply with the requirements and restrictions of urban microgrids, but is similar to the on-grid in sources and loads [4]. It is more suitable for remote regions where the utility grid is not available. It is often applied to lighthouses, auxiliary power units for emergency services, military applications, or water pumping [41].

3.3.2 Electric storage system

Microgrid with renewable DG has an intermittent generation. An efficient way to operate the customers as a microgrid is to install an energy storage system. The storage system provides a balanced frequency and voltage for maintaining the reliability of the system, such as the operation of the renewable energy sources [42]. Besides its use for load matching in off-grid systems, where, usually, the load demand is not at the generation period.

In on-grid operation, the storage system enables change the microgrid operation to islanded mode by a battery inverter in grid failure situation, to maintain system reliability [4]. In an islanded way, the storage system provides frequency and voltage by a grid-tie battery inverter to the generators to return to operation. Further, the storage system is capable of supplying the loads as a battery-backup grid, in the meantime, until the DG return to regular service. Still, the storage system accumulate the excess energy produced during generation peaks to use when the generation is not enough to supply the loads.

The storage of electricity can be done in battery bank, a set of several batteries capable of storing excess production for later consumption. The batteries can be connected in series or parallel. In series, the voltage of each is added and the capacity is kept the same, and in parallel it is the opposite.

3.4 Smart microgrid

This section presents a brief discussion about the concept of smart microgrid according to [4] and [43].

What distinguishes a smart grid from a conventional grid is the capability of their command/control strategies, communication, and information. These enable the utilities to put intelligence over their infrastructure, thereby allowing the introduction of new applications and processes. Table 3.1 presents a side-by-side comparison between the conventional grid and a smart grid, which helps to comprehend the barriers of geographies, components, and operation to the transition of a traditional to an intelligent grid. Although the differences, both grid should coexist adding to its capabilities, functionalities, and capacities employing an evolutionary path.

Table 3.1: Comparison between conventional grid and smart grid [43].

Conventional grid	Smart grid
Electromechanical	Digital
One-way communication	Two-way communication
Centralized generation	Distribution generation
Hierarchical	Network
Few sensors	Sensors throughout
Blind	Self-monitoring
Manual restoration	Self-healing
Failures and blackouts	Adaptative and islanding
Manual check/test	Remote check/test
Limited control	Pervasive control
Few customer choices	Many customer choices

The growth and evolution of the smart grid is expected to come through the integration of basic structures, such as smart microgrids. What sets a smart microgrid is the presence of intelligence, incorporated into local power generation, load control and classification, energy management, access authorization, and others. As well as the basic configuration of a microgrid, a smart microgrid can integrate the following components:

- Smart meters and sensors capable of measuring consumption parameters.
- Communication infrastructure that enables exchange information.
- Smart terminations, loads, and appliances, capable of communicating their status and accepting control commands.
- Intelligent core, composed of integrated networking, computing, and communication infrastructure elements. It appears to users in the form of energy management applications that allow command and control on all nodes of the network.

3.4.1 Information and communication

Information and communication technology is a critical component of future power grids. They are an essential role in smart microgrids to transfer the required information from the control center to the generating unit. These technologies with a power system is what transforms into an smart microgrid [4].

The manufacturers of microgrid devices adopt several protocols of communication. The SMA Solar Technology AG has its protocol called Speedwire. A wired Ethernet-based Fieldbus for the implementation of robust communication networks in decentralized large-scale PV power plants [44]. It enables direct data transmission between the inverters and an Internet portal, without any additional communication device.

3.4.2 Power management system

Power management system is related to three main functions: monitoring, optimization, and control [4]. Monitoring encompass data measurements across all components and share the power flow within the microgrid. With the information of generation and consumption data, it can optimize the energy management performance by predicting the future energy state. The optimization results into execution of control commands in the components of the microgrid.

The standard control systems are based on measurements, control algorithms, and actuators [35]. Voltage and frequency are measurements used for power-sharing and capture the local state, which usually the frequency is related whit active power and voltage with reactive power [40]. Control algorithms are applied to make decisions that facilitate the achievement of the control. Actuators are the power converters which interfaces primary sources and energy storage system with the local grid. Control strategies of frequency into inverters facilitate the sharing power. The active power control allows synchronization between active output power of generators and power demand in the microgrid as a function of frequency variation. SMA Solar Technology AG implement frequency-dependent active power limitation into its bidirectional battery inverter. The "frequency-dependent control of active power" [45] operates by a frequency variation imposed by the bidirectional battery inverter in the microgrid. It controls the energy production of sources connected to another inverter (which must be compatible with this control), i.e., PV inverter [46].

Figure 3.3 shows the control of active power by frequency control, and Table 3.2 shows an example of this frequency control. This control act when the generation is larger than the loads' consumption [46]. In this case, the excess power must be injected into the battery bank. If it is fully charged, the SI detects this situation and increases the frequency of the microgrid to limit the output power of the inverters. The SI increases the frequency of the microgrid above the nominal value (50 Hz). When the PV inverter feels the frequency increase, it starts to reduce the active output power. If the frequency continues to increase, PV inverter further reduce its active power nearly to 0 W. The PV inverter continue to monitor the frequency. When it decreases, it starts increasing their active power linearly to the available value.

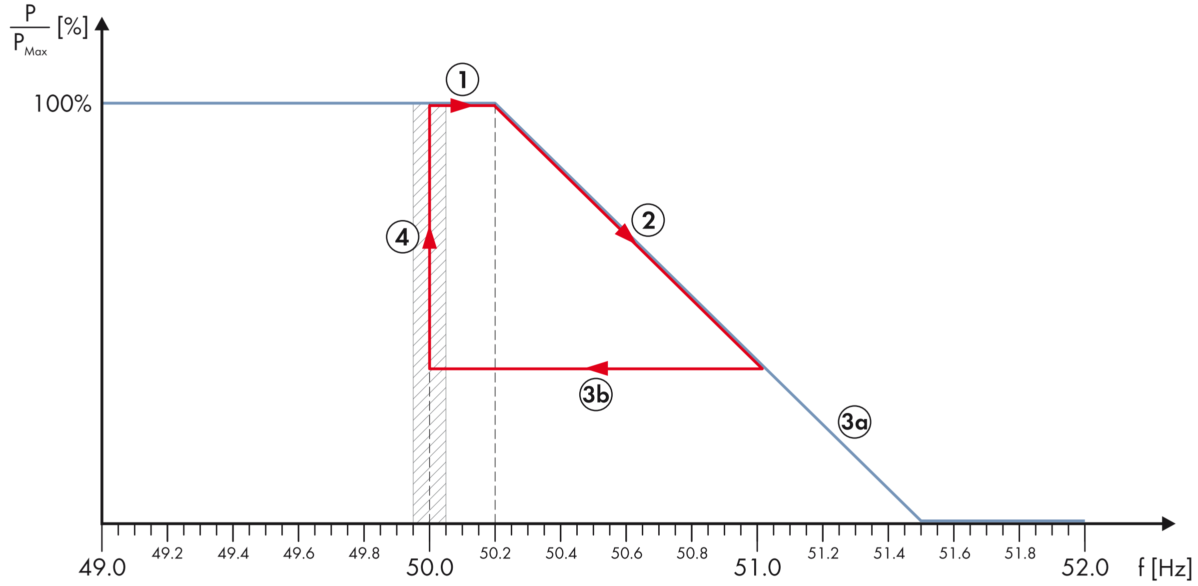


Figure 3.3: Control of active power by frequency control [45].

Table 3.2: Example of the frequency values for each stage of active power control by frequency in Figure 3.3.

Position	Stage	Frequency (Hz)
1	Normal operation	<50.2
2	Active power decreases linearly from maximum available power	>50.2
3a	Active power continues to decrease linearly up to 0 W	51.5>Freq.>50.2
3b	Frequency remains constant or returns to the nominal value PV inverter stops reducing active power	<51.5
4	Active power increases up to maximum available power	50.05

Chapter 4

Implementation of the Silk House smart microgrid

This chapter explores the microgrid developed for the Silk House. It contains the House of Silk description and presents in detail the microgrid project with its components, as well as its implementation and commissioning.

4.1 Silk House description

The Silk House is located in Braganga, in the north-eastern of Portugal, and integrates the Ciência Viva Center. This place was used for dyeing silk in the 18th century. During the 19th and 20th centuries was used as a mill and still retain its original architecture. The Municipality of Bragança acquired the building in 1990 and restored it in 2006 during the intervention of the Polis Program, maintaining the original constructive characteristics [47].

Nowadays, it is a small museum dedicated to the history of silk, with a permanent exhibit about it and to the dissemination of science. The museum receives about 11500 visitors per year and on-site is frequent exhibitions, lectures, and courses about several themes.

The building conserves the historical architecture built of original stones. It is located in the historical center of the city, next to the Fervença river. The museum has three levels, two galleries in the basement at river level, and a roof with ceramic tiles. Figure 4.1 shows the building and the galleries where the old mill was installed.

Figure 4.1: Silk house and the galleries where the old mill was installed.

4.2 Silk House electrical description

The Silk House has a three-phase electrical system (400 V, 50 Hz) powered by the mains with a contracted power of 13.8 kW. The electrical loads are, basically, computers, monitors, multimedia projectors, heaters, air-conditioning system, a stereo system, and lighting. The regular operation of the museum is from Tuesday to Sunday, from 10 a.m. to 6 p.m.. It closes on Mondays. Beyond regular operation, sporadic events are held, extending the activities up to around midnight.

For the consumption profile characterization of the building two analyzes were performed [48]. It was based on energy consumption history and power recording data requested by the building. The updated energy consumption history describes the monthly consumption in 2018, as shown in Table 4.1. The data was obtained through the energy bill analysis provided by the local concessionaire EDP (Eletricidade de Portugal).

The second analyzes was performed in a previous work developed at the building [48]. It used a power and energy recording equipment to register the power recording data requested by the building for seven weeks, between February 6th and April 2nd, 2017. Figure 4.2 shows the daily load consumption diagram for a regular Silk House operation, on Tuesdays. The average power consumption is near to 5 kW, and sometimes there are some power peaks. The same power is requested by the building on the other days, with the exception on Mondays.

Figure 4.3 shows the load consumption diagram on Mondays. As previously mentioned, on Monday, the museum is closed, and the power does not exceed 0.5 kW. This value represents

Table 4.1: Monthly consumption of electricity in 2018.

Month	Consumption (kWh)
January	1214
February	1064
March	1091
April	1049
May	1087
June	-
July	629
August	832
September	506
October	895
November	921
December	2718

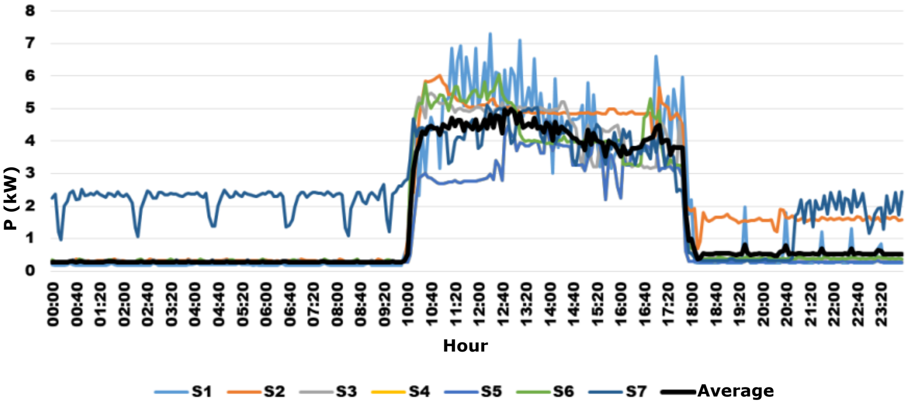


Figure 4.2: Load consumption diagram for a regular Silk House operation, rated for seven weeks [48].

some essential loads remain powered. An unusual case happened in the week S2, where the consumption was excessive due to an oil heater that was turned on.

4.3 Implementation of the smart microgrid in the Silk House

The development of the smart microgrid presented in this work started in 2017 with the first conceptual design [47], in the ambit of the SilkHouse Project - Development of a smart microgrid based on renewable energy sources and a monitoring system for the House of Silk. The project was based on previous experience of a small microgrid held in a laboratory of the ESTIG, at IPB,

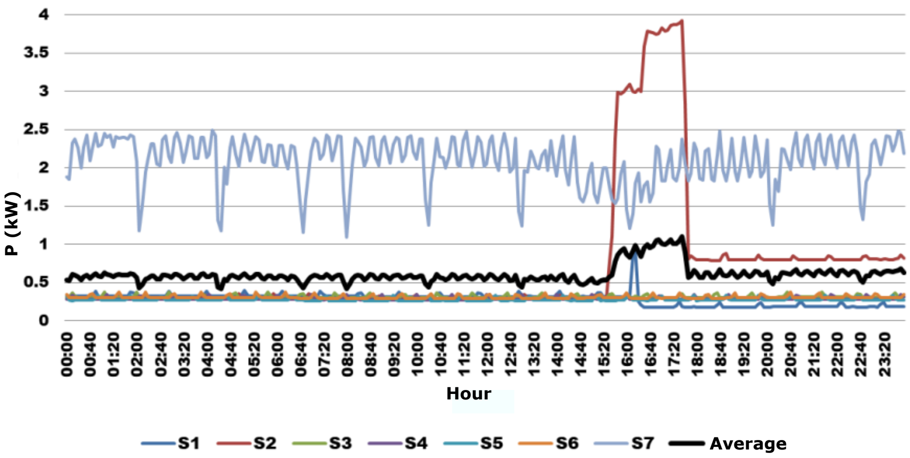


Figure 4.3: Load consumption diagram for Monday, rated for seven weeks [48].

using the solution provided by SMA [32] [49]. These demonstrate the feasibility and flexibility of this solution.

The project aims to transform the House of Silk in a self-sustainable museum, in annual average terms, and contribute to the dissemination of renewable sources and new technologies for future buildings in smart cities. The smart microgrid implemented in the House of Silk has some specific requirements considered during the project development to achieve these goals, as follows:

1. The microgrid design should consider the endogenous resources available for renewable energy generation. For this, the design takes into account the analysis of two places of the building for energy potential capable of taking advantage of the endogenous resources [48]: the roof and the original galleries by the former mill. The roof is used to photovoltaic energy generation taking advantage of solar radiation. The use of the galleries and the proximity of a small dam already available in the Fervença river revealed viable to generate hydropower.
2. The generated energy should use innovative solutions, such as the use of a PV inverter and a micro-inverter as the interface between turbines' generators and the microgrid [26] [27] [28].
3. The museum is supposed to be self-sustainable, which means that renewable energy produced must be equal to the energy consumed, annually.

4. The energy injected into the electric grid must be zero [46], since the Portuguese government promotes the generation for self-consumption in accordance with Decree-Law n^{o}. 153/2014 of 20th October [50].
5. The microgrid must have an energy storage system to improve the self-consumption and self-sufficiency quota [51] [52]. Self-consumption is a measure of the amount of energy used at the point of generation or in the immediate vicinity [52]. It is made up of direct consumption and battery charging and takes place naturally because loads are in operation while PV power is being produced. Also, makes the operator more independent of the feed-in tariff which now barely covers costs, and it increases the effective value of each generated kW. The self-sufficiency quota is the current ratio of internal power supply to the energy demand of all loads [52].
6. Power management and monitoring system are required for the increased self-consumption. Also, they are required since this project is intended to be a permanent activity of the museum aiming for the dissemination of the new technologies of microgrids for smart cities.

4.3.1 Silk House smart microgrid description

Two circuit design of the Silk House microgrid were previous developed [51] [47]. However, the final circuit conception developed is presented in this work and it was the basis for the microgrid implementation. Thus, the Silk House museum is now provided with an on-grid smart microgrid integrating renewable energy resources and energy storage in a microgrid with a management system. The microgrid maintains the existing three-phase electrical system (400 V, 50 Hz). The renewable sources and storage system were sized to suit the requirements of the museum [47] [48], which considered the consumption profile characterization, as presented in Section 4.2.

The smart microgrid was developed according to the requirements cited in Section 4.3, and it was based on the SMA Flexible Storage System with battery-backup and increased of self-consumption [53]. However, SMA offers other solutions that vary with the needs of each application, such as SMA Flexible Storage System with battery-backup function [54] or SMA

Flexible Storage System with increased self-consumption [55]. The system with battery-backup function takes care of the uninterrupted supply of the loads with electricity during a grid failure and is fitted with a customized battery-storage system [54]. The increased self-consumption can be achieved if loads are specifically switched on when excess PV power is available [56]. The battery-backup system also uses the battery for increased self-consumption.

The core of the smart microgrid is based on Sunny Island (SI) inverters and Sunny Home Manager (SHM). The most important elements of the system are the SMA PV inverters, SI inverters, the batteries, the SMA Energy Meter and/or a Sunny Home Manager 2.0 [52].

The microgrid of the Silk House is composed by three Sunny Island 4.4M, three PV inverters Sunny Boy 1.5 (SB), one Sunny Home Manager 2.0, two SMA Energy Meter, one PV microinverter, one PV inverter, a battery bank consisting of twenty four batteries, battery fuse, electrical panel, automatic transfer switch, and protections. The responsible for renewable electricity generation are three strings of six Panasonic PV modules, one 300 W horizontal water wheel, and one 1.2 kW low-head turbine. Figure 4.4 presents a circuity overview of the smart microgrid implemented in the House of Silk. This circuity was based on two diagrams schematic from SMA, as presented in Appendix A and B [54].

Figure 4.5 shows the installation process of the microgrid devices in the upper gallery and the photovoltaic modules in the roof. The microgrid is in full operation with the PV generation. Figure 4.6 shows the view of the equipment installed and a view of how museum visitors will be able to see the microgrid equipment through a glass window in the floor. Figure 4.7 shows the microgrid devices with theirs description, installed in a panel. By the time this work was written, the low head pico-hydro system was being installed, and the water wheel was under laboratory tests. The next topics of this section discusses the microgrid operation and its components.

Before the installation and commissioning of the microgrid devices in the Silk House, it was installed in a laboratory at IPB to understand the operation of each device and to test the system. Besides, all the microgrid equipment was not yet available. Thus, the microgrid used for the tests the PV modules available on the rooftop of the laboratory and a SB inverter to connect it to the system.

During the test period, it was realized that the SMA manuals do not specify all the information

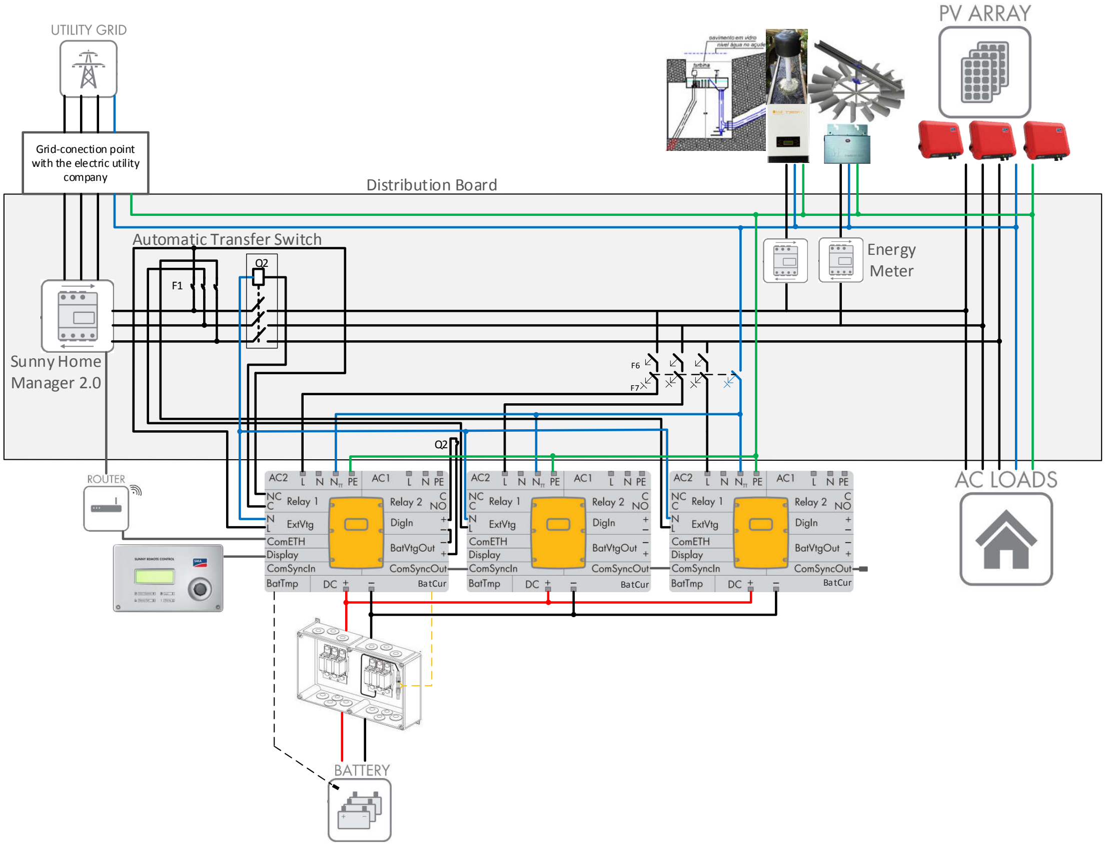


Figure 4.4: Overview of the smart microgrid implemented in the Silk House.

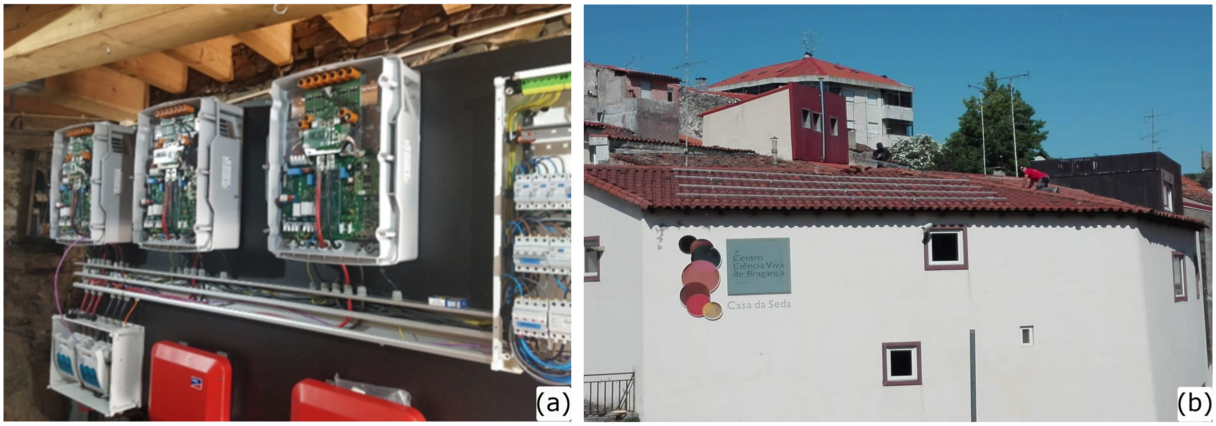


Figure 4.5: Installation process of the (a) microgrid devices and (b) photovoltaic modules.

to aid installation and commissioning. In this way, it was necessary to make several contacts with representatives of SMA in Portugal and Spain to assist with some issues. The representative in Portugal pointed out some system issues that would need to be changed to meet the requirements

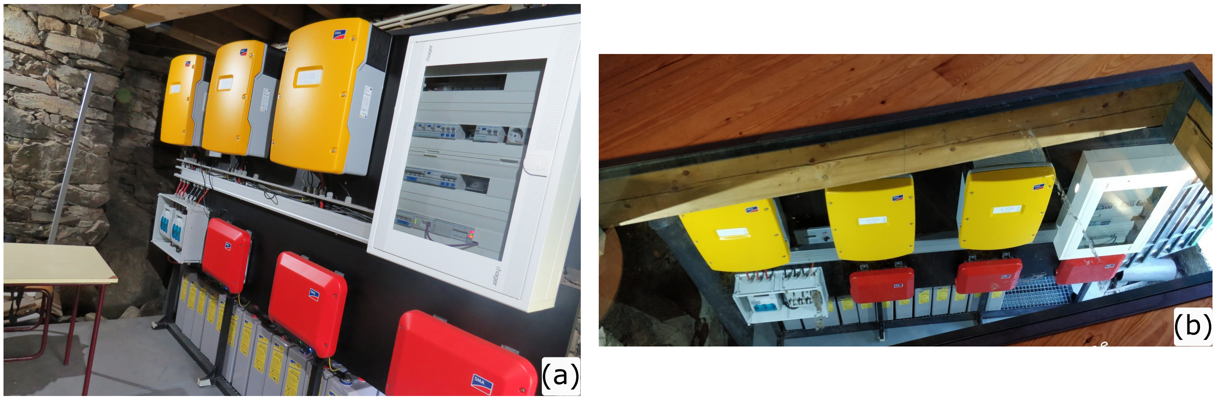


Figure 4.6: View of the (a) equipment installed in the gallery and (b) top view for visitors.

Figure 4.7: Panel with the microgrid devices.

of a battery-backup and self-consumption system. The first, it was the need to use an automatic transfer switch that was not considered in the original designs. Second, it was necessary to change the installation position of SHM in the electrical circuit, so that it accounts for the generation and consumption of the microgrid.

4.3.2 Operation of the smart microgrid

Figure 4.8 shows, in brief, the operation of the Silk House smart microgrid. The operation of the Silk House smart microgrid can be described as follows [46]. The microgrid is attached to the utility grid and the energy can flow to both side, to the loads or utility grid (system 1 in Figure 4.8). The three-phase microgrid is the external electric grid whenever it is available. In the case of grid failure, the smart microgrid is established by the three SI (system 2). For the grid-failure, an automatic transfer switch is responsible for disconnects (or reconnect) the battery-backup grid from the utility grid [53]. Thus, the microgrid starts working in stand-alone mode as a battery-backup system. This system is capable to supply the loads and a grid-tie PV system with voltage to synchronize it with the battery-backup grid and feed-in. However, in this operation mode, some hours of autonomy are available, but it strongly depends on the consumption, the generation, and the battery bank state of charge (SOC). In this case, some loads can be automatically disconnected.

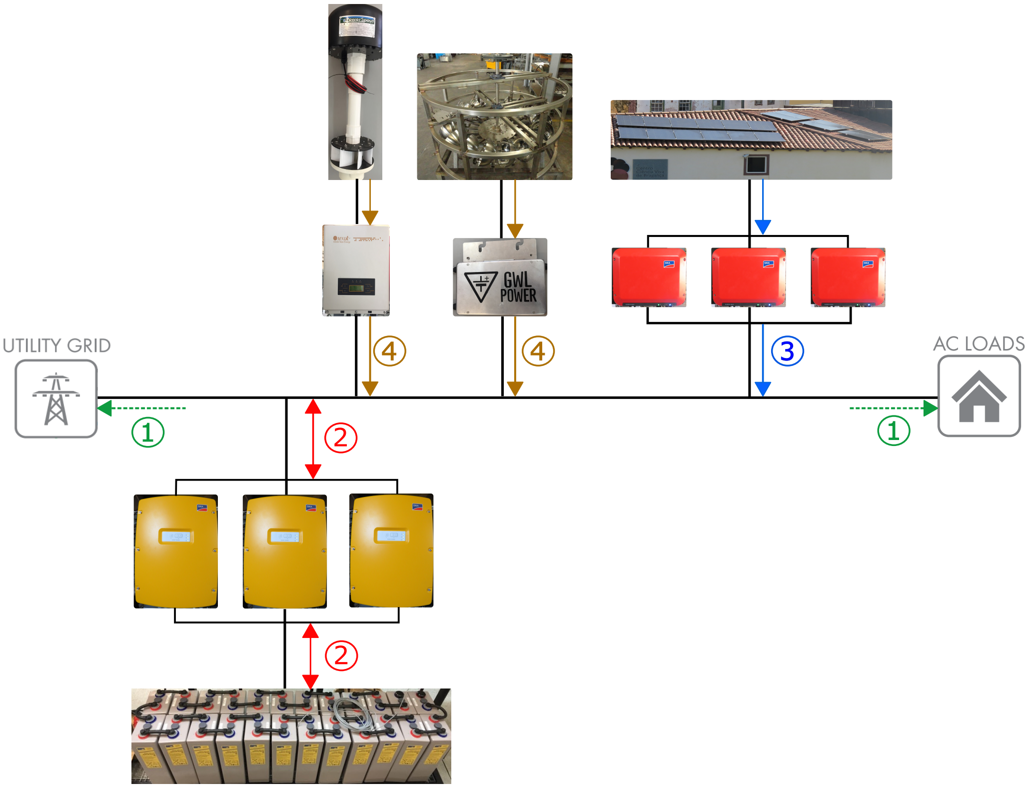


Figure 4.8: Operation of the Silk House smart microgrid.

After disconnection by the automatic transfer switch in grid failure, the local grid is not supplied for approximately five to seven seconds, until the battery-backup system can provide active power and reactive power again [53]. This situation happens because the SMA Flexible Storage System with a battery battery-backup system does not fulfill the requirements of an uninterruptible power supply (UPS) [45]. If any load requires an uninterruptible power supply, it will need a separate UPS.

The energy generated by the PV strings is feed into the microgrid (system 3), distributing the power by the three phases using the three Sunny Boy PV inverters. Also, it will have generation by the low head turbine and water wheel, distributing the power by an Omnik PV inverter and a GWL micro-inverter, respectively (system 4). When these generation is higher than the load consumption, the excess is stored in the storage system through the SI battery inverter. If the batteries are charged and the energy into the utility grid must be zero, control of the active power generated must happen. The active power generated by the SMA PV inverters is limited as a function of frequency variation to meet the power demand [45], as previously explained in Subsection 3.4.2. For this system, the SI increases the microgrid frequency above the nominal value (50 Hz). The SB detects it and starts to reduce its active power generated to follow the consumption. When the consumption is higher than the generation, the batteries supply the loads. If it is not enough, the remaining energy is purchased from the utility grid.

4.3.3 Storage system

The storage system is composed of SI, a battery bank, and a battery fuse. Sunny Island is a battery inverter for the parallel between on-grid and off-grid operation, that controls the electrical energy balance in a battery-backup system for increased self-consumption [52] [57]. Figure 4.9 shows a SI with its terminals.

The microgrid uses three Sunny Island 4.4M connected to form a three-phase cluster. The rated power of each SI is 3.3 kW [58], and the total to the system is 9,9 kW. They are connected in a master-slave configuration, where one represents the master and the other slave 1 and 2. For the three-phase cluster, phase L1 must be assigned to the master, L2 to slave 1, and L3 to slave 2,

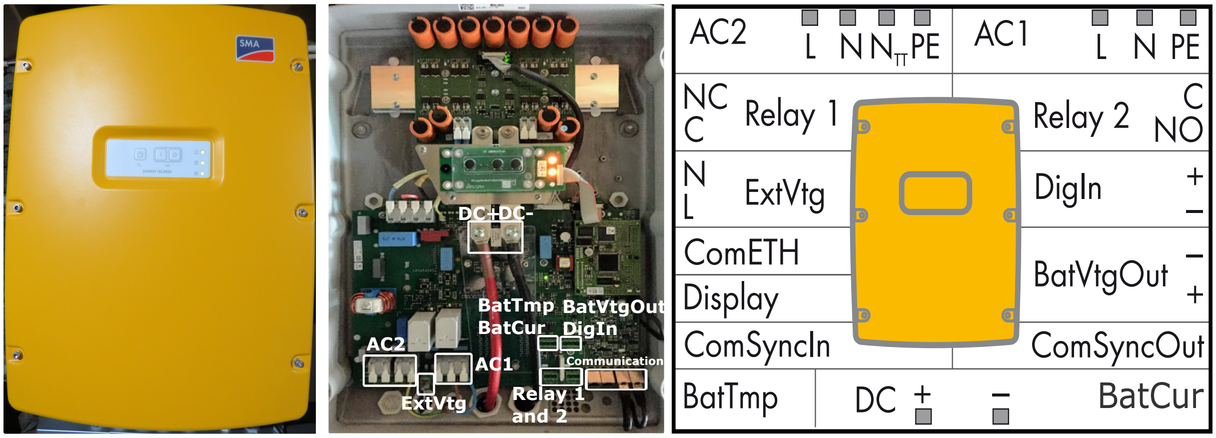


Figure 4.9: Sunny Island 4.4M and its terminals.

connected into the AC1 terminal. All the parameterization is performed on the master, which communicates to the slaves by an internal communication via data cable. This communication is realized by the terminal ComSyncOut of the master connected to the ComSyncIn in slave 1, which connects its ComSyncOut to the ComSyncIn of the slave 2. The communication bus is closed at the last slave with a terminator. Also, the SI master is connected to an Ethernet switch via data cable in the terminal ComETH. The SI of this microgrid has not this terminal. So, it was necessary to acquire an extra data module.

The SI can use different battery types with different battery capacities to offer great flexibility. In battery-backup systems, SI uses lead-acid batteries or lithium-ion batteries for energy storage [52]. The Silk House microgrid uses twenty-four valve-regulated lead-acid (VRLA) batteries 2 V battery blocks Sonnenschein's batteries A602/625 Solar [59]. The blocks are connected in series to meet the input voltage on the Sunny Island DC connection into 48 V [57]. Figure 4.10 shows the Silk House battery bank connected in series.

Figure 4.10: Battery bank.

The battery bank is connected to the terminals DC+ and DC- of each SI via a battery fuse (batfuse). It is an external DC fuse, that protects the battery connections of the SI [60]. Also, it enables the DC-side disconnection. A measuring cable is connected to a 50 mV battery current sensor and must be connected to the terminal BatCur of the master [58]. With lead-acid batteries, the battery management of the Sunny Island inverter must record the temperature of the connected battery via a temperature sensor. This sensor must be installed in the middle of the battery bank and connected to the BatTmp terminal of the SI master. Figure 4.11 shows the connections among the battery bank, battery fuse, and battery current sensor to the SI. Only the master measures these quantities in a cluster.

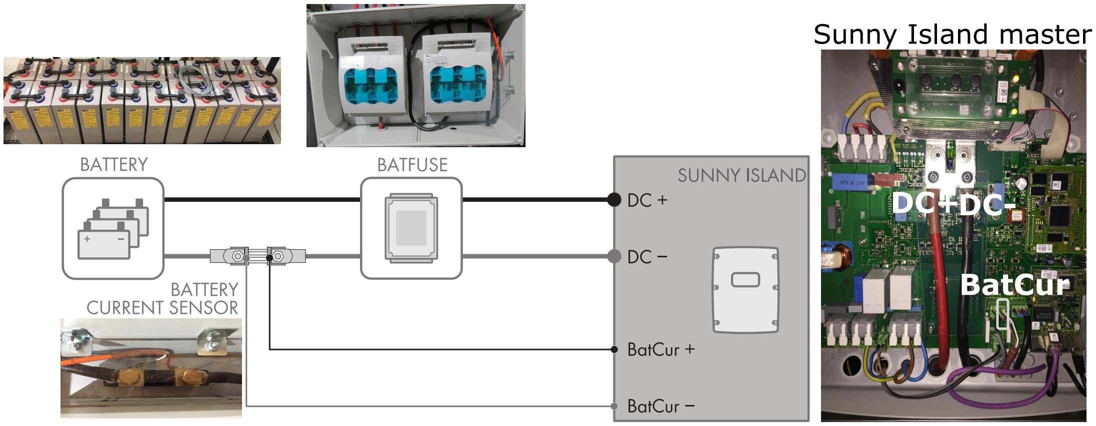


Figure 4.11: Connection of the battery bank, battery fuse, and battery current sensor to the Sunny Island (Adapted from [58]).

4.3.4 Photovoltaic system

The photovoltaic system consists of three strings with six PV modules each. It is installed on the roof with a slope of 12°. One string is oriented South and two oriented Southwest. The modules are installed in two roof surfaces to maximize and to improve the distribution of PV generation throughout the day by adjusting it to the opening hours of the museum. In the morning, the Southern string starts the generation before than the Southwestern, allowing a higher production. In the afternoon, the Southwestern string will have an extended generation. Figure 4.12 shows the modules installed in the Silk House roof.

Figure 4.12: Photovoltaic modules installed in the Silk House.

The modules are from Panasonic, series HIT, model VBHN325SJ47, maximum power 325 W, with 19.7% efficiency and 27% more output power than a standard one [61]. The maximum total power to the system is 5.85 kW. Each string is connected to a SMA PV inverter Sunny Boy 1.5-1 VL 40, with 97.2% efficiency [62]. The maximum PV array power in DC input is 3000 Wp and the rated power (at 230 V, 50 Hz) in AC output is 1500 W. The Sunny Boy 1 was connected to the Southern oriented string, SB 2 and 3 to the two Southwestern oriented string. Each SB feeds into one of each three-phase (L1, L2, and L3). Figure 4.13 shows the connections between each SB and the PV modules.

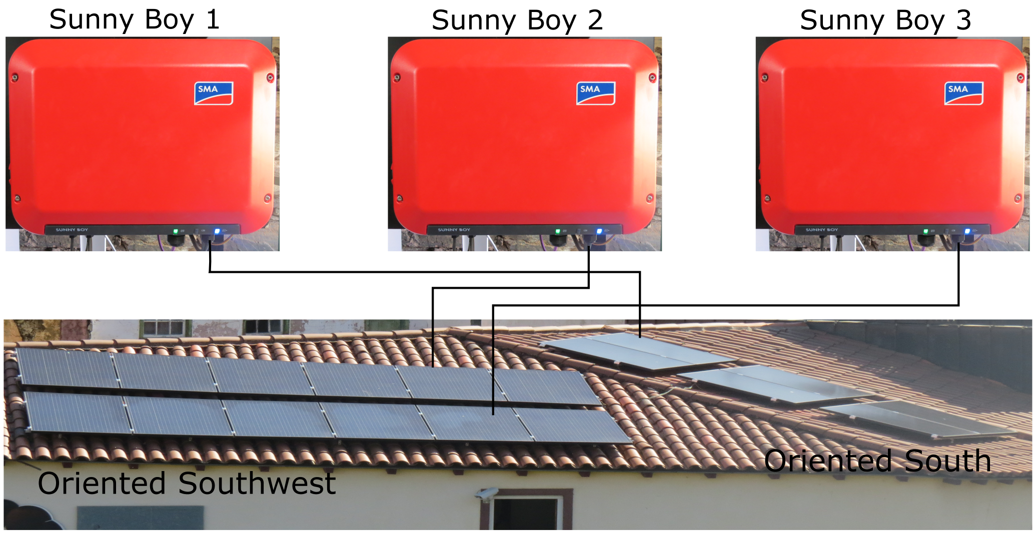


Figure 4.13: Connections between the photovoltaic modules and Sunny Boys.

4.3.5 Pico-hydro system

The installation of the pico-hydro system results from the proximity of the building to the Fervença river, the existence of a small dam (less than 10 m away), and the hydraulic infrastructure of the former mill (channel and galleries). This system recovers the historical heritage of the former mill and preserves the building's architecture [51]. The installation of the pico-hydro aims to complement the Silk House electric generation, mainly in the winter periods when the river flow rate allows a higher pico-hydro generation. Also, this small-scale system is capable of producing energy 24 hours a day, unlike photovoltaic systems, and it has an emerging potential.

In the context of the SilkHouse Project, the small-scale hydropower plant integrates a horizontal water wheel and a low head turbine. Two pipes were installed to capture water from the small dam and take it inside the gallery where the water wheel and turbine will be installed. For the diversion of water by the small dam of the Fervença River, the approval of the Portuguese Environment Agency (APA) was required. The water wheel will produce energy in place of the former mill and was designed to generate a maximum power of 300 W [63]. Figure 4.14 shows the water wheel under construction. The 1.2 kW low head turbine is from PowerSpout, model LH400 (Figure 4.15) [64].

Figure 4.14: Water wheel under construction.

A PV microinverter from GWL Power [65] and a PV string inverter from Omnik, model Omniksol - 2k - TL2 [66], are used to connect the 300 W generator of the water wheel and the 1.2 kW generator of the low head turbine to the microgrid, respectively. Figure 4.16 shows

Figure 4.15: 1.2 kW Low-head turbine from Power Spout.

the PV inverter and micro-inverter that will be used for the pico-hydro system. Inverters and micro-inverters from other manufacturers can be integrated in SMA PV systems with Sunny Home Manager provided that the requirements of the power output of these devices must be captured via a separate SMA Energy Meter [56]. However, these inverters will not have the same generation control functionality as SMA ones. It must be configured in Sunny Portal as a PV production meter [56]. Thus, the PV inverter and micro-inverter will need the use of two SMA Energy Meters in order to account for the energy produced by the pico-hydro system. It uses guarantee high measurement accuracy, excellent compatibility of the PV inverter and micro-inverter with the SMA system, and makes them available via Speedwire [52].

4.3.6 Electrical panel

The electrical panel of the microgrid contains protection devices, automatic transfer switch, and the Sunny Home Manager. Also, it will contain the two Energy Meters and the protection for the pico-hydro system. The PV system, pico-hydro system, and loads are secured with the protection

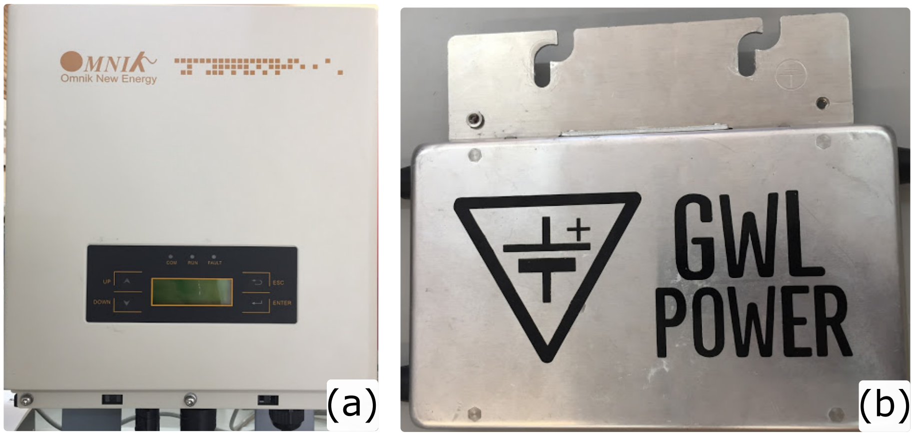


Figure 4.16: (a) Omnik PV inverter and (b) GWL Power PV micro-inverter.

devices. Figure 4.17 shows the electrical panel installed in the Silk House with the devices and Table 4.2 describes each one. Appendix C shows the circuity of this electrical panel elaborated with the cooperation of the company JG Instalações Elétricas, which is partner of the SilkHouse Project.

Table 4.2: Devices of the electrical panel based on Figure 4.17

Number	Device
1	Input circuit breaker 4x63 A, 400 V
2	Sunny Home Manager 2.0
3	Bus
4	Phase indicator
5	Automatic transfer switch composed by: 3 thermal fuse (1 A) and 1 contactor (400 V, 32 A)
6	Protection devices for the Sunny Island
7	Output circuit breaker 4x63 A, 400 V
8	Protection devices for the Sunny Boy
9	Protection devices for an outlet and lighting of the gallery

The automatic transfer switch is required in self-consumption and battery-backup systems. For the three-phase battery-backup system without all-pole disconnection, the transfer switch is composed by three thermal 1 A fuse (F1) for protecting the control and measuring cables, and a 400 V, 32 A contactor (Q2) for grid disconnection in event of grid failure. A control cable, measuring cable, and power cable link the automatic transfer switch to the SI (X4 and X5). Figure 4.18 shows the connections of the automatic transfer switch.

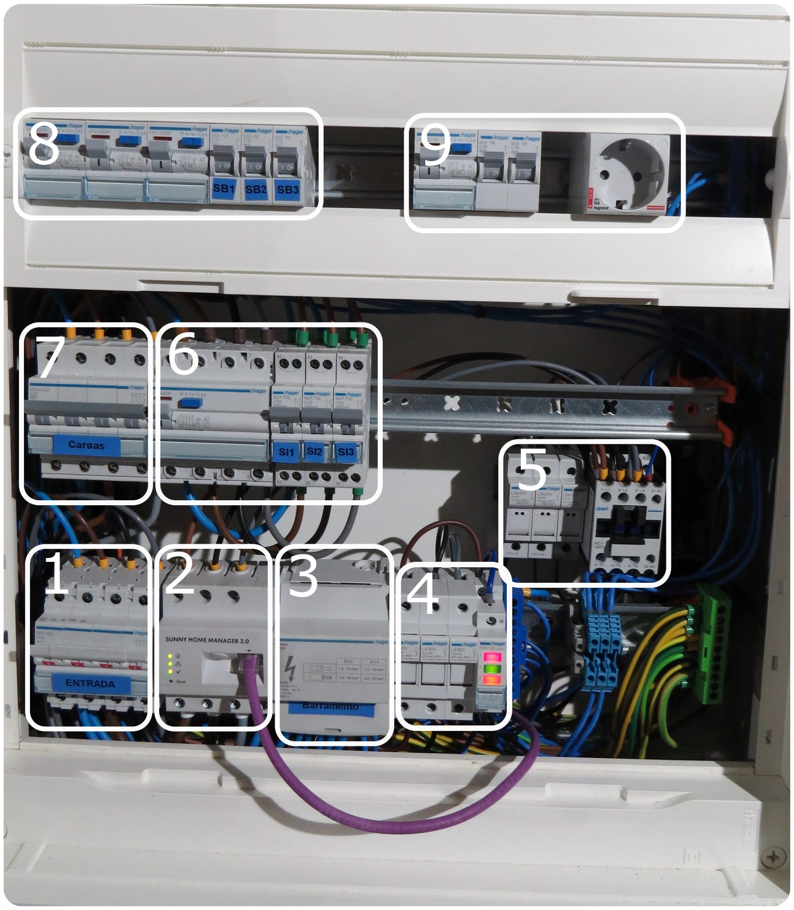


Figure 4.17: Electrical panel with devices of the microgrid.

The automatic transfer switch can only be activated when the grid voltage is present [45]. The contactor is controlled by the multi-function Relay 1 of the SI master. When Relay 1 is in non-operative mode, Q2 is activated. In the case of grid failure, Q2 is deactivated due to lack of voltage and disconnects the microgrid from the utility grid. When the utility grid is restored, the SI detects it and synchronizes the microgrid with the utility grid. Relay 1 back into the non-operative mode and Q2 is activated.

The Sunny Home Manager 2.0 is the central device responsible for energy management and self-consumption [56]. Its basic tasks are a collection of energy and power measured values, energy monitoring with a presentation of energy flows via Sunny Portal, energy management, limiting of active power, etc [56]. The SHM can communicate with other SMA devices via Speedwire if all devices are connected in the same local network.

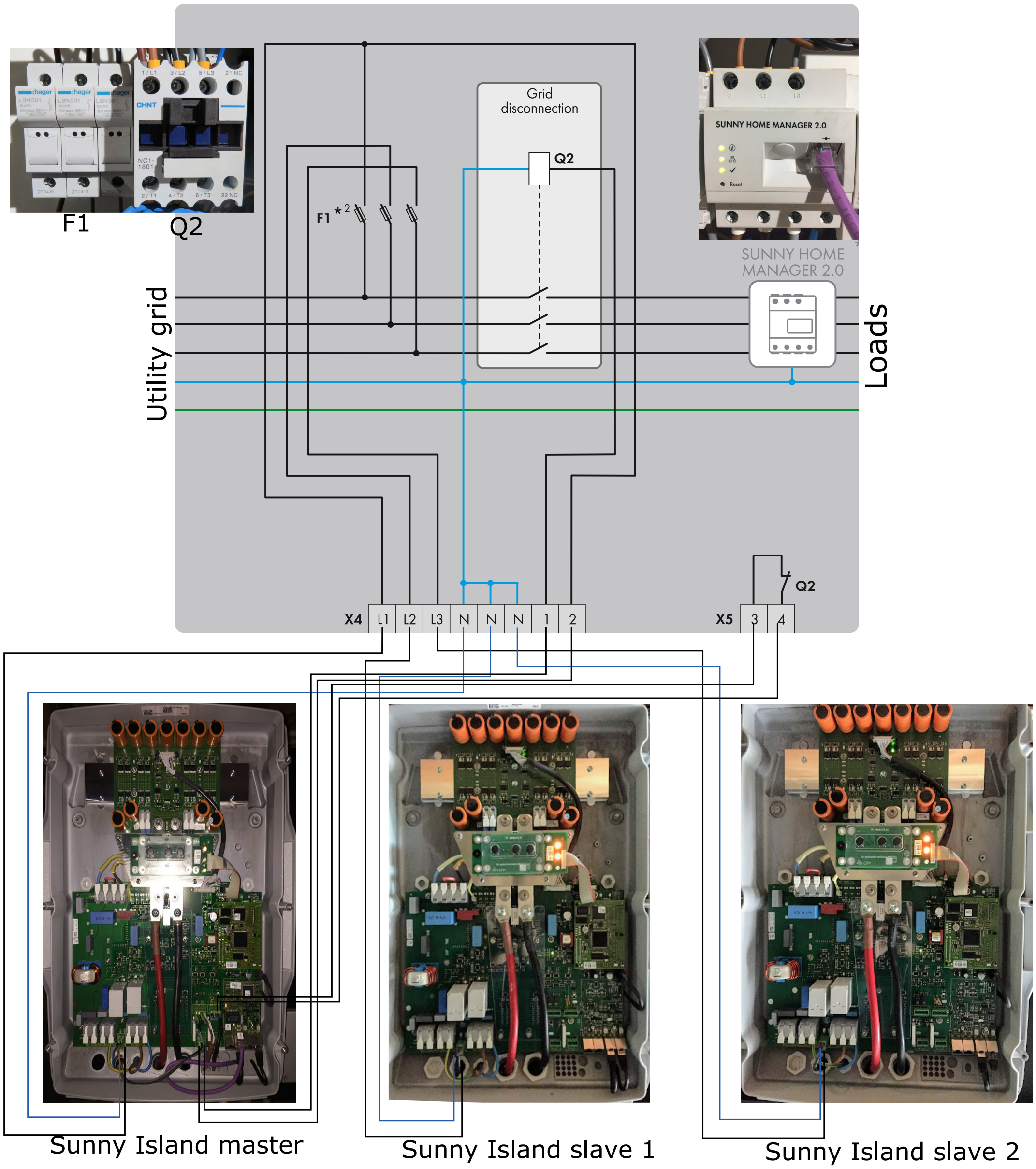


Figure 4.18: Schematic diagram of the automatic transfer switch (Adapted from [45]).

4.4 Parameterization of the Silk House smart microgrid

After installing the microgrid devices, they must be parameterized to the settings required for operation. This section presents the parameterization realized in the Sunny Island and in the Sunny Portal to meet the requirements for the SMA Flexible Storage System solution with battery-backup and increased self-consumption.

4.4.1 Parameterization of the Sunny Island

Before setting the microgrid, the system must be started. The SI is switched on by pressing and holding the "on" button (Figure 4.19) on the master until an acoustic signal sounds. If the parameters are already set up, the system must be started pressing and holding the start/stop button until an acoustic signal sounds or can press and hold the Sunny Remote Control (SRC) button. SRC is a central location used to configure the SI master. Figure 4.19 shows the Sunny Remote Control and its display, and Sunny Island with its control panel. The display of the SRC enables to visualize of the parameters and data. Also, when the SI is running, the SRC provides information on the status of the system for increased self-consumption. With the control panel of the SI (Figure 4.19) is possible to start or stop the system (A), switch the SI on (B), and switch off (C). Also, it is possible to visualize, by a LED, the SI status (D), if it is connected to the grid (E), and the status of the battery (F).

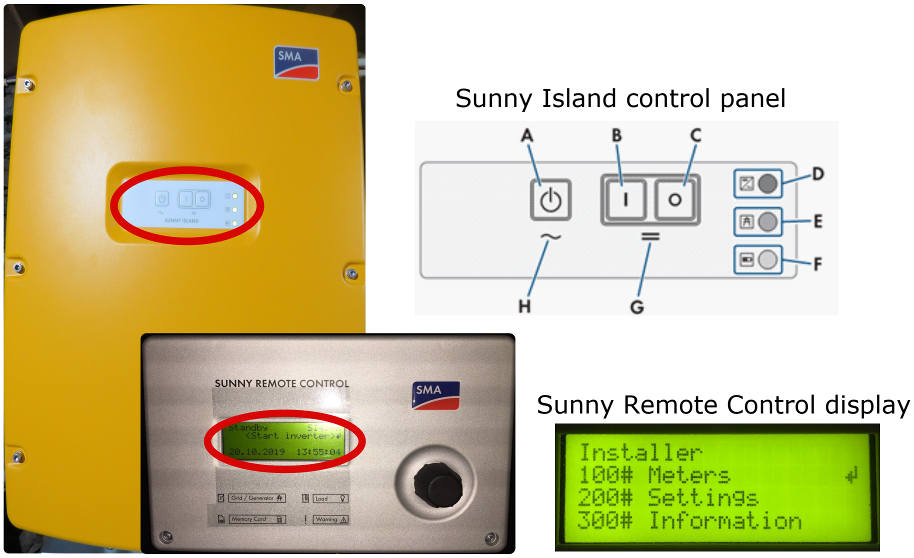


Figure 4.19: Sunny Remote control and Sunny Island, with they display and control panel, respectively (Adapted from [57]).

With the SI cluster switched on, a new system is configured in the SI master using the Sunny Remote Control. The basic configuration of the new system for the Silk House smart microgrid is shown in Table 4.3. The parameterization is set in the SI master and transmitted to the other inverters. With the basic configuration completed, the SRC prompts you to identify slaves 1 and

2. To identify the slave 1, it must press the start/stop button on slave 1. The same is realized for the slave 2.

Table 4.3: Basic configuration of the Sunny Island inverters.

Number	Set
001#01	New System
003#04	Date
003#05	Time
003#06	ApplSel - On-grid
003#07	Baterry Type - VRLA
003#10	Battery Capacity - 623 Ah
003#13	System - Self-consumption backup
003#14	Cluster Type - three phase

With the basic configuration performed, the system allows configuring the other parameters of the SI via SRC. The system has three operator modes which allow the access of these parameters (or not), as follows.

- User: Displays all important information for the system sorted by categories, such as electrical quantities and some inverter data. This mode allows access to the other by a password. The password is the sum of the system run time, i.e., for 123 h of run time, the code is the sum of 1+2+3 = 6.
- Installer: This mode allows the configuration of some parameters, but it has change limitations.
- Expert: The expert mode can be accessed only via installer mode. It has the highest degree of freedom of access and parameter setting.

In addition to the parameters accessible by these modes, some require a password provided by SMA. The Grid Guard code is a password that allows modifying some parameters to comply with the local grid conditions. In this microgrid was maintained the default parameters that characterize the electric grid and adopted the VDE-AR-4105 standard (parameters from 232#01 to 232#60).

Accessing the expert mode, it is realized the parameterization for the battery management and the self-consumption backup, as presented in the next topics. Appendix D summarizes the relevant parameters applied in this work.

Parameterization of the battery management

An exact determination of the state of charge in a battery-bank is a basic requirement for the correct operation of lead-acid batteries and to reach its service life [67]. A further feature of battery management is the extremely gentle charging control [67]. This control selects the optimum charging strategy for the battery type and the operating conditions in which it is used. This battery management is based on parameters set in the battery inverter SI.

The basic parameters of the battery type and its values used in charging mode are based on data provided by the battery manufacturer Sonnenschein [59]. Table 4.4 shows these basic parameters for the battery bank.

Table 4.4: Basic parameters for the battery bank.

Number	Name	Description	Value
221#01	BatTyp	Battery type	VRLA
221#02	BatCpyNom	Battery nominal capacity for a ten-hour electric discharge C_{10}	455 Ah
221#03	BatVtgNom	Battery bank nominal voltage	48 V
221#04	BatTmpMax	Maximum battery temperature	40 °C
221#05	BatTmpStr	Battery temperature as connection limit after overtemperature disconnection	35 °C

The SI controls the charging of the battery bank in three phases [67]: with constant current, constant voltage, and float charge. These phases and the parameters set for each one are demonstrated in Figure 4.20.

The constant current limits the current to the maximum permissible battery current. This maximum charging current is set on the parameter 222#01 BatChrgCurMax in 35 A. The battery charging current is also limited by the maximum AC charging current of the SI (parameter 210#03 InvChrgCurMax set in 14.3 A). The value that is reached first limits the charging current of the battery [67].

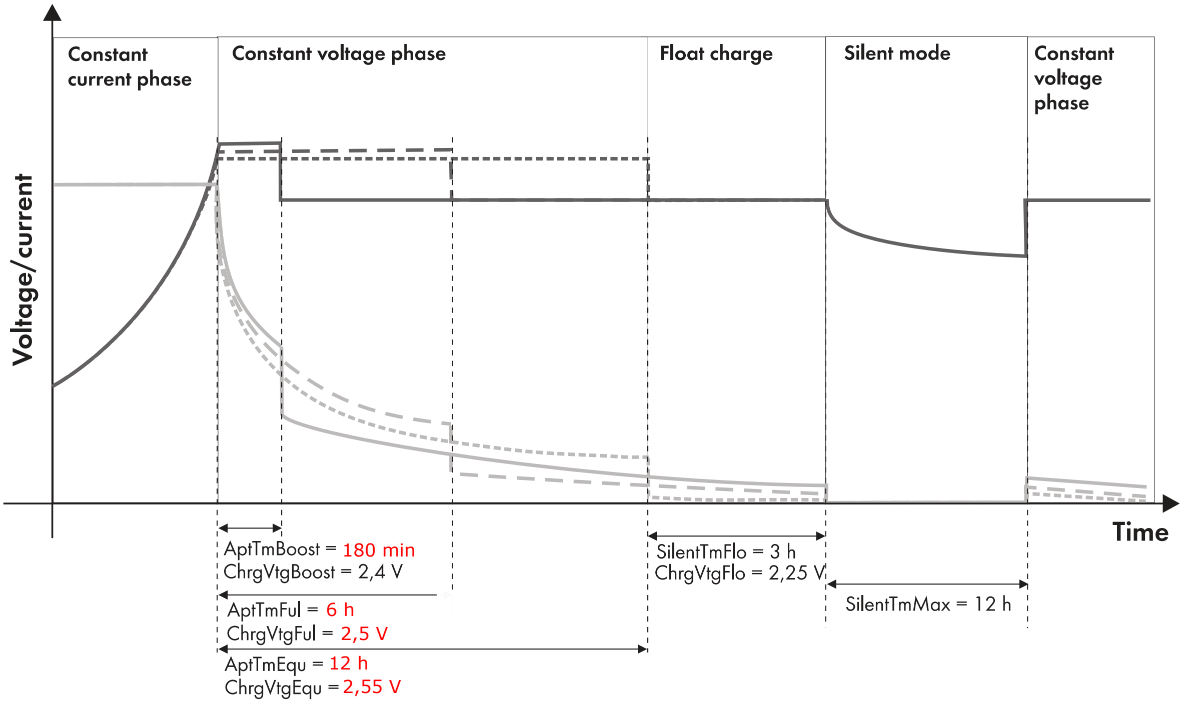


Figure 4.20: Sunny Island charging phases with values for Sonnenschein's batteries A602/625 Solar (Adapted from [67]).

In constant voltage phase, the voltage is controlled at a constant voltage and the battery current decreases continuously [67]. This phase has three charging processes, boost, full, and equalization charge. In each process it is possible to adjust the voltage level and charging time in the SI, always following the manufacturer's specifications. When the determined time of the process is reached, the SI switches to the float phase. The three charging processes are described below [67].

- Boost charge: A high charging voltage is applied to the battery bank which is charged to between 85% and 90% of its current usable capacity in a very short time. In this process, it is adjusted the charging voltage (222#07 ChrgVtgBoost set in 2.4 V) and the absorption time (222#02 AptTmBoost set to default value in 180 min).
- Full charge: It recharges the battery to a state of charge of at least 95%. This compensates for the effects caused by any insufficient charging and should also increase the service life. In this process, it is adjusted the charging voltage (222#08 ChrgVtgFul set in 2.5 V) and the absorption time (222#05 CycTmFul set to default value in 14 days).

- Equalization charge: The SI cancels out differences in the SOC of individual battery cells. Thus, it prevents the premature failure of individual battery cells and extends its service life. In this process, it is adjusted the charging voltage (222#09 ChrgVtgEqu set in 2.55 V) and the absorption time (222#06 CycTmEqu set to default value in 90 days).

The float charge maintains the battery bank in a fully charged state without overcharging. When this phase starts, battery management reduces the charging voltage until the setpoint specified for float charge has been reached (222#10 ChrgVtgFlo set in 2.25 V). At the end of this phase, the battery management switches back to the constant current phase.

After commissioning, the SI adopts the set nominal capacity (parameter BatCpyNom) as the available capacity and thus sets the State of Health (SOH) initially to 100% [67]. During the operation, the SI learns to define the SOH more precisely.

Parameterization of the self-consumption backup with increased self-consumption

The increased self-consumption depends to a large extent on the battery and the availability of photovoltaic energy [58]. Depending on the region, the PV energy available varies on the season and the hours of sunshine. The short days have few hours of sunlight and the SI can not charge the batteries fully due to insufficient PV energy [58]. Also, the SI should not discharge the batteries too much. On the contrary, long days with many hours of sunlight allows the use of as much of the battery capacity as possible for increasing self-consumption. In this context, the SI can usually charge the battery fully.

Through the region where the PV system is installed, the discharge behavior can be adjusted to the SI. This seasonal operation automatically adjusts the battery depth of discharge. In seasons with fewer hours of sunlight, the electric discharge of the battery will be lower. On the other hand, the SI uses a large portion of the battery capacity on long days. For the seasonal adjust, increased self-consumption, and determine the region, it must be set the parameters 261#03 Seasonable in "yes", 261#01 SlfCsmplnEna in "enable", and 261#02 SlfCsmpPosSel in "north", respectively.

To use the battery optimally, it can adjust the depth of discharge of the battery to the necessary application. The parameters to meet this can be set automatically during the basic configuration for the respective system. Considering the smart microgrid of this work with just the PV generation installed, it was contemplating the default parameters. These parameters are based on five adjustable ranges for battery-backup systems with increased self-consumption. Figure 4.21 demonstrates an example of the SOC ranges of the battery bank according to the seasonality.

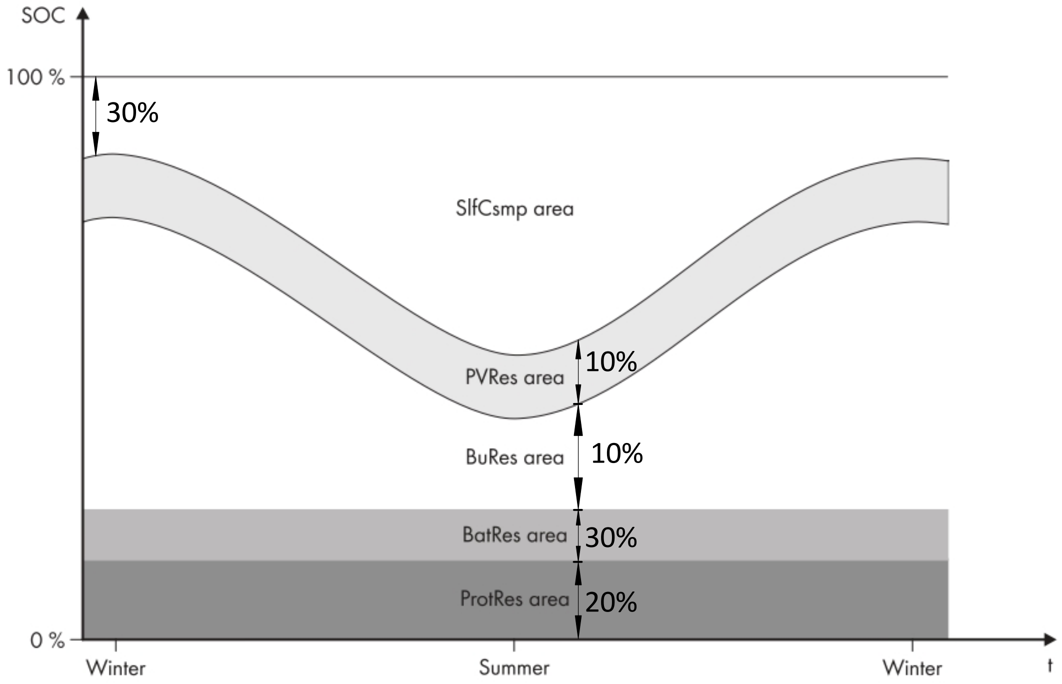


Figure 4.21: State of charge ranges of the battery according to the time of year (Adapted from [58]).

Due to the seasonal battery operation of the SI inverter, a larger range is reserved for the battery-backup function in winter than in summer [54]. This makes sense, as consumption in summer is lower and the PV yield is also much higher. Each range is described as follows [54] [58].

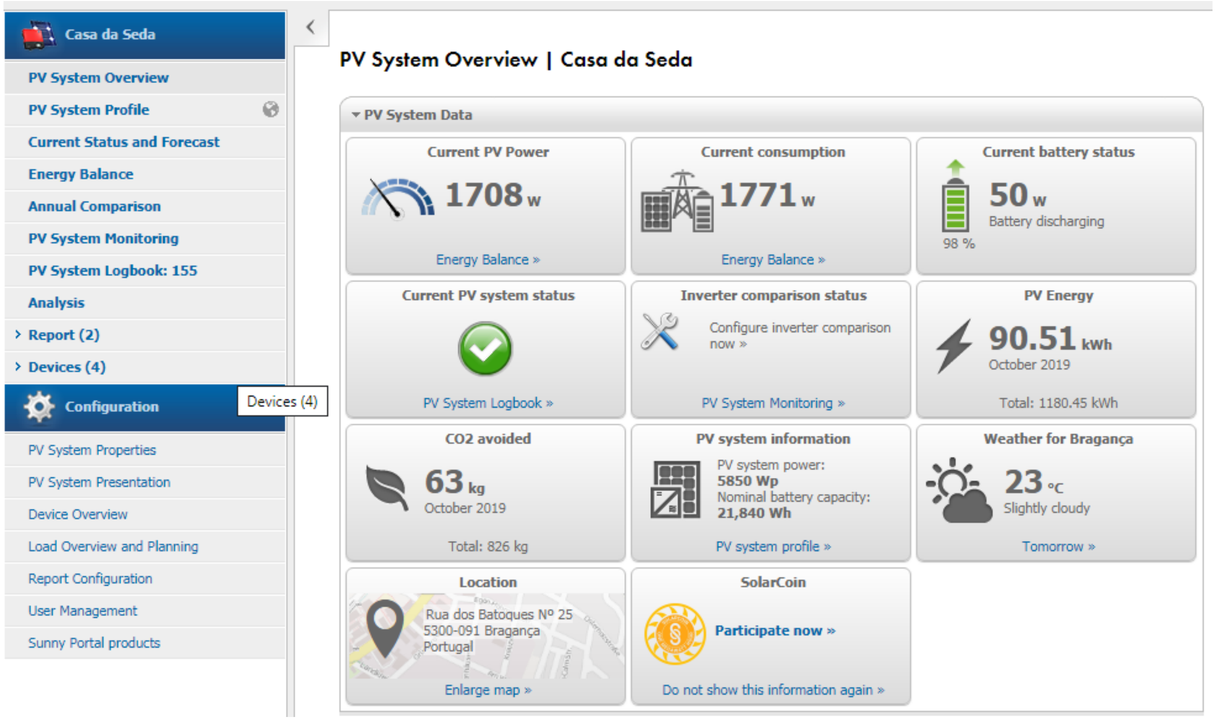
- SlfCsmp: Range for increased self-consumption, that uses the battery-bank for this purpose and for intermediate storage. The parameter set is the 262#05 MinSlfCsmpSOC, the minimum width of the self-consumption range on the shortest day of the year as a percentage of the battery capacity. The value set is 30%.

- PVRes: This range maintains the SOC of the battery by the excess generation. If the SOC reaches the BatRes area limit, the SI charges the battery bank up to half of the PVRes area from the utility grid with maximum efficiency at 25% of the nominal power. The parameter 262#04 PVResSOC is set in 10%.
- BuRes: Range for the battery-backup system function. It applies to the longest day of the year in the Summer with seasonal adjustment activated. This range is used to supply the loads when the utility grid fails. It is set the parameter 262#03 BUResSOC in 10%.
- BatRes: Range for protection against deep discharge. It can only be reached in grid failure events. In this case, the SI switches into standby mode and checks every two hours if it is possible to charge the battery with PV energy. When the grid is restored, SI charges the battery bank from the utility grid. The parameter set is 262#03 BatResSOC in 30%.
- ProtRes: Range for protection in the event of deep discharge, which can only be reached in event of utility grid failure. If this range is reached, the SI switches off in order to protect the battery. The parameter set is 262#02 ProtRecSOC in 20%.

When pico-hydro generation is in operation, it will need to change these parameters to meet new system requirements. Essentially because the pico-hydro system aims to complement the Silk House electric generation, mainly in the winter periods when the river flow rate allows a higher pico-hydro generation. Thus, the complementary energy available in the winter season will be able to charge the battery bank and allow it uses as much of the battery capacity as possible.

4.4.2 Parameterization of the Sunny Portal

Sunny Portal is an Internet portal that allows the user to monitor systems and to visualize and present system data from components of the SMA Flexible Storage System [56]. It works as a user interface for configuring the Sunny Home Manager and the loads [56]. The SHM sends the read-out data of the microgrid to Sunny Portal via an Internet connection. Figure 4.22 shows the interface for the Silk House system in the Sunny Portal.



PV System Overview | Casa da Seda

PV System Data

Current PV Power: 1708 W

Current consumption: 1771 W

Current battery status: 50 W, Battery discharging, 98 %

Current PV system status

Inverter comparison status: Configure inverter comparison now »

PV Energy: 90.51 kWh, October 2019, Total: 1180.45 kWh

CO2 avoided: 63 kg, October 2019, Total: 826 kg

PV system information: PV system power: 5850 Wp, Nominal battery capacity: 21,840 Wh

Weather for Bragança: 23 °C, Slightly cloudy

Location: Rua dos Batoques Nº 25, 5300-091 Bragança, Portugal

SolarCoin

Figure 4.22: Sunny Portal interface for the Silk House system.

The data presented in the Sunny Portal are described as follows [56]. PV system overview summarizes current consumption and generation data, CO_2 avoided, battery status, etc. Current status and forecast show the power flow among the PV system, the power distribution grid, and the household. Energy balance allows visualize the temporal progression of energy generation and energy consumption and displays how the loads in the household have been supplied and how the PV energy has been used. Annual comparison displays the total yield and specific system yield over the year. PV system monitoring displays information of communication monitoring and inverter comparison. PV system logbook shows messages regarding the system status, such as info, warning, disturbance, and error. On the page analysis, it can compare the power and yield values of individual inverters with one another or with the complete system.

The next step after commissioning the SI is configured the Sunny Portal. The SHM automatically establishes the Internet connection to Sunny Portal via a Cisco switch, where the microgrid devices are connected, allowing the parameterization. Accessing the Sunny Portal website, a new system must be configured in eight steps for registration and detection of the PV system.

The main steps that need configuration are as follows. The first step is user registration. Second, create a new PV system. Third, identify the SHM with the PIC (Product Identification Code) and RID (Registration Identifier) code found on the supplied label. Fourth, select the devices that were found on the local Ethernet network and that the user want to add to the system. All devices must have the same password to form a system. Seventh, configure the extended PV system properties, such as nominal PV system power and specific annual yield.

Created the new system and performed the first basic configuration, it has access to Sunny Portal and the other parameters. These parameters are available on the Configuration - PV system properties - Parameters tabs and are described below.

- Reimbursement: It can feed the electricity generated into the utility grid. In this case, it can be configured the amount of the respective feed-in tariff and the SHM will take this information into account during load control. However, in the Silk House microgrid, the intention is not to sell to the utility grid because it is a self-consumption system. Thus, the tariff is set in 0 Euro/kWh.

- Limiting of the active power feed-in: Through this parameter, it is possible to meet the objective of the microgrid not to allow injection of power in the utility grid. Thus, it was set the "Zero Export" in 0% of the nominal system power.

- Grid management via Ethernet-based communication: The Sunny Home Manager can receive the specifications for grid management services via Ethernet-based communication [56]. The SHM does not have to implement any grid operator specifications, so it was deactivated the interface for grid management.

- Electricity Tariff: It is set in 0.156 based on the energy bill.

- Time window control for charging the battery-storage system: The battery bank is charged based on defined times (typically at low tariffs at night) due to time-dependent electricity tariffs from the electric utility company. It is not applied to this configuration in the Silk House microgrid.

- Optimization Target: The optimization target indicates whether the SHM should prioritize ecological or economical factors for load management. The ecological uses the greatest self-consumption. Economical is the highest possible cost savings. It was set the ecological target.

- CO_2 avoided: Sunny Portal can use the CO_2 factor to calculate how much CO_2 was saved due to the power generation of the system [56]. It was set the default value in 700 g/kWh.

- Yield expectations: Predicted annual yield of the system is likely to be distributed throughout the months of the year [56]. It is calculated using the specific yearly yield 1500 kWh/kWp at the location of the PV system and the PV system power in 5850 kWp (nominal power).

Chapter 5

Results and analysis

This chapter contains the results for the generation and operation of the smart microgrid implemented in the Silk House museum. They were obtained via Sunny Portal and operation tests, respectively. Also, it presents the analysis and discussions about the results demonstrating the real operation of this microgrid.

5.1 Generation results

This section presents the generation results obtained since the implementation and commissioning of the microgrid on 31st July, 2019. The focus of the results and analysis is on photovoltaic generation since the pico-hydro system is in the installation phase at the time this work was written. Thus, it is possible to evaluate the microgrid operation by analyzing several data and graphics obtained via Sunny Portal.

Figure 5.1 shows an energy balance, the temporal progress during September 3rd, 2019. The consumption graph shows when and from which sources the microgrid has been supplied with energy (photovoltaic, battery bank or utility grid). The generation graph shows when and how much energy was generated and how much is used for (direct consumption, battery charging, or grid feed-in).

On September 3rd (Figure 5.1), the daily yield was 25.93 kWh representing a self-sufficiency quota of 100%. This means that the PV generation was capable to produce the energy necessary for the load demand. The self-consumption quota was 100%, which means that all the energy generated was used on-site (for loads and battery-bank charging) and not fed into the utility grid as expected considering the requirements of this microgrid (Section 4.3). However, a minimum feed into the utility grid is inevitable (grid feed-in). The direct consumption rate was 78% and corresponds to 20.20 kWh of photovoltaic energy used directly in the loads.

Figure 5.1 also shows the museum's period of operation on regular days. From 10 a.m. to 6 p.m. of this day, Tuesday, the power remains at an average of 2500 W (direct consumption). As a consequence, the generation follows the consumption graph, meeting only the demand (loads and battery charging). The rest of the day, the power is below 500 W and the remaining loads are supplied from the battery-bank (battery discharging). In two moments of the day, 9 a.m. and 7 p.m., it needed to purchase electricity from the utility grid (external energy supply) because production was not enough to meet the demand. Thus, demonstrating the operation of the microgrid in which it only purchases power from the grid when production is not sufficient.

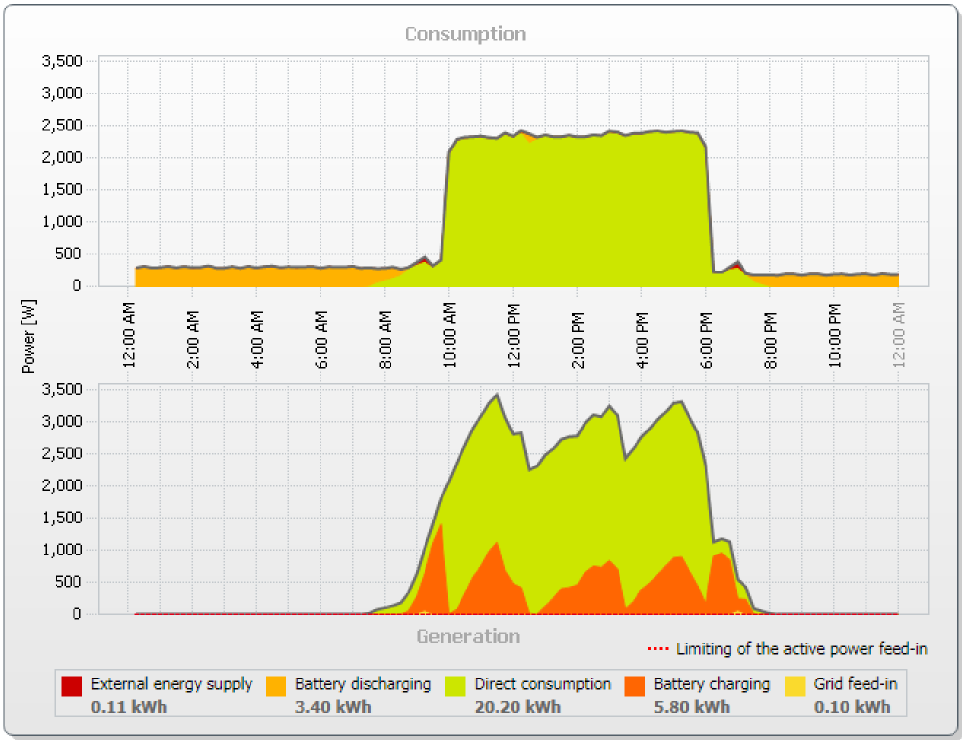
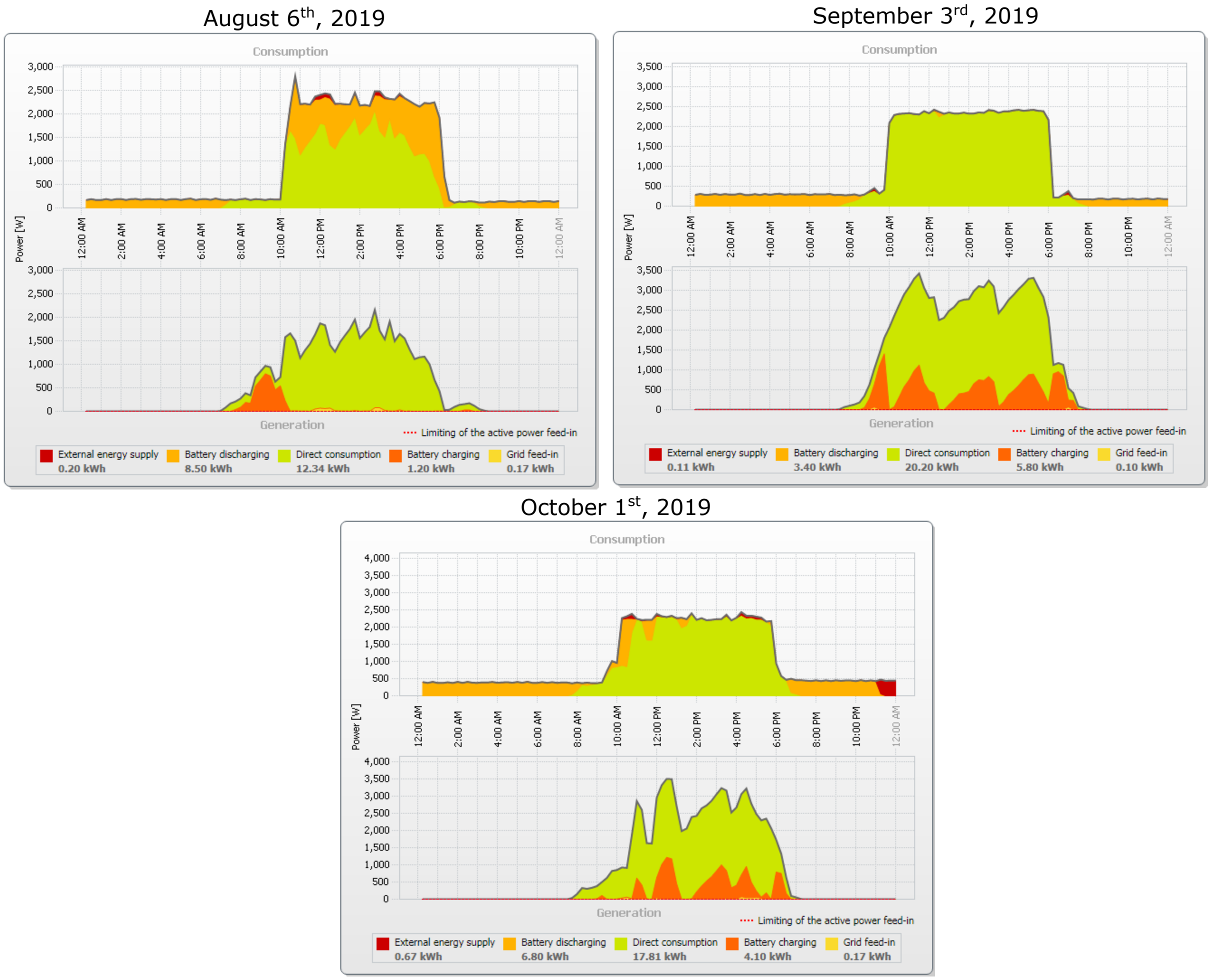


Figure 5.1: Energy balance of September 3rd, 2019.

Figure 5.2 shows an energy balance for the first three months of the microgrid operation. One day of each month (August, September, and October) was chosen to demonstrate the operation of the microgrid regarding generation and consumption. Table 5.1 presents the quota and rates for these days (all of them on Tuesdays). The self-sufficiency quota demonstrates that the museum became self-sufficiency in average energy terms with the implementation of the smart microgrid.

The self-consumption rate was made up of direct consumption and battery charging. Also, the energy balance quotas highlight the power management system which controlled generation and consumption to meet system requirements.



August 6th, 2019

September 3rd, 2019

October 1st, 2019

Figure 5.2: Energy balance for a day of each first three months of microgrid operation.

Table 5.1: Energy balance quota of the first three months of microgrid operation (one day of each month).

Balance	August 6th, 2019	September 3rd, 2019	October 1st, 2019
Self-sufficiency quota	99%	100%	97%
Self-consumption rate	99%	100%	99%
Direct consumption rate	90%	78%	82%

Table 5.2 presents a comparison of some relevant data about the energy balance demonstrating the real operation of the microgrid for three days in different months. On these days, the average

daily consumption was kept close. However, the daily yield had a divergence on August 6th. An answer to this is the weather conditions of the day which may have fewer hours of sunshine affecting PV generation and demanding from the microgrid purchase energy from the battery bank.

Table 5.2: Energy balance data of the first three months of microgrid operation.

	Energy (kWh)		
Balance	August 6th, 2019	September 3rd, 2019	October 1st, 2019
Daily consumptiom	21.04	23.71	25.28
Daily yield	13.67	25.93	21.71
External energy suppply	0.20	0.11	0.67
Internal power supply	20.84	23.60	24.61
Battery discharging	8.50	3.40	6.80
Battery charging	1.20	5.80	4.10
Grid feed-in	0.17	0.10	0.17
Direct consumption	12.34	20.20	17.81
Self-consumption	13.50	25.88	21.54

Figure 5.3 demonstrates the PV generation during the week of August 2 - 8, 2019. On Mondays, the museum is closed and therefore has less consumption. This is visible on the curve of August 5th, during which production was the lowest. It is worth remembering that PV generation is based on the consumption of the loads and energy stored, and not just on the available solar radiation. This results from the control of the active power generated by frequency control [45], as there is no energy supplied to the utility grid.

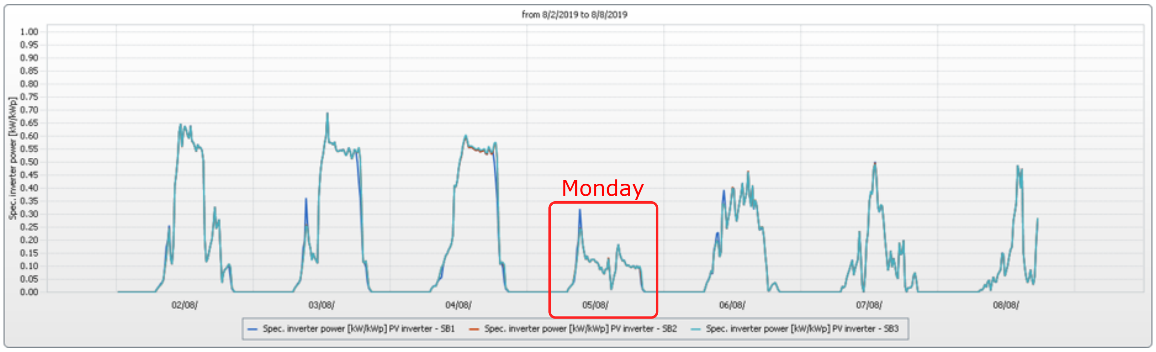


Figure 5.3: Photovoltaic generation analysis during the week August 2 - 8, 2019.

Figures 5.4 and 5.5 show the PV generation of the three strings connected to the microgrid via the PV inverters SB 1, 2, and 3. It is analyzed for two days in a row, October 2$^{\text{nd}}$ and October 3$^{\text{rd}}$, but the same happens in the other days with PV generation. They show the way that the strings were installed with different orientations, one string Southern oriented and two Southwestern oriented. These orientations make possible to improve the distribution of photovoltaic generation throughout the day. It is worth mentioning this is important when the excess of power should be immediately consumed or stored, not supplied to the utility grid. SBs 2 and 3 curves overlap, indicating that the strings are installed on the same roof face. Also, it shows PV generation prolongation between 5 p.m. to 7 p.m.. The curve of SB 1 shows a PV generation higher between 9 a.m. to 11 a.m.. During the rest of the day, the generation was the same to the three SB, i.e., PV strings.

Besides, the operation of active power control adopted by the frequency of the microgrid is also evident, as the maximum power generation was not achieved. This was because consumption was lower than an electric generation [46].

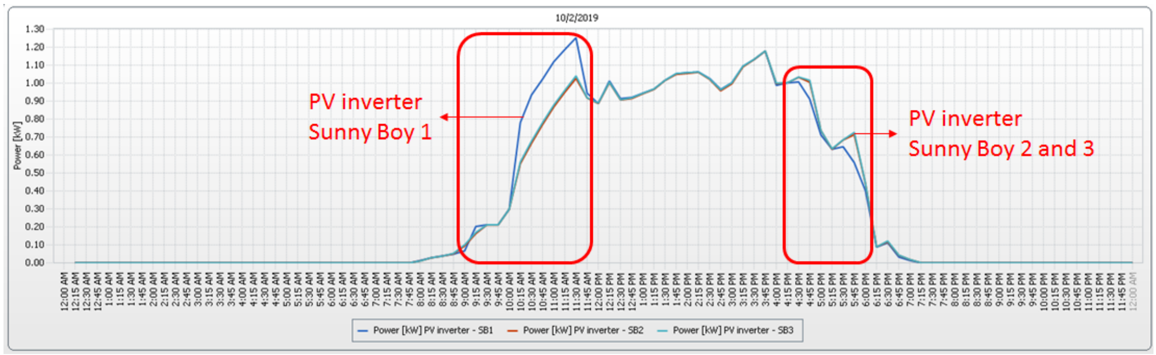


Figure 5.4: Photovoltaic generation analysis on October 2$^{\text{nd}}$, 2019.

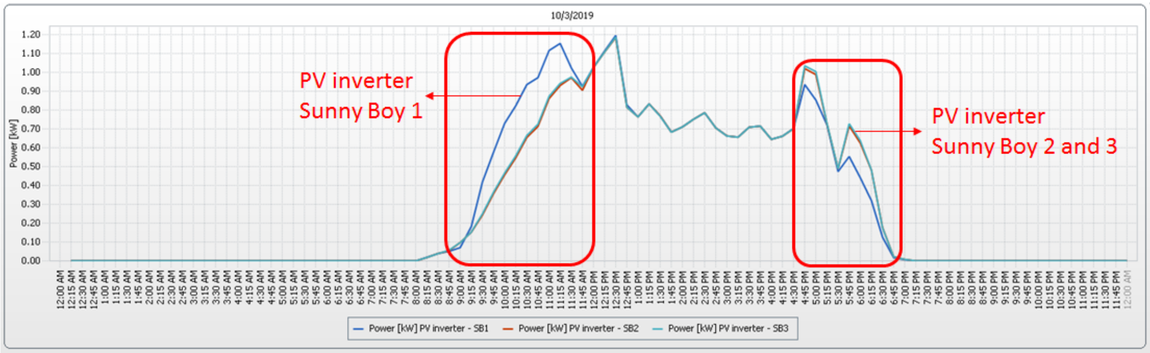


Figure 5.5: Photovoltaic generation analysis on October 3$^{\text{rd}}$, 2019.

Table 5.3 shows the PV generation of each SB during the last months and the total generation since the implementation of the microgrid at the end of July 31st, 2019. It is noteworthy that these data were obtained until October 5th, 2019. Although PV strings connected to SB 2 and 3 have a prolongation generation, they have a smaller generation than SB 1. This is because SB 1 has a generation peak in the morning that is sufficient to outperform the other two.

Table 5.3: Total PV energy of each PV inverter Sunny Boy.

	PV inverter SB 1 (kWh)	PV inverter SB 2 (kWh)	PV inverter SB 3 (kWh)
July	0.14	0.16	0.16
August	180.53	180.92	176.24
September	169.17	167.40	167.83
October	30.37	29.90	30.04
Total	**380.21**	**378.38**	**374.30**

Table 5.4 shows the total energy balance data since the microgrid implementation. A total of 1445.34 kWh (energy) was consumed in the last three months by the loads and battery bank charging, 80% of this was generated with PV renewable energy of the Silk House (self-sufficiency quota). The self-consumption rate was 99% and the direct consumption rate was 73%.

Table 5.4: Total energy balance data since the microgrid implementation on July 31st, 2019 and October 5th, 2019.

Balance	Energy (kWh)
Yearly consumption	1445.34
Annual yield	1133.06
External energy supply	288.60
Internal power supply	1156.74
Battery discharging	326.90
Battery charging	466.30
Grid feed-in	7.38
Direct consumption	829.85
Self-consumption	1125.57

Table 5.5 shows a side-by-side comparison of the consumption and energy bill before and after the implementation of the Silk House microgrid. A comparison is made for August and September 2018 and 2019, when the microgrid was fully operational. The data were obtained through energy bills. The consumption reading of August 2019 was taken 15 days after

implementation, thus not having the exact value of the consumption difference for that month. Nevertheless, it is possible to notice a significant difference in consumption and value in the invoice. However, in September, a large difference in consumption and invoice value is noted. The savings in consumption was approximately 75% and in energy bill 65%.

Table 5.5: Comparison of consumption before and after the implementation of the microgrid.

	August		September	
Year	2018	2019	2018	2019
Consumption (kWh)	629	495	832	212
Energy bill (Euro)	154.00	122.10	196.30	67.47

5.2 Operation results

This section presents the results obtained via experimentation with the physical implementation of the microgrid in the Silk House. The tests were executed to evaluate the system operation.

The following two tests were conducted with a three-phase power quality analyzer, the "Fluke 434 Power Quality Analyzer". The first test was to demonstrate the microgrid during normal operation (on-grid) by the instantaneous voltage signal obtained at the load output circuit breaker. Figure 5.6 shows the graph for the three-phase (L1, L2, and L3) system during the normal operation.

During the microgrid operation, either on-grid or in stand-alone mode, the control of active power by frequency control is always acting. A test was conducted in the Silk House microgrid to visualize this frequency control. Figure 5.7 shows a graph of this frequency control during a stand-alone operation. This test was realized on a Monday when the museum is closed and the consumption is lower. In this way, the system increased the frequency value so that the SB inverters would decrease the generation and meet the current load demand. During 30 s of analysis, the frequency ranged from 50.35 Hz to 50.37 Hz. These values of frequency are above the value set for the second phase of the control (>50.2 Hz), as previously explained in Figure 3.3. In this phase, the active power decreases linearly from maximum available power.

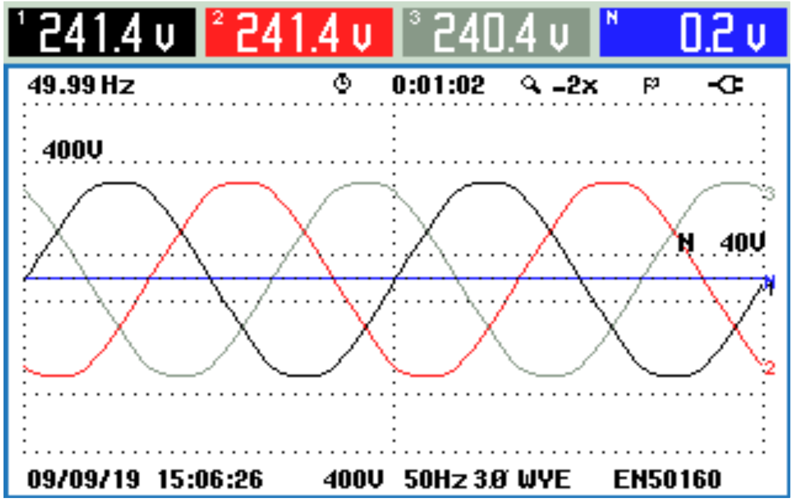


Figure 5.6: Microgrid line-to-line voltages during the normal operation.

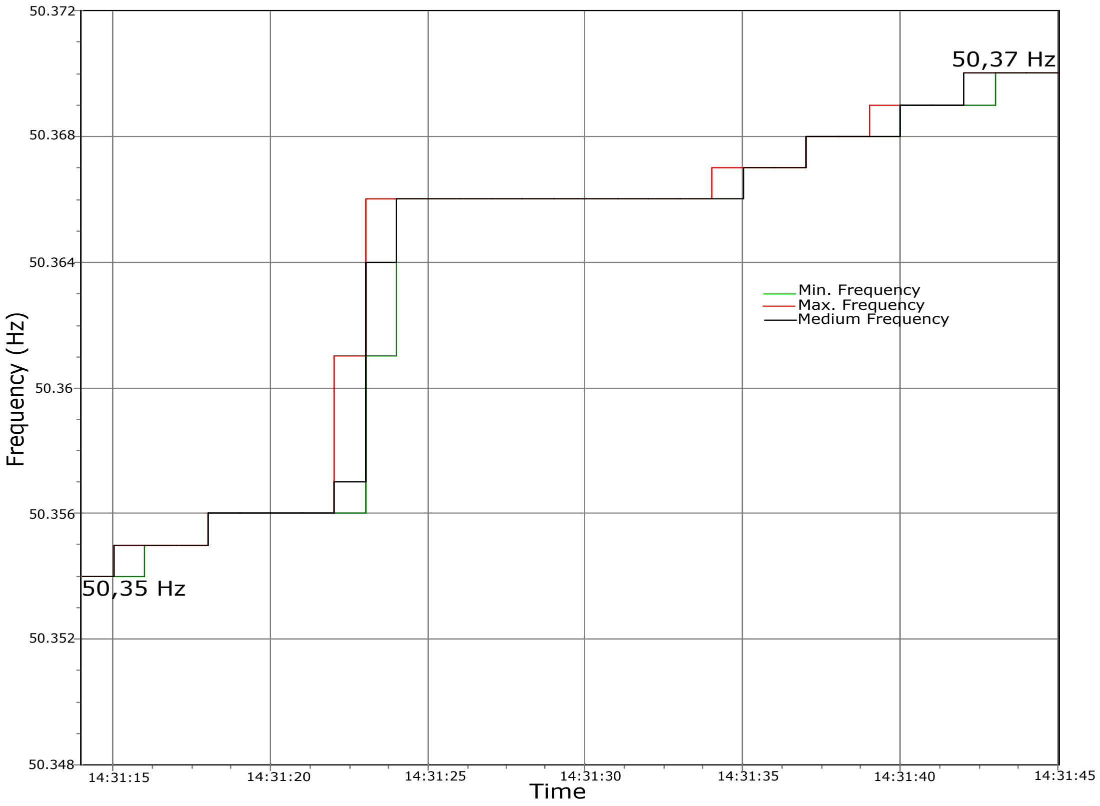


Figure 5.7: Frequency variation during stand-alone operation.

The automatic transfer switch operation is evaluated by a test realized with an application developed and that was made available by Professor José Batista from IPB. The application consists of a software and a data acquisition system. The transition from the utility grid to microgrid grid-tied operation modes is executed when a voltage zero-crossing is detected. Thus, the test consists of obtaining the voltage signals from the microgrid output circuit breaker during a public grid failure simulation by turning off the input circuit breaker. This enables the automatic transfer switch operation to be checked during a grid failure. Figure 5.8 shows this grid failure simulated. In the moment of the failure (Figure 5.9), instant 1.15 s, the voltage zero-crossing is detected and the system of the microgrid goes out of power. Complete re-synchronization takes approximately 10.1 s starting after the SI battery inverter form the grid-tied. Figure 5.10 shows the re-synchronization starting at the instant 11.05 s.

The result presented in this test has a disparity than shown by the manuals of the SMA manufacture. In contrast with the 10.1 s switching time presented in the results, the SMA presents that the loads and the PV system are not supplied for approximately five to seven seconds [45]. Such results may differ due to the types of tests and the measurement point at which they were performed.

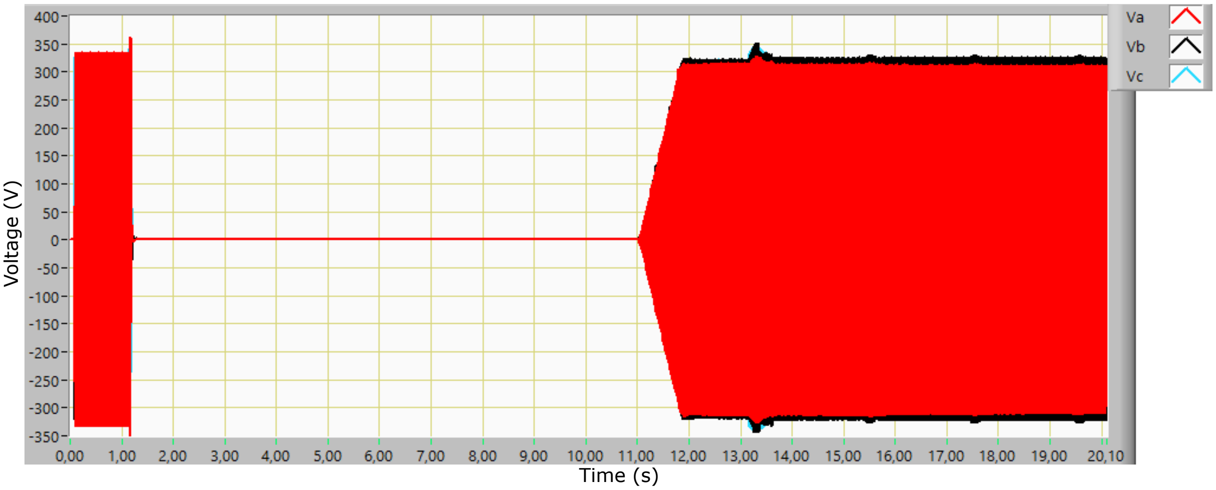


Figure 5.8: Utility grid failure.

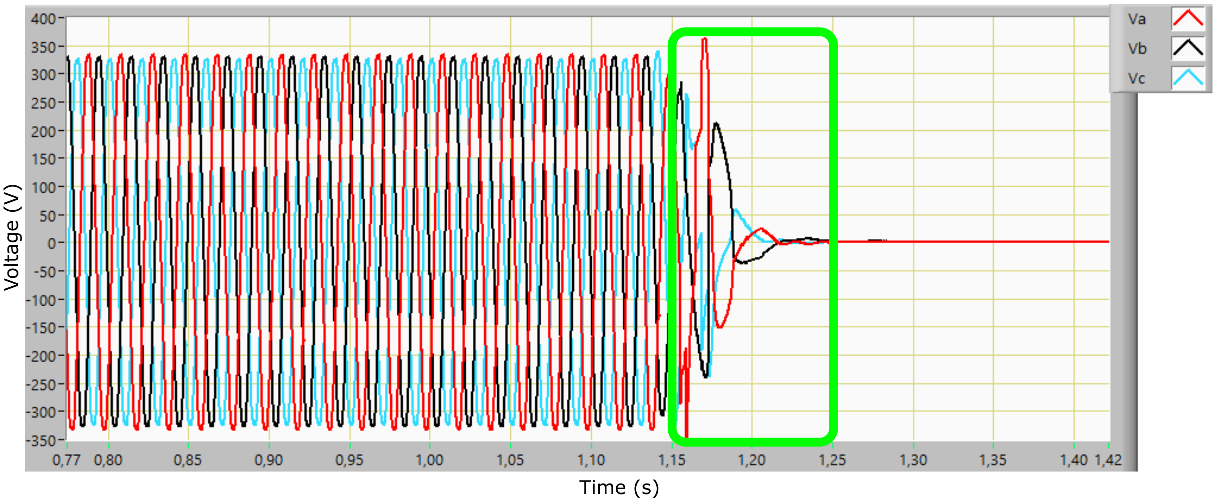


Figure 5.9: Start of utility grid failure.

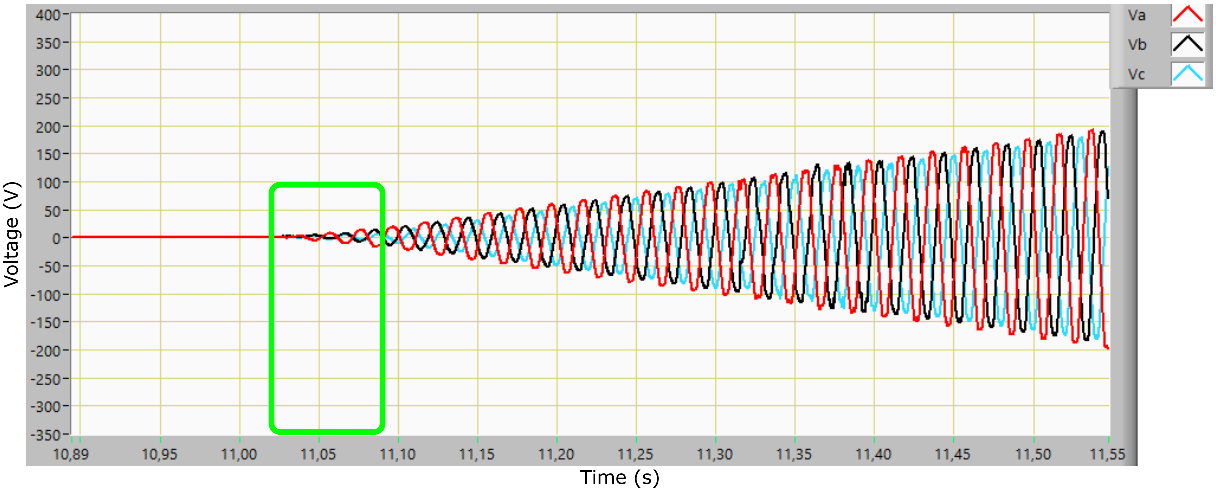


Figure 5.10: Microgrid forming the local grid.

Chapter 6

Conclusions

The installation and commissioning of a smart microgrid in the Silk House were presented in this work. The Silk House is a small museum dedicated to the dissemination of science. It is located in the center city of Bragança, Portugal. This project was carried out under the SilkHouse Project - Development of a smart microgrid based on renewable energy sources and a monitoring system for the House of Silk, funded by the Foundation for Science and Technology of Portugal. This project aims to transform the House of Silk in a self-sustainable museum, in annual average terms, and contribute to the dissemination of renewable sources and new technologies for future buildings in smart cities.

The smart microgrid is based on SMA technology for obtain the solution of a Flexible Storage System with battery-backup and increased self-consumption. The microgrid is comprised of renewable energy generation, loads, energy storage system, and energy management system. The generation is achieved with photovoltaic modules installed on the roof and pico-hydro system formed by a water wheel and a low head turbine both installed in a gallery of a former mill.

The Silk House smart microgrid was installed and commissioned, and is in full operation showing good results since the end of July 2019. However, the pico-hydro system is under implementation during the writing of this work. Thus, the evaluation of the microgrid operation was performed with only the photovoltaic generation installed.

Results for PV generation demonstrated the system's ability to meet the load demand and battery-bank charging. Over the months of the operation system, it was self-sufficient in average terms and capable to consume the energy generated on-site. A comparison of the consumption and energy bill between August and September 2018 to 2019 revealed significant savings after implementing the microgrid.

The energy management system was validated by photovoltaic generation analysis and energy balance. This management system was in a position to control the generation to meet the consumption demand. The control of generation is realized via the operation of active power control via frequency control of the photovoltaic inverters. Also, the system was capable to control the energy flow to the loads, battery-bank, and the requirement of no energy inject into the utility grid.

The system was tested and demonstrated the real operation of the microgrid. The frequency control was capable to control the generation of PV modules with the frequency variation. The separation of the microgrid from the utility grid was tested by the automatic transfer switch and was able to act during a grid failure.

Experimental tests and generation data further corroborate the expected results meeting the previous requirements. The microgrid was capable to be self-sustainable and it will be a showcase to disseminate to the society about renewable resources to generate energy integrated into smart microgrid for smart cities. The system was evaluated demonstrating reliability and able to effectively control the power flow.

6.1 Future work

The suggestions for future work are related to the objective of complete the implementation of the Silk House smart microgrid, as follows.

- Installation of the low head turbine, water wheel, and their PV inverter and micro-inverter, respectively. Also, install the Energy Meter and protection devices in the electrical panel;
- Pameterizate the PV inverter and the Energy Meter into the Sunny Portal;
- Evaluate the data generation and test the operation of the system with the pico-hydro system installed and commissioned.

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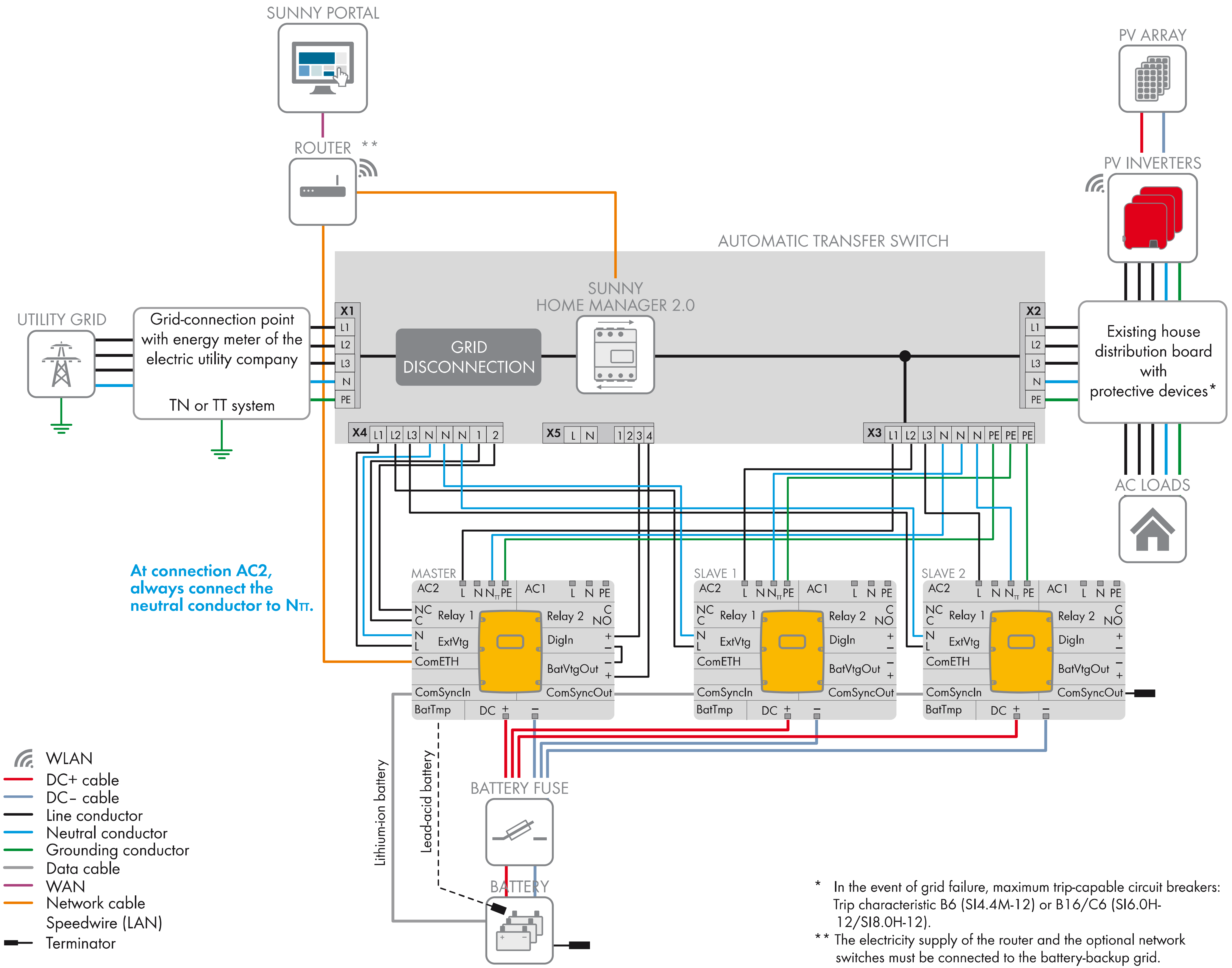
Appendix A

Circuity overview of the SMA microgrid



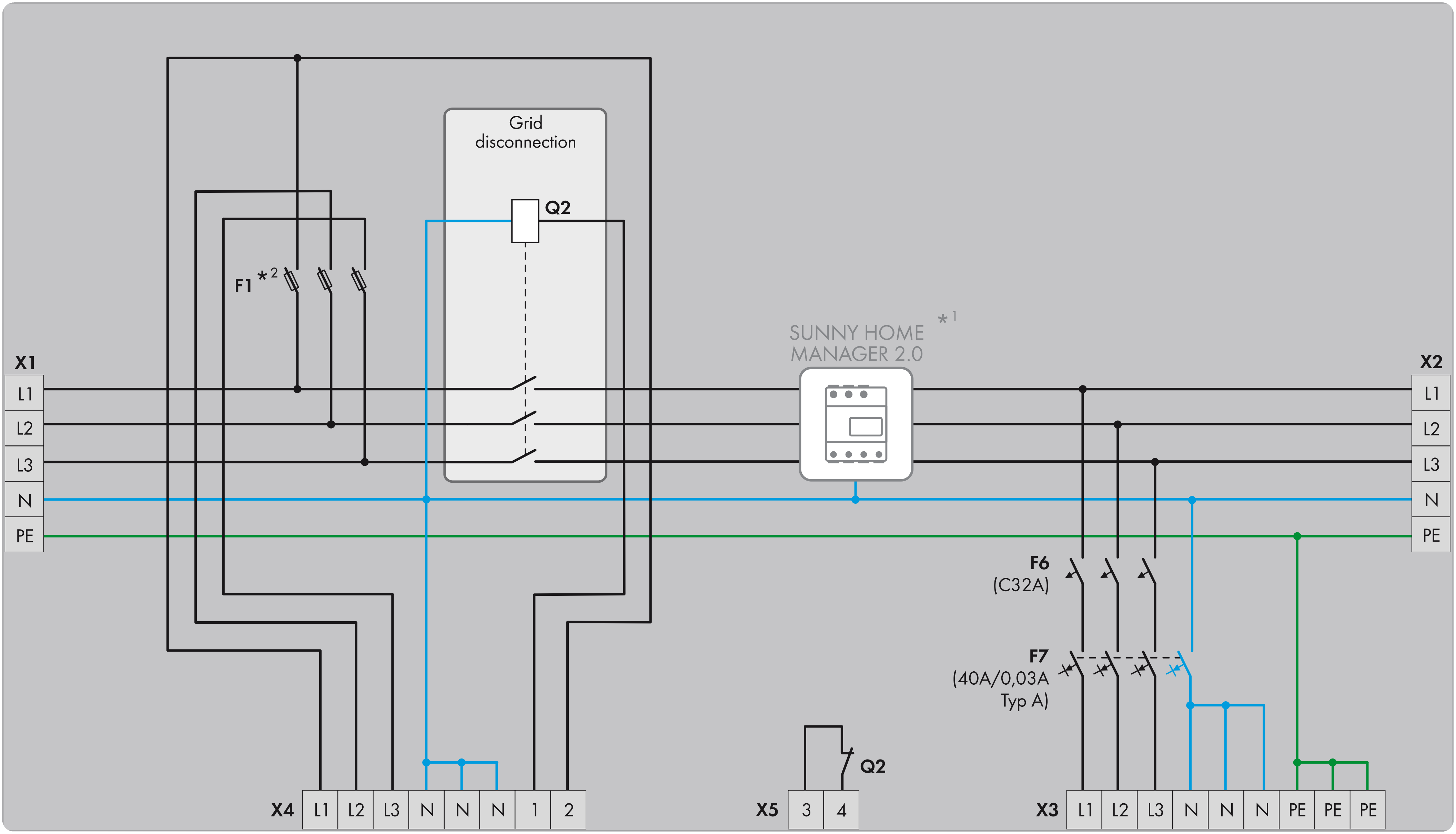
At connection AC2, always connect the neutral conductor to NTT.

* In the event of grid failure, maximum trip-capable circuit breakers: Trip characteristic B6 (SI4.4M-12) or B16/C6 (SI6.0H-12/SI8.0H-12).

** The electricity supply of the router and the optional network switches must be connected to the battery-backup grid.

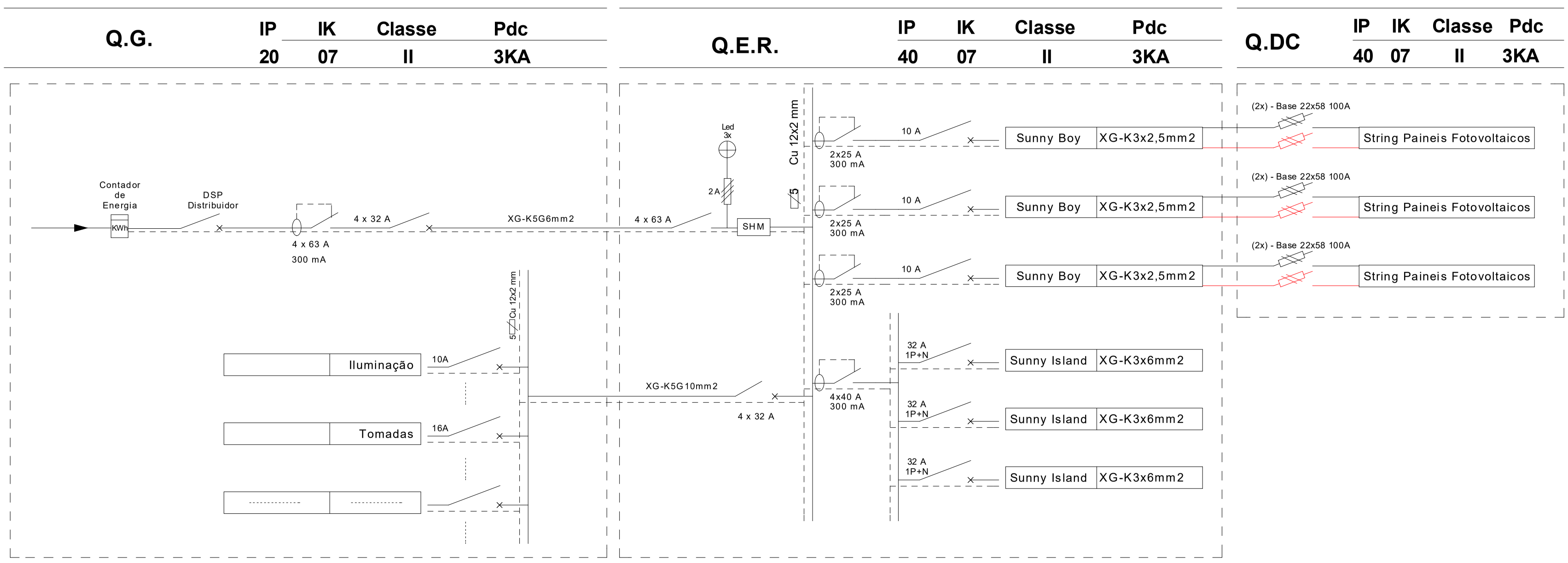
Appendix B

Schematic diagram of the three-phase automatic transfer switch


Grid
disconnection
Q2
F1 *2
SUNNY HOME MANAGER 2.0
*1
X1
L1
L2
L3
N
PE
X2
L1
L2
L3
N
PE
F6
(C32A)
F7
(40A/0,03A
Typ A)
Q2
X4
L1
L2
L3
N
N
N
1
2
X5
3
4
X3
L1
L2
L3
N
N
N
PE
PE
PE

Appendix C

Electrical Panel



Identificação:	**Data:**
Req: Instituto Politécnico de Bragança	Maio 2018
Local: Casa da Seda, Bragança	**Esc:**
Autor do Projecto: Helder Caseiro	**Processo:**

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GPS - 41°47'25.14"N - 6°46'44.94"W

Conteúdo:

QUADRO ELECTRICO

página nº:

01

Appendix D

Sunny Island parameters

Inversor 210#			
Number	**Name**	**Description**	**Value**
210#01	InvVtgNom	Nominal voltage of the Sunny Island inverter in V	230 V
210#02	InvFrqNom	Nominal frequency of the Sunny Island inverter in Hz (expert mode)	50 Hz
210#03	InvChrgCurMax	Maximum AC current during charging and discharging in A (expert mode)	14,3 A
Battery 220#			
221.01	BatTyp	Battery type	VRLA
221#02	BatCpyNom	Battery nominal capacity C10 in Ah	455 Ah
221#03	BatVtgNom	Battery bank nominal voltage in V	48 V
221#04	BatTmpMax	Maximum battery temperature in °C (expert mode)	40º C
221#05	BatTmpStr	Battery temperature as connection limit after overtemperature disconnection in °C (expert mode)	35ºC
Charge mode 222#			
222#01	BatChrgCurMax	Maximum battery charging current in A	35 A
222#02	AptTmBoost	Absorption time of the boost charge in minutes (expert mode)	180 min
222#03	AptTmFul	Absorption time for full charge in hours (expert mode)	6 h
222#04	AptTmEqu	Absorption time for equalization charge in hours (expert mode)	12 h
222#05	CycTmFul	Cycle time of full charge in days (expert mode)	14 days
222#06	CycTmEqu	Cycle time of equalization charge in days (expert mode)	90 days
222#07	ChrgVtgBoost	Setpoint of the cell voltage at boost charge in V (expert mode)	2,4 V
222#08	ChrgVtgFul	Cell voltage setpoint for full charge in V (expert mode)	2,5 V
222#09	ChrgVtgEqu	Cell voltage setpoint for equalization charge in V (expert mode)	2,55 V
222#10	ChrgVtgFlo	Cell voltage setpoint for float charge in V (expert mode)	2,25 V
221#11	BatTmpCps	Battery temperature compensation in mV/°C (expert mode)	4 mV/ºC
222#12	AutoEquChrgEna	Automatic equalization charge (expert mode)	Enable
222#13	BatChrgVtgMan	Manual setpoint of the battery charging voltage with disabled battery management in V (expert mode)	54 V
Current Sensor 225#			
225#01	BatCurSnsTyp	Type of battery current sensor	50 mV
225#03	BatCurGain50	Type 50mV in A/50mV	100 A/50mV
Grid Control 232#			
232#01	Country	Set country standard (protected by SMA Grid Guard)	VDE-AR-4105
SlfCsmpBackup #260			
General 261#			
261#01	SlfCsmpInEna	Increased self-consumption	Enable
261#02	SlfCsmpPosSel	Highest-yielding month for battery utilization range	North
261#03	Saisonenable	Seasonal operation (expert mode). Automatic adjustment of the battery depth of discharge: In seasons with fewer hours of sunlight, the electric discharge of the battery will be lower.	Yes
Battery Usage 262#			
262#01	ProtRecSOC	Lower limit of the deep-discharge protection range for disconnection (%) of the battery capacity (expert mode)	20%
262#02	BatResSOC	Minimum width of the deep-discharge protection range (%) of the battery capacity (expert mode)	30%

262#03	BUResSOC	Minimum width of the backup power supply range on the longest day of the year as a percentage of the battery capacity (expert mode)	10%
262#04	PVResSOC	Width of the range for the maintenance of the battery state of charge (%) of the nominal capacity (expert mode)	10%
262#05	MinSlfCsmpSOC	Minimum width of the self-consumption range on the shortest day of the year as a percentage of the battery capacity (expert mode)	30%

Appendix E

Article - 2nd Double Diploma Summer School & Symposium DD2019

IMPLEMENTAÇÃO DE MICRORREDE INTELIGENTE EM UM EDIFÍCIO DE DIVULGAÇÃO DE CIÊNCIA

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Resumo

O sistema elétrico vem passando por grandes transformações, no qual tem se integrado a rede elétrica novos sistemas descentralizados de produção de energia baseados em recursos renováveis e redes inteligentes, que abrangem comunicação e tecnologia de informação. Uma microrrede é uma abordagem alternativa para o fornecimento de energia em pequena escala, que interliga produção descentralizada, geralmente renovável/não convencional, com cargas elétricas em uma rede local [1]. As microrredes podem ser conectadas a rede pública (*on grid*), com a possibilidade de importar ou exportar energia, ou em modo ilha (*off grid*).

O presente trabalho apresenta a instalação e comissionamento de uma microrrede inteligente, a ser instalado em um edifício de divulgação de ciência. Este local é conhecido como “Casa da Seda” e pertence ao centro de Ciência Viva de Bragança/Portugal, e fica localizado na zona histórica do município.

O sistema a ser instalado está no âmbito do projeto Silk House, projeto este desenvolvido pelo IPB em parceria com a Câmara Municipal de Bragança, financiado pela Fundação de Ciência e Tecnologia de Portugal e que visa utilizar recursos endógenos identificados no local para produção de energia [2].

O intuito deste projeto é tornar o local energeticamente autossustentável em termos médios anuais após a implementação da microrrede, que possuirá inversores bidirecionais e fotovoltaicos, equipamento de gestão inteligente de energia, banco de baterias e a produção de energia será baseada nas fontes renováveis presentes no local, nomeadamente fotovoltaica e hídrica.

Após à implementação da microrrede inteligente, a Casa da Seda será capaz de produzir à energia demandada para o seu consumo utilizando de recursos renováveis presentes no local e gestão inteligente. Tornando assim, o espaço, um modelo real de disseminação dos benefícios deste tipo de solução.

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Appendix F

Article - Ibero-American Congress of Smart Cities (ICSC-CITIES 2019)

Implementation of a smart microgrid in a small museum: the Silk House

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Abstract. Microgrids are an alternative approach for the supply of energy integrating decentralized power sources, electrical loads, energy storage, and management in a local grid. The system has the capability of power control and energy management using communications' network between all devices, and is known as smart microgrid. This paper presents the implementation of an smart microgrid in the Silk House, a museum dedicated to dissemination of science located in Bragança, Portugal. It was funded by the Foundation for Science and Technology of Portugal under the SilkHouse Project. The goal is to transform the House of Silk in a self-sustainable museum contributing to the dissemination of renewable sources and new technologies for future buildings in smart cities. This work presents the context and requirements for the microgrid and describes the implementation of the renewable sources (photovoltaic and pico-hydro) and the SMA Flexible Storage System based on Sunny Island and Sunny Home Manager. This work also presents and analysis the first operating results since the start of operation at the end of July 2019.

Keywords: Microgrids · Renewable sources · Energy management.

1 Introduction

The worldwide need for more electricity results in a demand that grew at a rate of 2.9% in 2018, which is supplied by fossil fuels [1] [2]. Despite this growth, the use of fossil fuels has been debated continuously, nowadays, for its consequences, such as 2% carbon emissions growth - the highest in seven years [1]. Environmental concerns related to these issues have been changing the behavior on the use of energy sources, which is increasingly adopting the use of renewable sources to generate electricity and supply the growing demand. Renewable sources lead to an increase in world power generation, with the growth of 14.5% [1].

The main primary sources of renewable energy, among the many available, are solar, wind, and hydro. The distributed generation of this energy brings environmental, technical, and economic benefits to the consumers and the distributions systems. Microgrids are a recent concept for the integration of renewable sources in the power grid.

A microgrid and the conventional distribution power system have basic differences [3]. The first has smaller generation capacity of the sources, the generated power is directly injected to the grid, and the sources are closer to the consumers. The concept of microgrid has several descriptions in the literature, but there is not a specific one adopted. In [3], a microgrid is essentially described as an active distribution network, because integrates distributed generation and different loads at the distribution voltage level. In [4] microgrid is described as an interconnected system of loads and a local generation that can operate independently of the power grid (off-grid) or is tied to it (on-grid). In short, microgrid is a distributed generation network, integrating renewable sources (or not), connected to loads (which are usually close to each other), with energy storage capacity, and with a management system (with higher or lower intelligence level), that can supply the electrical demand of a house, a building or a region. It may (or not) be connected to the conventional grid.

This paper presents the implementation of a smart microgrid in a small museum called Silk House. The microgrid integrates renewable sources, energy storage, and management system. It is connected to the main grid as an additional external source. The project aims to ensure the self-sustainability of the museum, in annual average terms. It will also be a showcase to spread to the society the use of local resources to produce renewable energy and the new technologies of microgrids for smart cities. The microgrid was installed, commissioned, tested, and is being monitored. The first results of its operation are shown and analyzed in this work.

2 Silk House

Silk House is part of the *Centro de Ciência Viva*, located in Bragança, in the north-eastern of Portugal. This place was used for dyeing silk in the 18th century and sometime later, during the 19th and 20th centuries was used as a mill. The Municipality of Bragança acquired the building in 1990 and restored it in 2006, maintaining the original constructive characteristics [5].

Nowadays, the place is a museum dedicated to the history of silk, with a permanent exhibit about it and to the dissemination of science, receiving about 11500 visitors per year. Exhibitions, lectures, and courses about several themes are frequent on-site.

The building is located in the historical center of the city, next to the Fervença river and conserves the historical architecture built of original stones. It has three levels, two galleries on the basement at river level, and a roof with ceramic tiles.

Before implementing the microgrid, the building's three-phase electrical system (400 V, 50 Hz) was powered by the mains, with a contracted power of 13.8 kW. The electrical loads are, basically, computers, monitors, multimedia projectors, heaters, air-conditioning system, a stereo system, and lighting. The regular operation of the museum is from Tuesday to Sunday, from 10 a.m. to 6 p.m.. It closes on Mondays, but some essential loads remain powered. The average daily consumption is 45 kWh in normal working days, and the annual average is about 16000 kWh [5].

3 Previous microgrids developed

The SilkHouse Project - Development of a smart microgrid based on renewable energy sources and a monitoring system for the House of Silk - is promoted by the Polytechnic Institute of Bragança (IPB), in cooperation with four other partners: Bragança Ciência Viva Center, Cávado e Ave Polytechnic Institute, Guarda Polytechnic Institute and the company JG Instalações Elétricas. The project is funded by the European Union through the Foundation for Science and Technology, supported by the Municipality of Bragança.

The SilkHouse project development started in 2017 with the first conceptual design [6]. The microgrid design took into account the analysis of two places of the building for the energy potential: the roof and the original galleries used by the former mill. They revealed viability for renewable energy generation using endogenous resources: solar irradiance and water, respectively. The roof is used to generate photovoltaic (PV) energy. The water and galleries are used to generate hydropower taking advantage of the proximity of a small dam already available in Fervença river [5]. Thus, the Silk House was provided with a smart microgrid by integrating both energy sources and energy storage in a microgrid with a management system. The renewable sources and storage system were size considering the annual energy consumption of the building [7].

The project uses SMA technology and is based on the Sunny Island inverters and Sunny Home Manager. Previous experience, with a small microgrid held in a laboratory of the School of Technology and Management of the IPB, demonstrated the feasibility and flexibility of this technology [8] [9]. Based on these works and surveys aiming the application to the Silk House, it was designed the first schematic to the microgrid [6], as shown in Fig. 1. The following equipment composed the solution: three Sunny Island Inverters (SI), four Sunny Boy inverters (SB), one pico-hydro turbine, photovoltaic tiles, photovoltaic modules, battery bank, and an undefined control system [6].

The design was changed in a second phase. In fact, the use of PV tiles would be too expensive. On the other hand, tests achieved with 30 PV tiles (ZEP F10-U 9Wp) in the laboratory revealed the existence of shadow caused by the tiles themselves, in the morning and the afternoon [7]. Therefore, the project adopted high-efficiency PV modules instead of PV tiles.

Fig. 2 presents the second microgrid design composed by: three Sunny Island inverters, five Sunny Boy inverters, one Sunny Home Manager 2.0, twenty four 2 V batteries blocks to form a 48 V battery bank, eighteen PV modules, a water wheel for electricity generation, a pico-hydro turbine, electrical board with protections, and breaking devices [7].

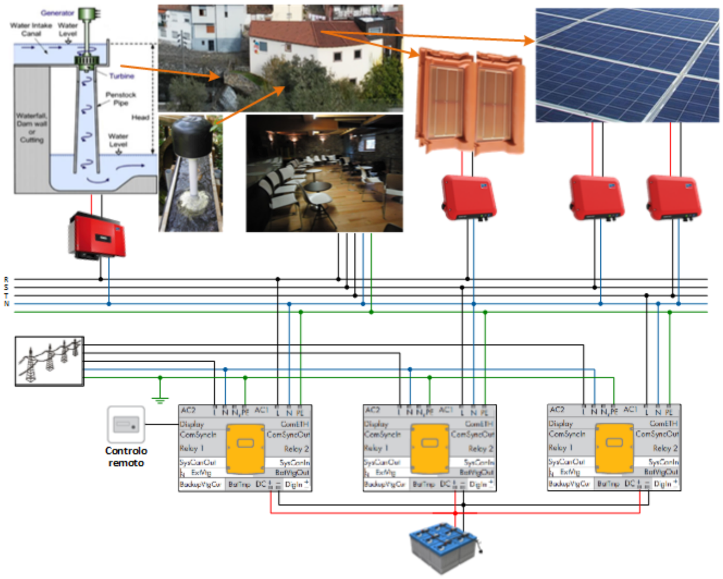

Fig. 1. First microgrid conceptual design [6].

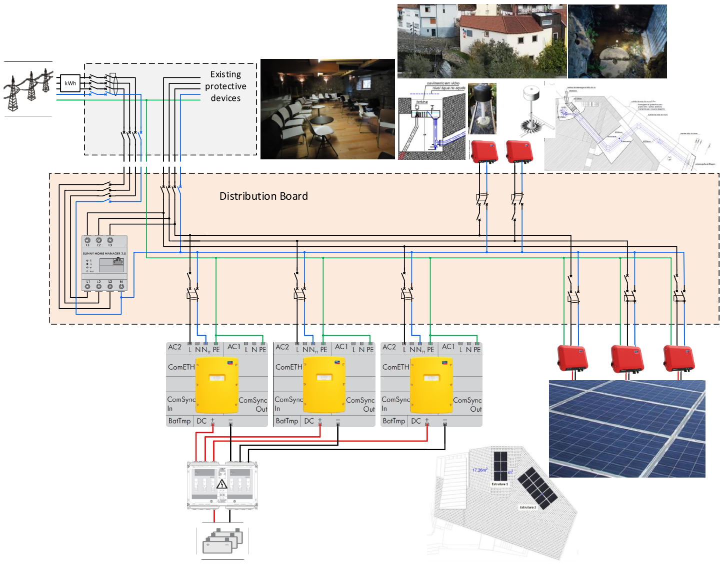

Fig. 2. Second microgrid conceptual design [7].

4 Microgrid implemented

The microgrid implemented in the House of Silk has some specific requirements considered during the project development. The first one is that the museum is supposed to be self-sustainable. In other words, in annual average terms, the energy produced by the renewable sources must be equal to the energy consumed. Second, the electric grid must be an external energy source, but the energy injected into it must be zero. Hence, a third requirement is the energy storage in order to improve the self-consumption and self-sufficiency quotas [7] [10]. Fourth, the generated energy from renewable sources - photovoltaic and pico-hydro - should use innovative solutions. Indeed, the pico-hydro embraces an innovative approach, which will use a PV inverter and a microinverter as the interface between turbines' generators and the microgrid [11] [12]. Fifth, power management and monitoring system are required since this project is intended to be a permanent activity of the museum aiming the dissemination of the new technologies of microgrids for smart cities.

4.1 Silk House microgrid

This section introduces the smart microgrid developed according to the above requirements. The microgrid integrates distributed generation (PV and pico-hydro), energy storage based on the battery bank, management, and monitoring system. It is three-phase (400 V, 50 Hz) microgrid to supply the House of Silk loads.

The smart microgrid is based on the SMA Flexible Storage System with battery-backup and increased of self-consumption [13]. It is composed by three Sunny Island 4.4M, three PV inverters Sunny Boy 1.5, one Sunny Home Manager 2.0, two SMA Energy Meter, three strings of six Panasonic's PV modules VBHN325SJ47, one 300 W horizontal water wheel to recover the historical heritage of the former mill, one low-head turbine (LH400 from PowerSpout), one PV microinverter, one PV inverter, a battery bank consisting of twenty four VRLA 2 V battery's blocks Sonnenschein's batteries A602/625 Solar, battery fuse, electrical panel, automatic transfer switch, and protections. Fig. 3 presents a circuity overview of the smart microgrid implemented in the House of Silk and Fig. 4 shows the Silk House building with the PV modules installed and the microgrid devices. It is in full operation with the PV generation. By the time this work was written, the low-head pico-hydro system was being installed, and the water wheel was under construction.

The operation of the microgrid can be described as follows. The three-phase microgrid is the external electric grid whenever it is available. If the case of grid failure, the microgrid is established by the three Sunny Island (SI) 4.4M connected in a master-slave configuration. An automatic transfer switch is responsible by the external grid connection or disconnection [13]. The energy generated by the PV strings is injected into the microgrid, distributing the power by the three phases using three Sunny Boy 1.5.

When the generation is higher than the consumption, the excess of energy is stored in the battery bank by the three bi-directional battery inverters, SI. These inverters use the batteries to control the power flow and, thus, to improve self-consumption [14]. The active power generated by the inverters connected to the PV strings is limited by frequency control [15], as better explained later.

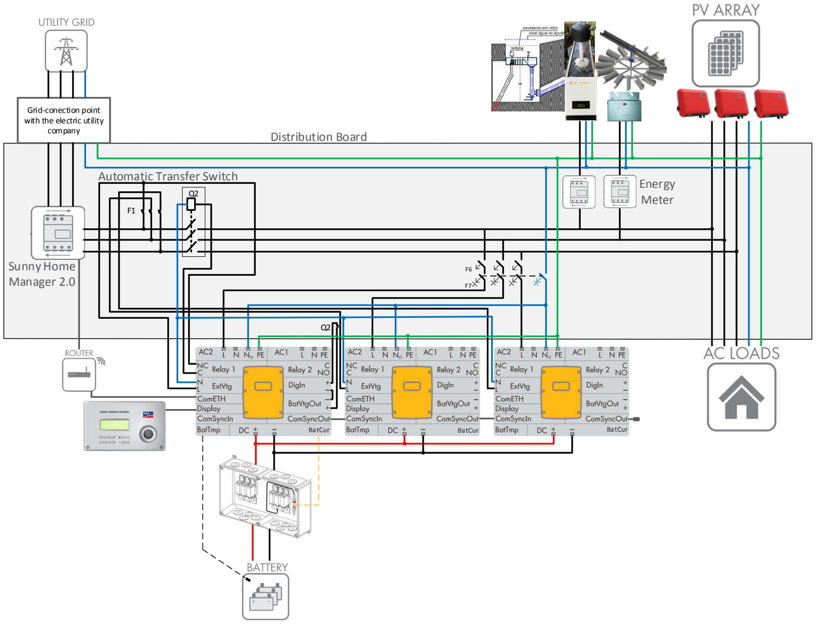

Fig. 3. Microgrid implemented in the Silk House.

Fig. 4. (a) Silk House, (b) Microgrid devices.

This happens whenever the generation is higher than consumption, the batteries are charged, and the energy fed into the external grid must be zero.

When the consumption is higher than the generation, the energy comes from the batteries and, if it is not enough, the remaining energy is purchased from the external grid to feed the loads. In case of grid failure, the microgrid is disconnected from the grid using the automatic transfer switch and starts working in stand-alone mode. In this operation mode, some hours of autonomy are available, but it strongly depends on the consumption, the generation, and the battery bank state of charge. In this case, some loads can be automatically disconnected.

4.2 Photovoltaic system

The photovoltaic system consists of three strings with six PV modules each and was installed on the roof with a slope of 12° and two shadowless areas. The first is oriented South and the second is oriented Southwest. Taking advantage of this, the PV strings were divided by these two roof surfaces to improve the distribution of PV generation throughout the day. One PV string is oriented South and the other two are oriented Southwest. In the morning, the Southern oriented string starts the generation before than the Southwestern oriented ones, allowing a higher production. In the afternoon, the Southwestern oriented strings will extend their generation longer. These orientations make possible to improve the distribution of photovoltaic generation throughout the day, adjusting it to the opening hours of the museum.

The modules chosen are from Panasonic, model VBHN325SJ47, series HIT with 19.7% efficiency [16]. The maximum power (P_{max}) is 325 W, and the maximum total to the system is 5.85 kW. Each string is connected to a SMA Sunny Boy 1.5-1 VL 40 (SB) PV inverter [17] which, in turn, is connected to one of three phases (L1, L2, L3). This inverter is compatible with the active output power control by the microgrid frequency control, as explained later.

4.3 Pico-hydro system

The Silk House electric generation will be complemented, mainly in the winter periods, by two pico-hydro systems that are being installed. These systems are small-scale hydropower generation units up to 5 kW that converts the power of flowing water of a canal, river or stream in electricity [18]. These low power systems, but capable of producing energy 24 hours a day, unlike what happened until a few years ago, it is possible to use permanent magnet synchronous generators, with variable speed, depending on the flow rate and head [19] [20]. This happens because innovative results show that the energy produced can be harnessed using PV inverters, flexibly, and efficiently [19] [20]. Furthermore, those generators and PV string inverters and micro-inverters are, nowadays, off-the-shelf and widely available components used in wind and photovoltaic applications.

The installation of the hydroelectric plant results from the proximity of the Silk House of the river Fervença, the existence of a small dam (less than 10 m) and the hydraulic infrastructure of the old mill, channels, and galleries, which has been conserved. On the one hand, the adopted solution preserves the building's architecture and, on the other, it recovers the building's historical heritage by installing a horizontal water wheel to produce energy in place of the former mill [7]. There are two galleries available. The first, at the upper level, was used to install the microgrid equipment. The other, where the mill was located, a 300 W horizontal water wheel and a 1.2 kW low-head turbine (LH400 from PowerSpout) are being installed. Two pipes were installed to capture water from the small dam and take it inside the gallery where the water wheel and turbine will be. The water is returned to the river 18 m downstream.

A PV microinverter from GWL Power [21] and a PV string inverter from Omnik, model Omniksol - 1.5k - TL2 [22], are used to connect the 300 W generator of the water wheel and the 1.2 kW generator of the low-head turbine to the microgrid, respectively. After extensive tests in the laboratory, the results show that the inverters presenting the best performance are not from SMA. Because of this, SMA Energy Meters must be used in order to account the energy produced by these renewable resources in microgrid energy management.

4.4 Microgrid power management

A smart system requires high-level control and a suitable communications' network. SMA technology has monitoring of the energy generated and also controls and regulates all the microgrid through a digital interface using the Internet portal Sunny Portal. The infrastructure should contain devices sharing the communications' network to turn the microgrid in a smart microgrid, being integrated into intelligent energy management.

SMA's devices have an integrated technology called Speedwire, which enables communication among each device used. It is a wired Ethernet communication for networks used in decentralized power generation, with a communication protocol optimized for PV systems [23]. The devices in this microgrid are connected to an Ethernet switch by UTP cables, which allows having Speedwire communication.

The Sunny Home Manager 2.0 (SHM) acts as a centralized energy manager in households with a PV system for self-consumption [24]. It receives data from other devices, as Sunny Boy and Sunny Island inverters and offers some functions which allow taking decisions about the microgrid.

The SHM carries out some important tasks [10], such as data collection of energy and power measured, energy monitoring via Sunny Portal presenting energy flows, energy management, dynamic limiting of the active power feed-in and support to self-consumption increase and its optimization.

The power management occurs when some decision of the microgrid is taken to control the generated energy. The SHM is capable of doing this and measuring the loads at the grid-connection point. This measure is presented in Sunny Portal, which also allows visualizing instantaneous data of the PV generation received via the integrated measuring device of the SB, the battery bank status connected to the SIs, and others SMA Flexible Storage System's devices connected to the local network.

An important parametrization of the microgrid is the limitation of active power supplied to the utility grid. This limit was set in 0 W (Zero Export), which means that the smart microgrid can not provide the generated energy to the utility grid and all the power should be stored or consumed by the microgrid loads (self-consumption system) [10].

When the generation is larger than the loads' consumption, efficient management is required of the microgrid power flow. The first step is to inject the excess power into the battery bank. If it is fully charged, the SI detects this situation and increases the frequency of the microgrid in order to limit the output power the SB inverters. The control strategy adopted by SMA called "frequency-dependent control of active power" to limit the power generated whenever it is excessive. The SI increases the frequency of the microgrid above the nominal value (50 Hz). The PV inverter must be compatible with this control. In this case, when they feel the frequency increase, they start to reduce the active output power out. If the frequency continues to increase, PV inverters further reduce its active power nearly to 0 W, as shown in Fig. 5. The SB inverters continue to monitor the frequency. When it decreases, they start increasing their active power linearly to the available value [25]. Fig. 5 shows the active power control by frequency, and Table 1 shows an example of this frequency control.

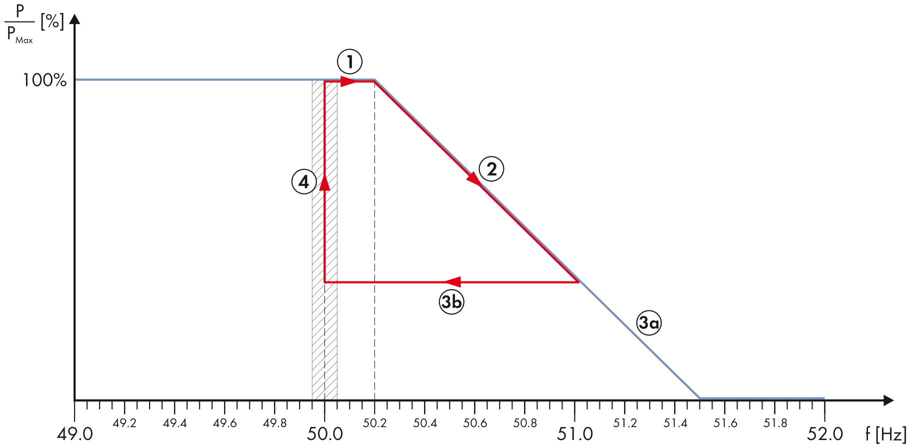

Fig. 5. Control of active power by frequency control [25].

Table 1. Example of the frequency values for the each positions in control of active power by frequency in Fig. 5.

Position	Stage	Frequency (Hz)
1	Normal operation	<50.2
2	Active power decreases linearly from maximum available power	>50.2
3a	Active power continues to decrease linearly up to 0 W	51.5>Freq.>50.2
3b	Frequency remains constant or returns to the nominal value PV inverter stops reducing active power	<51.5
4	Active power increases up to maximum available power	50.05

5 Analysis of operation

This section presents the first results obtained immediately following the implementation and commissioning of the microgrid in the Silk House. Now, it is possible to see the microgrid operation by analyzing several data and graphics obtained via Sunny Portal. The smart microgrid with PV generation is in operation since the end of July. The operation with pico-hydro generation will be available during the next months, once it is being installed.

Fig. 6 shows an energy balance, the temporal progress during the August 8^{th}, 2019. The consumption graph shows when and from which sources the microgrid has been supplied with energy (photovoltaic, battery bank or utility grid). The generation graph shows when and how much energy was generated and how much is used for (direct consumption, battery charging, or greed feed-in).

On August 8^{th}, 2019, the self-consumption rate was 100%, shown in Fig. 6, which means that all the energy generated was used on-site (for loads and battery-bank charging) and not fed into the utility grid as expected considering the requirements of this microgrid [26]. However, it should be noted that if the system allowed to feed into the utility grid, the self-consumption rate would be about 50 - 60% for this microgrid [7]. Direct consumption, which was 79%, corresponds to photovoltaic energy used directly in the loads. A minimum feed into the utility grid is inevitable and was 0.9 kWh feed-in. Table 2 presents some relevant data about the energy balance demonstrating the real operation of the microgrid on that day.

Table 2. Energy balance data of August 8^{th}, 2019.

Balance	Energy (kWh)
Daily consumption	19.31
Daily yield	22.17
External Energy supply	0.09
Internal power supply	19.22
Battery discharging	1.60
Battery charging	4.60
Direct consumption	17.62
Self-consumption	22.11

Fig. 7 shows the production diagram of the three PV strings connected to the microgrid. It shows that the way they were installed, with different orientations, even though small, allows distributing better the energy generated throughout the day. It is worth mentioning this is important when the excess of power should be immediately consumed or stored, not supplied to the utility grid. The curves of SBs 2 and 3 show the PV generation prolongation between 6 p.m to 8 p.m., while the SB 1 generation is higher around 9 a.m.. During the rest of the day, the generation was the same to the three SB, i.e., PV strings.

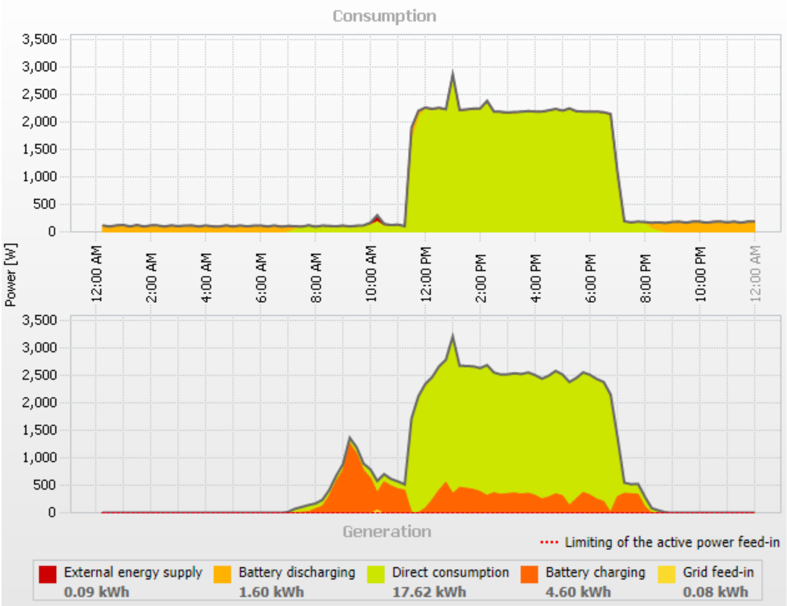

Fig. 6. Energy balance of August 8th, 2019.

In addition, the operation of active power control adopted by the frequency of the microgrid is also evident, as the maximum power generation was not achieved. This was because of the fact that consumption was lower than an electric generation.

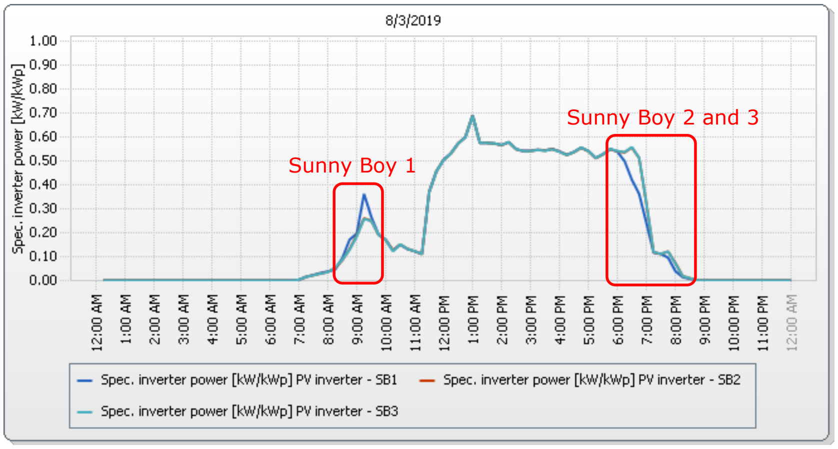

Fig. 7. Photovoltaic generation analysis of August 8th, 2019.

Fig. 8 shows PV generation during the week of August 2 - 8, 2019. On Mondays, the museum is closed and therefore has less consumption. This is visible on the curve of August 5th, during which production was the lowest. That week, the three PV strings produced 255 kWh. It is worth remembering that PV generation depends on the consumption of the loads, and energy stored, and not just on the available solar radiation. This results from the control of the active power generated by frequency control, as there is no energy supplied to the utility grid.

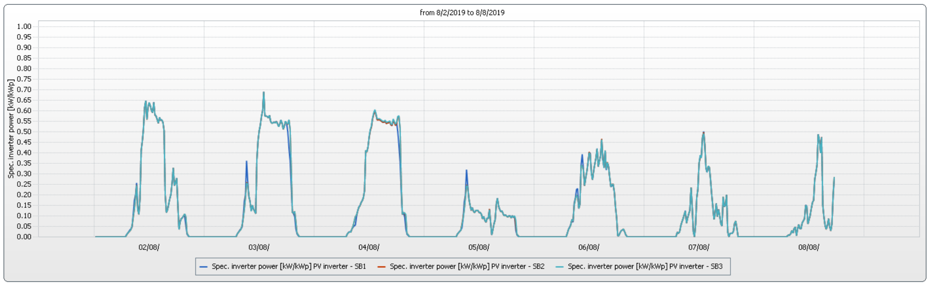

Fig. 8. Photovoltaic generation analysis during the week August 2 - 8, 2019.

An interesting data also available are the 174 kg avoided CO_2 during two weeks of operation. This information represents an avoided value of gas emissions into the atmosphere, given the operation of this building.

6 Conclusions

A smart microgrid was installed and commissioned in the Silk House. The Silk House of the Bragança Ciência Viva Center is a small museum dedicated to science dissemination located in Bragança, Portugal. It was carried out under the project SilkHouse funded by the Foundation of Science and Technology. This project aims to transform the House of Silk in a self-sustainable museum, in annual average terms, and contribute to the dissemination of renewable sources and new technologies for future buildings in smart cities.

The microgrid is based on SMA Flexible Storage System with battery-backup and increased self-consumption. The global system includes renewable energy generation, energy storage in a battery bank, energy consumption by the Silk House loads, power and energy management, and monitoring. The generation is obtained from local renewable resources: solar photovoltaic and pico-hydro, taking advantage of Fervença river and a small dam less than 10 m away. Pico-hydro systems are small-scale power plants (less than 5 kW). In the Silk House, they are a 300 W horizontal water wheel (to recover the historical heritage of a former mill) and a 1.2 kW low-head propeller turbine. These small plants are to be finished in the next months, and the rest of the microgrid was installed and commissioned and is in full operation since the end of July 2019. The microgrid is connected to the utility grid as an external source but not for power injection. This paper presented the microgrid implementation and analyzed the first results of its operation

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