

UNIVERSITÀ
DI PAVIA

UNIVERSITY OF PAVIA
FACULTY OF ENGINEERING
DEPARTMENT OF ELECTRICAL, COMPUTER AND BIOMEDICAL ENGINEERING

MASTER'S DEGREE IN ELECTRICAL ENGINEERING

MASTER THESIS

KEY PERFORMANCE INDICATORS SUPPORTING THE OPTIMAL DESIGN AND MANAGEMENT OF RESILIENT ISLANDED MICROGRIDS

Indicatori Chiave di Prestazione a Supporto della Progettazione e Gestione Ottimale di Microreti Resilienti in Isola

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Academic year 2025/2026

Abstract

In the context of action against climate change and decarbonization of the energy system, microgrids have proven to be a powerful tool to enhance the diffusion of distributed energy sources thanks to their close local control, which allows them to tackle the intrinsic technical challenges of renewable generation that endanger the power quality of the system. In particular, islanded microgrids have their strength in allowing the continuity of the energy supply regardless of the national grid conditions. The quality of resilience, in fact, has become increasingly more valuable due to the increasing frequency of extreme high-impact natural events. However, resilience is still lacking a normative definition and many studies do not directly consider it in the initial design of the microgrid. The writing of a Decision Support Software (DSS) code aims to provide different design solutions described through the aid of Key Performance Indicators (KPI) that are able to embed the different quality of sustainability, resilience, and economic investment. The graphical display of the various design results in a single graph allows the designer to carry out a sensitivity analysis of the design parameters taken into consideration, which may lead them to choose a design solution that they were not originally considering, determining a more responsible use of resources.

Keywords: Islanded Microgrids, Optimal Microgrid Design, Resilience, Decision Support, Key Performance Indicators.

Abstract

Per contrastare il cambiamento climatico e promuovere la decarbonizzazione del sistema energetico, le microreti si sono dimostrate un valido strumento per allargare la diffusione della generazione distribuita, grazie alle loro tecnologie di controllo locale che permettono una più facile gestione delle problematiche tecniche legate alle fonti di energia rinnovabile che minano alla qualità dell'energia del sistema elettrico. In particolare le microreti ad isola sono caratterizzate dalla loro capacità di continuare ad alimentare i carichi indipendentemente dalle condizioni della rete elettrica nazionale. La loro resilienza, infatti, si sta dimostrando una qualità sempre più rilevante a causa dei più frequenti disastri naturali. Nonostante questo, la resilienza manca ancora di una definizione normativa e molti studi tendono ad escluderla nella progettazione iniziale di microreti. La stesura di un software per supportare l'analisi decisionale (DSS) ha come scopo quello di mostrare diverse soluzioni di progettazione, descritte da indicatori chiave di prestazione (KPI) che integrano in loro stessi le diverse caratteristiche di sostenibilità, resilienza e investimento economico. La rappresentazione grafica delle diverse soluzioni in un singolo grafico permette al progettista di sviluppare un'analisi di sensibilità sui parametri presi in considerazione nella progettazione, che può portare l'utente alla scelta di un progetto inizialmente ritenuto non ottimale, determinando un uso più responsabile delle risorse a disposizione.

Parole Chiave: Microreti in isola, Progettazione ottimale di microreti, resilienza, Supporto all'analisi decisionale, Indicatori chiave di prestazione.

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Introduction

In the fight against climate change and in contrast to its inevitable evolution, the energy sector has an important role to play. The integration of Renewable Energy into the generation mix of electrical power systems is one of the key actions needed for decarbonization. However, this is not an easy task since the increase of renewable generation sources brings with it a series of technical, economical, and environmental challenges that need to be effectively tackled to allow their best contribution to the electrical system. In fact, their characteristics of non programmability and of fluctuation in the production make them very difficult to allow for a reliable supply of energy; they require the aid of proper tools and control strategies. In this regard, distributed generation sources are proven to be a valuable asset in the integration of renewable energy into the power system because of their intrinsic characteristic of having a closer proximity between demand and production, allowing for limited electrical losses. Their small scale allows for a closer management and a better control of energy flows, with all the technical issues related to that, bringing an optimization in the resources implemented. Furthermore, distributed generation sources can avoid the most violent environmental impact of ordinary renewable power plants thanks to their reduced soil consumption. A clear example of that is the implementation of multiple residential photovoltaic power plants on the roofs of buildings, rather than in open fields, lowering the environmental impact they are born to contrast.

These concepts have led to the rise of energy communities and microgrids. The first have their benefits on the shared production between small prosumers, i.e. entities that consume but also generate energy, for example with residential photovoltaic power plants, while microgrids are local electrical power systems that are able to work even without the connection to the main grid. An islanded microgrid is a microgrid

that, for whatever reason, is operating disconnected from the main grid, in what is called islanded mode. Exactly on this last characteristic lies the main strength of a microgrid: the resilience. Resilience is the ability of the microgrid to withstand blackouts from the outer distribution network by continuing to supply its load with its own generation sources, without the aid of the national grid. This quality is even more vital in the case of standalone microgrids, so the ones that completely lack the connection to the outer network. The electrical grid blackout risk has increased recently due to aging infrastructure, the rise of electricity demand, transmission congestion, equipment failures, renewable-energy variability, and climate-related extreme events such as storms, heatwaves, droughts, wildfires and severe winter conditions, which even in the case of short-duration outages can cause economic losses, operational disruption, and safety concerns. For these reasons, the resilience of microgrids has become a valuable asset to avoid these damages, making it essential to consider the role of reliable supply directly in the design of these electrical systems[1].

Although resilience is one of the core capabilities needed by a microgrid, there is a lack of studies that consider it from the beginning as an essential criterion for microgrid design. This is in part due to the lack of a normative definition of resilience. Many studies tackle this problem through management operations, prioritizing specific loads in case of insufficient generation, through control techniques, and the reorganization of the grid configuration. Our proposal of resilience goes beyond that. Although we implemented a way of considering, right at the start of the microgrid design, the priority of the most critical loads, we took into account also the duration of the emergency state, allowing the microgrid operation to survive for a defined amount of time. To better underline this concept, let us consider, for example, one of the most common implementations of a microgrid: a hospital. In the event of a grid blackout, we must continue to supply life-saving equipment inside the building. We do not know the duration of the blackout, but our aim is to supply those critical loads for the entire duration of it. Although blackouts usually do not have a long restoration time, generally a couple of hours, we must be ready even for unusual situations, such as the recent experience of the 2025 Iberian Peninsula Blackout that lasted up to ten hours, causing many damages, including civilian injuries and deaths. To correctly enhance

the resilience of islanded microgrids we must consider also long duration interruption and the extreme event of completely lacking generation to fulfill the demand of the microgrid costumers. In order to do so we must be equipped with the sufficient storage unit capacities. On the days of autonomy that the battery storage can sustain, we will base our definition of resilience. In particular, we will consider a battery storage unit that is able to supply the prescribed percentage of critical load for the number of days of autonomy needed.

Usually, having defined the battery storage unit on those parameters, we find vary large battery capacities that are generally underutilized in the normal operation of the microgrid, since those quantities are merely prescribed for the emergency state, to allow the required level of resilience. However, these large battery capacities tend to determine a very high investment. The designer of a microgrid, therefore, must face a difficult decision. The qualities of resilience, economic investment, and sustainable operation are usually opposing each other, and prioritizing one might inevitably damage the other. The designer must look for the best trade-off between these features that allows them to reach the best operation of their microgrid, fulfilling the customers specific needs. Since there is always a trade-off between these main qualities of a microgrid, the optimal solution for a designer might not be the best one for the designer who prioritizes a different feature. Generally most common commercial tools prioritize the minimization of the economic investment, without any consideration regarding the sustainability and resilience of the microgrid. The purpose of the thesis work was to provide the designer with a tool that could integrate all the definitions of the different qualities in its microgrid design solutions description, helping the designer see what a particular design entails with respect to each one of the previous aspects. In order to help in the decision process we will base the description of the microgrid operational behavior on key performance indicators (KPI). These KPI are conceived to integrate in themselves the different qualities of economic investment, sustainability, and resilience of the design solutions we want to study, in order to give a direct response regarding the microgrid design collocation with respect to those specific features. They will help the designer in the comparison between different microgrid designs, quickly showing what each of them entails for the quality that is taken into consideration in that

moment.

The thesis project work then consists in writing a MATLAB code that focuses on the study of multiple design combinations and their description through the aid of KPI. Providing an array of possible design solutions, and not merely a single one that strictly follows one single criterion, will help the designer to carry out a sensitivity analysis regarding the different designs that will help them in finding the one that is ultimately able to satisfy each desired requirements. This work will answer the need for a tool that is able to study different design criteria in the choice of the optimal microgrid design, letting the users themselves decide which one actually follows the required qualities on their specific prescribed level. For this reason, we will refer to the code as Decision Support Software (DSS) code. The different designs that will be studied by the code are made up with different combination of sizes of the photovoltaic power plant and the battery storage capacity. To define these quantities the code will ask the user to select different values for three different design parameters regarding general high-level aspects of the system, which the code will use to automatically calculate the sizes of the different units. The chosen design parameters that will determine the size of the battery storage system are the days of autonomy of the battery and the percentage of critical load that the battery will sustain the state of emergency, so in the absence of any generation; while for the size of the installed peak photovoltaic power, the user is required to insert the months from which we will extract the average daily irradiance value. On the irradiance data the peak power installed will be calculated by imposing the supply of a percentage of the maximum load defined by the user. For each design combinations the code will run the optimization of the microgrid operation for a typical day of each month, adding up to describe one year of operation. The scope of the optimization, based on a Mixed Integer Linear Programming algorithm, is to minimize the consumption of yearly liters of fossil fuel used for the fossil fuel generators, increasing the energy independence of the microgrid and decreasing the CO_2 emissions and the cost of fuel purchase. At the end of the optimization the code shows several graphs that will exhibit some selected KPIs. On the same graphs the code portrays the values of the selected KPI for all the microgrid design combinations studied. With the aid of these graphs the designer can better compare the different

design combinations on the base of the KPI they entailed. This operation will allow the designer to elaborate a form of sensitivity analysis that might lead them to choose a design solution that they were not initially considering.

The thesis is organized in four chapters that aim to describe the main passages that have led to the writing of the DSS code and its results when applied to a real life scenario. The topics covered in each chapter are:

- **Chapter 1:** State of the Art analyzes the present solutions in the literature regarding the core aspects at the base of the thesis project, from the indispensable role of reliability and resilience in islanded microgrids, the optimization of microgrid operation and design, the necessity of the battery storage system, with its proprieties and its sizing choices, to the comparison of the most common commercial software Xendee and Homer, highlighting their output choices, both from the indicators point of view and from their graphical representations, their limits, and how the DSS code aims to overcome them.

- **Chapter 2:** Critical Load Evaluation Code regards the explanation of another MATLAB code born to flank the user in the input of the data regarding the difficult definition of critical load percentage on the overall load demand in the DSS code. This code, in fact, is based on the definition of a load priority, which is set by the user, and it is able to calculate the most probable percentage of load remaining after the evaluation of the grid layout consequent to a fault on a feeder. It iterates through all the feeders composing the grid, providing each time the percentage of load that is still supplied, following the order set by their priority, after a fault happens on that feeder.

- **Chapter 3:** DSS Code explains the structure of the code, guiding the user in how to input the data needed, and presenting how the code works, how it bases its design choices regarding peak photovoltaic power to be installed and the battery capacity, paying particular attention on the depiction of results, explaining the chosen KPI and their graphical representation. In particular, in this chapter we also find the explanation of another MATLAB code, the Rainflow code that is used to calculate the useful life time of the battery storage, an information that

could provide additional insights for the business plan of the project.

- **Chapter 4:** Case Study regards the real life application of the DSS code on the Kamal Adwan Hospital in Gaza, where the load data are known thanks to the report of the United Nations Development Programme (UNDP) on the Solar Electrification of the Health System in the Gaza Strip[2]. It focuses on the input of the specific data, the analysis of the results, and the possible interpretation that a designer could give to them, providing a sensitivity analysis of the results.

Chapter 1

State of the Art

Microgrids are becoming more and more popular nowadays thanks to their new asset of distributing energy, which is able to guarantee an improved service, with respect to the traditional distribution system that usually operates on a national scale. This is mainly due to their design. The design of a microgrid, in fact, is born to be strictly connected to the demand to be covered, in all its peculiarities and needs. A microgrid is described as a network which interconnects loads under a restricted geographical zone, therefore not too far from each other, such as a neighborhood or a small community. Thinking about a microgrid we imagine a small network in which the users under it produce the energy they need, through distributed or centralized sources that are directly owned by the community itself. For a series of reasons, the implementation of microgrids represents a more sustainable way of energy production and distribution, but it can also enhance a sense of community between its customers, making them more responsible about their consumption and therefore leading to a great benefit from the reduction of waste point of view. In particular, this effect could be even increased through a communication network interconnected with the microgrid one, responsible for the sensing and monitoring of its functions, that makes the customers aware of their own consumption. The relevance of microgrids is heavily supported by the growing popularity of distributed renewable energy sources. Renewable Energy Resources (RERs) are characterized by unpredictability and non programmable operation, making them not sufficient to guarantee a continuous supply of energy without the appropriate devices that can substitute them, such as energy storage systems

or programmable generation sources like diesel generators. In the optic of climate change and of the necessity of the reduction of carbon emissions, we would prefer the implementation of completely renewable energy microgrids but unfortunately this entails much more difficult challenges. Because of the non-programmability of renewable generation sources, the continuous operation of microgrids could be severely impacted. We cannot rely entirely on the forecasting of renewable production, especially considering the amount of critical loads that we must cover at any given time, which is one of the main benefits of the microgrid implementation. Microgrids designed with a control feature focused on optimizing the share of energy between loads and energy storage systems allow a better use of resources, and consequently a lower use of fossil fuels, offering the perfect tool to integrate renewable energy sources and determining an overall reduction of CO_2 emissions to benefit the environment. Furthermore, microgrids allow a closer proximity between generation sources and loads, reducing losses due to transportation.

In addition to that, in the latest years the increasing request of reliability has become one of the biggest challenges in the energy distribution system. Reliability means the ability of a system to deliver electricity to customers within acceptable standards and in the quantities demanded[3]. The requirement of reliability has become of greatest importance in all our daily activities, but it is strictly fundamental for those institutions characterized by high priority, such as hospitals and airports. In fact, the resilience of microgrids is what makes them such an essential tool, that is to say, the ability of microgrids to provide power with the application of their own distributed energy sources, making them able to withstand disruptions caused by extreme events[4]. This ensures the continuity of supply and, therefore, a higher reliability of the system.

In the case of a blackout of the distribution network, high priority services cannot afford to be left without energy, and they need to rely on their own sources of generation. This is where islanded microgrid show their relevance. Islanded microgrids are able to maintain normal operation, continuously supplying all loads or at least a significant portion of them, defined as critical, even in the case of disconnection from the distribution system. In addition to the continuous balance between generation and demand, an islanded microgrid must simultaneously maintain voltage stability,

frequency regulation, and power quality within tight limits[3] to avoid damages to electronics components which are particularly sensible to these fluctuations of power. The equipments that constitute an islanded microgrid must be sufficiently advanced to provide all the power quality services that are intrinsic in large scale distribution networks due to the presence of big synchronous generators that maintain the inertia of the system, something that in small scale electrical systems like microgrids needs to heavily rely on power electronics, like grid forming inverters, to set the correct values of frequency and voltage in a AC microgrid. An islanded microgrid is also the preferable solution for rural areas in which it would be very difficult to install the infrastructures needed by the distribution system. In this case, we might also experience a difficult supply of fuels needed for the generators, so the possibility of having to rely only on renewable sources would be very high, making it indispensable to have an energy storage system. That is why storage systems can result in a powerful solution to avoid as much as possible the use of fossil fuels for combustion engine generators. The advantage of a completely renewable source-powered microgrid, in fact, lays also its energy independence from natural gas or fossil fuels, therefore not so dependent on geopolitical conflicts.

One of the biggest obstacles to the microgrid diffusion is their high capital cost. The prices for components such as battery storage have been slowly decreasing in recent years, but still the price for the protection devices and communication infrastructures needed for the microgrid operation is very high. Besides that, incentives that could enhance their diffusion are very often damaged by the abrupt change in government priorities. [5]

1.1 Microgrid Design Optimization Problem

Therefore, we can see how the optimization problem of a microgrid plays a pivotal role in its efficient operation and aim. The design regards not only the size of components but also the management of energy throughout the whole day of operation, finding the best solutions to fulfill our standards. The Energy Management System (EMS) of a microgrid is what deals with the management of the generation sources

and demand side by fulfilling system constraints, achieving sustainable, economical, and reliable operation of the microgrid[6]. In fact, the designer of a microgrid must take into consideration all the aspects concerning its implementation, operation, outcomes and future life, such as the work needed as maintenance of its devices, to provide for the best final use of the microgrid. In doing so, the designer must bend the design criteria of sustainability, economic investment, and reliability of operation, to the main goal they set. The concept of optimization of a microgrid is not the same for every use: a design solution might be considered the best when it determines a certain level or reliability regardless of the cost of installation, while for another designer the main priority may be the least impact on the environment. Usually these different scopes outline very different solutions, heavily impacting on each other. For example, a higher reliability based on enhancing the resilience of the system, might determine the need for more devices, more connections between feeders, bigger storage and generation, causing a higher investment cost; the same happens for the design chosen on the highest reduction of emissions, where the generation mainly comes from renewable sources, therefore, on the aid of storage. An Example of the effects that a specific optimization aim has on the features of the microgrid is shown in Figure 1.3. In this graph we see three possible scenarios, in scenario A we prioritize the minimum investment cost, which might lead to a reduction in the capacity of the battery storage and of the renewable generations installed, causing an higher use of diesel generators. Scenario B prioritizes reliability and to do so is willing to spend more, and implement a good quantity of renewable generation and battery storage as backup. Scenario C focuses on minimizing CO_2 emissions, installing large-power renewable sources and also big battery storage.

Generally, optimization approaches and algorithms found in the literature focus mainly on cost-optimization designs, and the other parameters of interest are shown only as consequences. This kind of optimization, though, overlooks all those benefit that come from a higher investment cost. This is particularly noticeable in the decision of the size of the battery storage system. The truth is that, as seen before, battery storage has a fundamental role in the design of a microgrid, not only for its cost but also for its functionality of load-leveling and time-shifting of renewable energy, so its

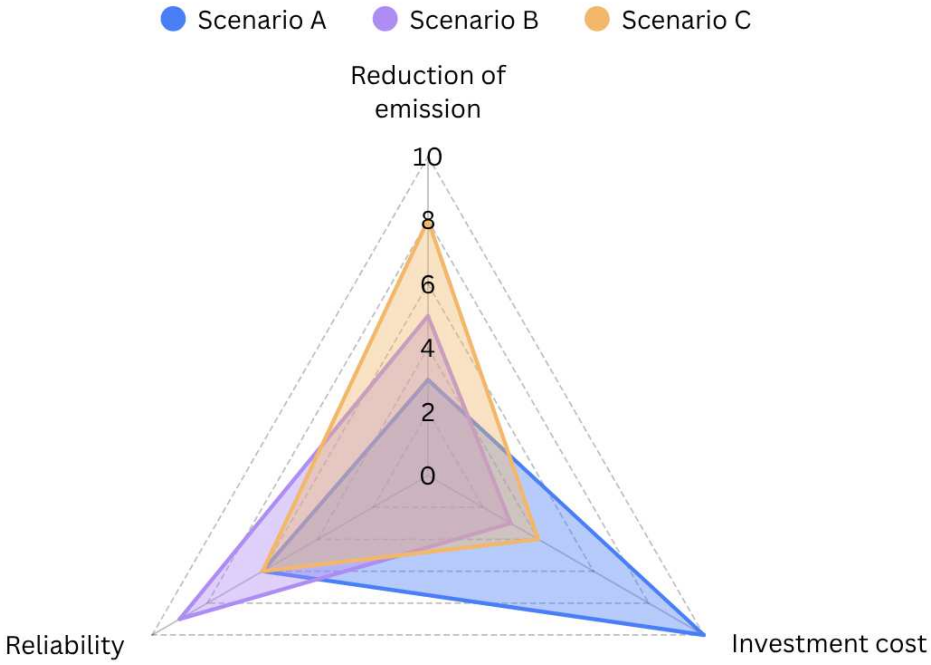


Figure 1.1: *Example of how prioritizing one aspect might affect the other two.*

size highly affects the outcomes, and the aim of our design could be heavily relying on that.

The role of battery storage is fundamental in the definition of the resilience of the microgrid. When an abrupt event comes, the microgrid must sustain its loads and if we apply that definition to an islanded microgrid particular attention must be paid to the limits of its generators. If an extreme event causes the complete lack of energy production, for example caused by the impossibility of fossil fuel delivery in remote areas following a flood or a landslide, and weather conditions that null the renewable generation, the only thing remaining is the energy stored in the battery storage system.

Regarding the resilience of microgrids we do not find many studies in literature that approach that aspect, especially centered on the initial design of islanded microgrids. Kexin et al. focused on the function of a microgrid as a backup system, due to its distributed generation, to the electrical power system and proposed a stochastic optimization with the aid of deep learning methods of the Microgrid Expansion Planning (MEP) based on the reduction of Greenhouse Gas emission and the enhancement of the power system resilience[4].

Another way of tackling resilience issues is through the management of priority of critical load during the microgrid operation. Ding et al. proposed a load restoration optimization based on a master-slave control with the aim of picking up critical load. The paper suggests that the distribution system could be divided, with sectionalizing switches, into microgrids that are able to supply the critical loads in that area, enhancing the overall system resilience[7], but still it gives no proper answer to the optimal sizing of the devices that should tackle the distribution of energy in the microgrid during an emergency state.

To enhance resilience of microgrid another possible solution that is under research is the interaction between different microgrids. This would enable peer to peer energy transactions that could help in balancing power and make for a more cost effective implementation of resources. This solution was studied by Xu et al. where they proposed a resilience-oriented planning method focused on the destructive impacts on clustered microgrids of extreme events[8]. However, also in this work we do not have any reference regarding the sizing of the devices that allow for the microgrid operation, but the study focuses only on the minimization of the annual total cost of the operation of the clustered microgrids.

Mathematical optimization applied to microgrids often falls under the category of Linear Programming (LP) algorithms, in all their variants, such as the case of Mixed Integer Linear Programming (MILP). That's because they provide an effective trade off between model flexibility and computational effort.However, Linear Programming is limited by its inability to capture discrete decisions and nonlinear behaviors that are essential in realistic microgrid systems, that's why MILP has emerged as the dominant mathematical optimization technique in microgrid planning. With the aid of integer variables we are able to model discrete designs and operational decisions, such as the switch status and the energy storage charging and discharging state. It's frequently used to solve scenario-based formulation in which each scenario is described with a set of linear constraints, whereas it struggles in describing non-linear processes such as battery degradation. Moreover, when the time-horizon increases, for example to a full year, to take into consideration the seasonability, we experience the exponential growth of binary variables, highly impacting the computational effort. While Meta-

heuristic algorithms, like Genetic Algorithm (GA) and Particle Swarm Optimization (PSO), can handle complex, nonlinear, and multi-objective microgrid planning formulations involving discrete design choices and reliability constraints[3].

1.2 Battery Optimization

Energy Storage Systems (ESS) help the proper integration of renewable energy sources by balancing power, thereby maintaining the stability of the electrical network. ESS stores electrical energy by converting it to other forms of energy like mechanical or chemical energy. ESS can be divided into mechanical, electrochemical, electrical, thermal, hybrid, and chemical. The most commonly used ESS for microgrid applications is Battery-based Energy Storage System (BESS)[6]. Commercially there is a lack of tools that match the appropriate battery storage size to the microgrid generation. The decision of the correct size of battery storage is directly connected to the desired operation of the system. From the battery size depends the utilization of Renewable Energy at their fullest potential. In fact, as said before, battery storage allows for the time-shifting operation of renewable sources: the production of photovoltaic (PV) is highest in the central hour of the day, but that might not be the hours in which our load is maximum; with the appropriate capacity we can store that energy to be used during night hours when the production from PV is totally absent. Let us consider the case in Figure 1.2.

In this scenario we are considering a microgrid directly connected to the main grid and where the microgrid generation only comes by a photovoltaic power plant. Having the direct connection to the grid, the Load Profile that characterizes the early hours of the day is directly supplied by it, since the photovoltaic production is still null. While during the peak hours of PV production, which are the hours around midday, the load is completely fulfilled by the direct solar consumption but in addition to that we have an excess of generation and therefore the overproduction is used to charge the battery. When we reach the maximum state of Charge of the battery, which means that the percentage of energy stored cannot be overcome because of technical limits, we must feed the over generation to the grid. During night hours then we can use

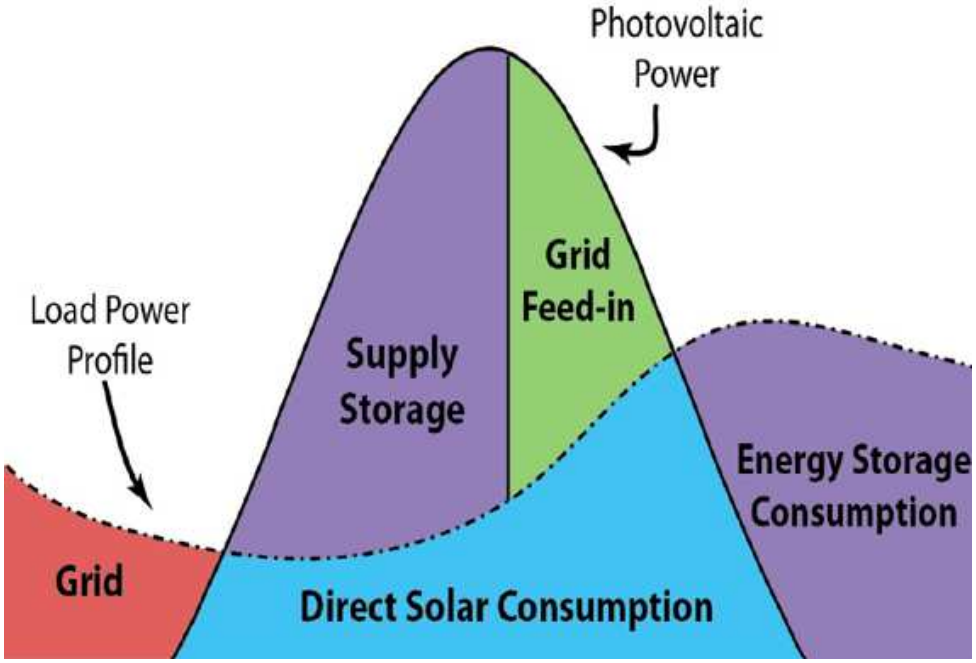


Figure 1.2: *Peak Demand Shifting using Energy Storage*

the energy stored in the battery during the day to fulfill the consumption. In case of a missing connection to the grid, that is when we are working in the islanded operation of the microgrid, and an insufficient battery storage we might fall under the case in which we have to cut off some of the renewable generation at our disposal. That is the case of Curtailment of renewable energies. A higher capacity allows the highest utilization of renewable energy, avoiding the need of curtailment, therefore a more sustainable use of resources and a lower emission of CO_2 derived from a lower use of fossil fuels to fulfill our demand. Furthermore on the capacity of the Battery Energy Storage System (BESS) we can base the reliability of an islanded microgrid in case of emergency, that is to say when the power generation is completely lacking. On this regard we might also talk about the connected propriety of resiliency: the ability of a microgrid to withstand a natural disaster that expectantly interrupts the supply of energy. If the disaster is so that the generation is completely cut off from the loads but the battery is not, our only way to supply the remaining loads, the most critical ones or the ones that are not interrupted because of feeders' faults, is trough the aid of the battery. Usually these types of fault may require many days to be sorted out, for example by replacing the damaged equipment, and therefore a higher capacity might allow for a

longer supply of loads, until the ordinary operation is properly recovered. Moreover the presence of a BESS can help in other important tasks of distribution related to the power quality. It's very important for a reliable operation not only for the supply to be continuous but also to respect the quality limits of voltage and frequency imposed by the correct supply of loads, in particular electronic loads which are very sensible to variations of said parameters. BESS have the ability to act as a voltage back up and as a synthetic inertia, meaning the feature usually associated with big synchronous generators. for their big mechanical inertia, to keep the frequency of the grid sinusoid as fixed as possible, avoiding operation in over or under frequency. This is particularly relevant in islanded microgrid in which we can not rely on the many synchronous generators that are present in the national distribution network, but only on smaller sizes of generators therefore with less mechanical inertia, and on grid forming inverter, in which the inverter has the job to produce the correct frequency sinusoid. On the other hand, to the technology of the battery we can link the lifetime of our unit. The life cycle of a BESS can very a lot, going from 2000 full-cycles with Lead acid-based energy storage systems (PbA ESS) to 8000 with Lithium-ion-based energy storage systems (Li-Ion ESS), determining a huge difference in both its maintenance cost and substitution cost during the overall lifetime of the microgrid. BESS faces numerous issues in its integration, such as control, protection, state of charge (SoC), state of discharge (SoD), safety, life span, capacity, reliability and cost, therefore all these parameters should be taken into consideration in approaching the problem of optimization[6]. Usually software that regard the electrical planning of renewable generation plants do not automatically associate the best size of storage, based on specific criteria like maximizing the self-consumption, but let the user choose its capacity independently. In literature a lot of optimization of capacity of the battery storage focus on minimizing the cost and do not consider other benefit. For example, Premadasa et all proposed a MATLAB code using genetic algorithm to match the sizing of photovoltaic generation to the battery sizing that minimizes the investment cost while keeping an high efficiency, for domestic prosumers[9]. Similarly Wongyai et all uses Particle Swarm Optimization (PSO) to define the battery capacity and its output power, minimizing capital cost, maintenance and operational costs in an industrial context where a microgrid is connected to

the main grid and acts as a tool to reduce energy prices during peak load periods[10]. While with Alsaidan et all we can see a mixed integer linear programming optimization problem which is able to take into account critical factors regarding the battery life, such as the impact of depth of discharge and the number of charging/discharging cycles on the Battery Energy Storage (BES) degradation, so on its life cycle, and the coordination of the different microgrid operation modes, providing the optimal BES size, technology, since different technologies of battery storage have different life cycle versus depth of discharge relationship, number,and maximum depth of discharge. In fact, the BES degradation is greatly related to its operation: how deep it discharges and how many charging/discharging cycles are performed. Usually the degradation phenomenon, which is both calendric and cycling aging, is represented in an additional cost described as $/kWh [11]. It's important to consider the useful life of a battery since it might be needed to consider its substitution during the operational life of the microgrid, impacting not only the cost but also the environmental aspect, since we must care for its disposal.

1.3 Commercial Software: Homer and Xendee

At the moment, There are many commercial software that can help in the design of a photovoltaic power plant and are able to make analysis regarding the yield, the business plan and also the electrical design of the plant. Furthermore, no single tool fully integrates techno-economic optimization, electrical feasibility, and reliability assessment within a unified framework. As a result, many studies rely on multi software workflows in which capacity optimization, reliability evaluation, and electrical validation are performed sequentially rather than jointly[3]. The most common software utilized for the design of microgrids are Homer and Xendee.

Homer is a software specifically created for designing distributed generation systems, both on and off the grid. Its key functionalities include: simulations of various configurations of Hybrid Renewable Energy systems, so when fossil fuels generators are also present, based on predefined models, optimizing them using economic criteria optimization, and performing sensitivity analysis to assess the impact of possible

changes on the results, due to the unpredictability of renewable energy sources[12]. Homer Pro's popularity as a microgrid design tool comes from its characteristic of providing easy instructions to the users while designing, and providing a detailed techno economic design solution, easy to implement and understand[13]. The following figure outlines the methodology employed by Homer to perform techno-economic analysis and size optimization tasks.

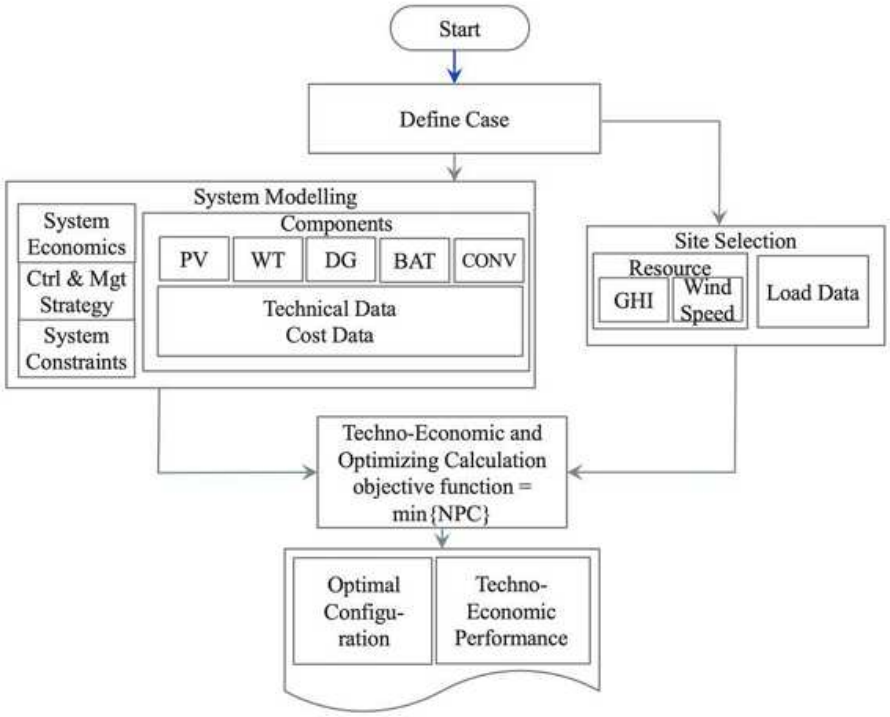


Figure 1.3: *Homer methodology for techno-economic analysis.[12]*

The software is able to simulate different system configurations, using different components, providing an economic assessment of their installation and operation, covering the all lifetime of the project, therefore considering also replacement cost and maintenance cost. The sensitivity analysis is based on the variables set by the user as the most likely to change because they are beyond the designer control, such as wind speed or irradiance. The simulation performs the energy balance for each time step of the year deciding when to operate the generators, if present, and when to charge or discharge the battery[14]. Homer allows the user to set a high range of generators sources, from renewable as photovoltaic, wind and hydro, but also biomass, to fossil fuel gen-

erators and fuel cells, of storage technology, like batteries, hydrogen or flywheels, an energy storage system based on mechanical energy storing, and loads that can be defined daily with seasonal variations. The best solution proposed automatically by the software is the one with the lowest Net Present Cost (or life-cycle cost) of the overall system. Homer's graphical and tabular output capabilities allow to efficiently analyze all that data. The Tabular mode is the default format to view results, but it is possible to change to a graphical view. The graphical view can represent different graphs, the Optimal System Type plot, which is shown in Figure 1.4, portrays with different colors the areas, in the plane defined with an economic variable on y-axis, such as Net Present Cost or fuel cost, and a certain sensitivity variable, chosen by the user, as x-axis, in which a certain system combination determines the lowest Net Present Cost, where the lowest points are highlighted by a diamond.

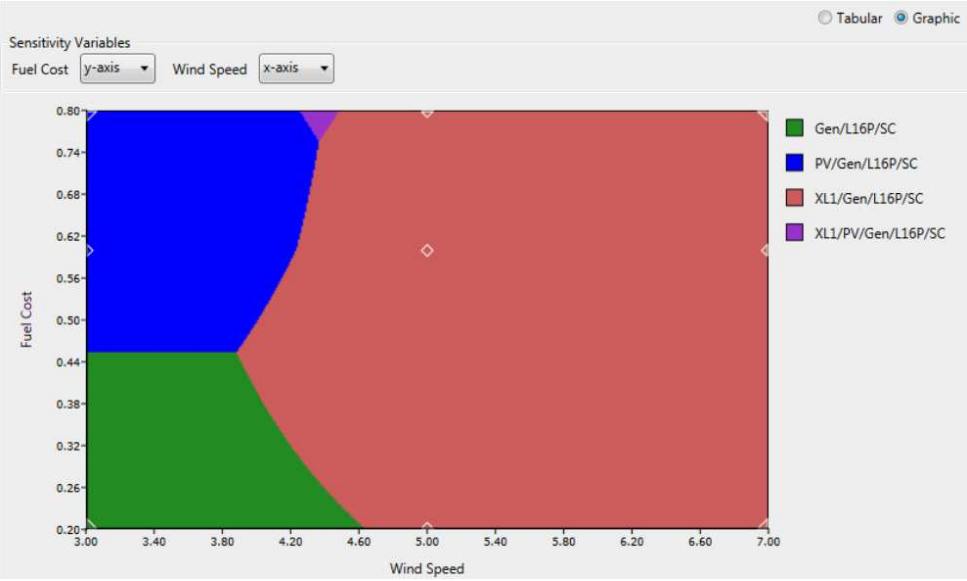


Figure 1.4: *Optimal System Type plot given by Homer optimization results[14]*

Another useful graph is the Optimization Plot, which shows each simulation as a single point on a set of axes chosen by the designer. An example can be seen in Figure 1.5 where the x-axis represents the Total Capital Cost, and the y-axis represents the Total Net Present cost.

If minimizing the Net Present Cost is not the designer's first scope, the solution that follows the criteria of most interest, for example, which simulation has the lowest annual utility bill or which system has the highest renewable fraction, can be found

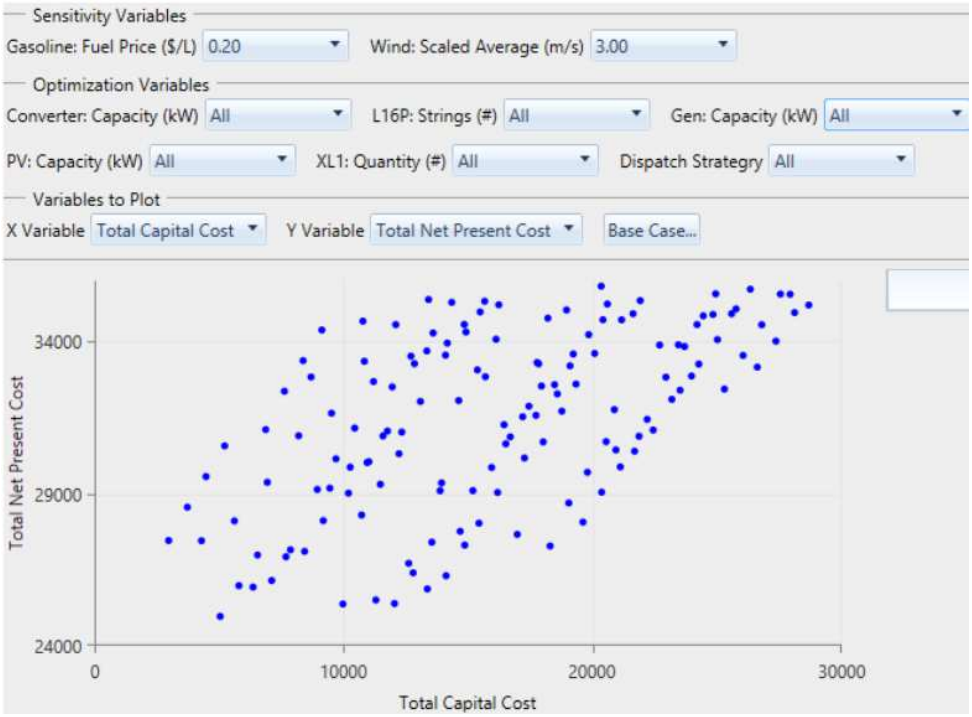


Figure 1.5: *Optimization plot given by Homer optimization results[14]*

in the list of all feasible configurations; an automatic search for these purposes is not predisposed[14]. An Optimization plot might be useful in this regard once the axis are appropriately selected by the designer to portray the variable of their choosing. HOMER has emerged as the dominant industry and academic standard, particularly for early stage microgrid feasibility analyses, but it is particularly lacking in the system resilience and reliability evaluation that, as said before, are becoming more and more relevant and required features. In fact, it is important to notice that HOMER does not incorporate standard reliability indices, outage costs, contingency modeling, or value-of-lost-load formulations.

To answer these requests a high number of optimization software that place greater emphasis on representing reliability-related requirements alongside least-cost design, has emerged; one of these is Xendee. Xendee is built around a mixed-integer linear programming (MILP) formulation and can be configured to consider multiple objectives and constraints within a single optimization problem[3].

At the start of a project, the designer can specify organizational goals like cost savings, CO_2 reduction, and resilience to ensure accurate modeling. As well as these

aims the designer can define site specific variables, such as funding terms, incentive programs, existing utility and load information, and the desired Distributed Energy Resources technologies to include in the project. This includes over 25 technologies including solar, geothermal, BESS, hydrogen, hydrokinetic, and more which can be used to expand projects and use technologies outside your typical deployments[15]. Xendee allows to take into considerations also outages scenarios and critical load requirements to be considered in the economic evaluation. In addition, it is also capable of considering battery degradation, in a multi-year overview, making it very appropriate for islanded microgrid modeling, while Homer adopts only a simplified evaluation of it[3]. In fact, Homer does not take into account the degree of drain on batteries, which is a fundamental parameter, since discharge depth plays an important role in system optimization due to the adverse correlation between battery capacity and their lifespan[16].

The main difference between the two software is the ability of Homer to provide multiple different solutions in a single run of optimization, letting the user see the differences between the implementation of different combination of generation sources, while Xendee, to do so, requires a new simulation every time, changing the input of the desired generation sources[13]. Although it's important to notice one key difference on how the programs represent the time sequence of electricity demand and solar resources, which leads to faster computational time for Xendee. In fact, HOMER uses full chronological profiles for its simulations, while Xendee uses representative day profiles to limit the size of the linear programming formulation, enhancing faster solutions at the expense of a possible inferior precision due to the data simplification[5]. Moreover, the input of values in Homer may be easier than Xendee. For instance, in Homer, it is required to give specific values regarding the components to be implemented, such as voltage, current, capacity, string size, state of charge for the battery. While in Xendee more system level information is needed, rather than device level: charging or discharging efficiency, rate of charge, annual cycle, reserve state of charge (SOC), self-discharge, incentives, and charging source[13]. Furthermore, Homer is unique in its output of the share of energy coming from each type of generators, highlighting the renewable energy factor of the system. In particular, Homer is able to find the optimal

energy management strategy that prioritizes the production from renewable or battery storage, so avoiding as much as possible the withdrawal of energy from the network in the case of a grid connected system, while Xendee has no specific controller mentioned, the grid is always prioritized in grid connected mode[13].

1.4 Our aim

There is a great variety of commercial tools that already do the electrical design of PV plant, matching the proper technology, like inverter and cables, to design the plant, efficiency reports, showing the real output of the power plant considering the various losses, and the economic analysis of the system, considering investment and possible gain from incentives or selling energy. Xendee and Homer are able to go over the merely economical results, the first proposing insights regarding the resilience of the system, while the other showing different possible feasible solutions and not only the cheapest one. But what is missing is a software that compares various solutions based on different criteria, to assist the designer in choosing the optimal combination of utility sizes for their specific case, portraying a broader array of solutions that might have different benefits then the one they were firstly aiming to, something that they could have not have imagined without a proper evaluation. What would be of interest is a tool that compares different configurations not only in economical sense, but that is able to portray the overall impact of the system regarding other parameters, such as reliability and environmental impact. These considerations should be expressed in a way that allows the designer to see how much a difference in a certain parameter might cause the increase of a different feature. In this way the designer may realize that they are willing to accept that variation in order to gain the resulting advantage for the other quality, even though they were not expecting to do so in the first place. For example: If the tool were to show that a small increase in the investment cost, like for the capacity of the battery, realizes a significant improvement on the emissions released by the system, they might decide to go for that design which is not the least expensive one.

What is needed is a sensitivity analysis that goes beyond the results regarding one

single quality, but that inspects how a change on one parameter affects the others. Ultimately, the variables to be considered in the optimization of a microgrid are too many and too interconnected between them for a designer to be sure that the solution that follows entirely their initial scope is actually the one that can guarantee the higher benefit for the microgrid's customers. To model the design of the microgrid one of the main aspects will be finding the most relevant parameters that affect our system and connect them together, calculating for different starting scenarios the consequent outputs. So, for example, starting from the battery capacity we could then evaluate the impact on other parameters such as the hourly fuel consumption needed, the total reduction of carbon emissions, the battery life, which is, as said before, significantly impacted by the battery operation so its cycles in charging and discharging mode, that determine a great impact in the maintenance or investment costs, and also the amount of critical load covered in case of different faults. The final aim of the project is therefore letting the designer aware of all the possible combinations that can be implemented and their consequent advantages, determining more conscious decisions for a more responsible use of resources. A relevant part of this work will also be the graphic representation of those results to be able to evaluate each different simulation scenario on the base of the most relevant indicators found. This will help the designer in deciding the best solution required for its specific case. It is therefore essential to have a simple representation of data, especially considering the large quantity of data to be evaluated, that leads to an easy comprehension of what the different solutions entail and how they impact the overall system.

A way of portraying the results in the most efficient way is through the aid of Key Performance Indicators (KPI). Those should exactly represent the interconnection between the different features of the microgrid, providing the designer with a numerical variable that is able to justify their choices and that helps them in the comparison with the other solution. Since the market concentrates on economic indicators, such as net present value, we will focus our work on finding KPI that embed economic and environmental aspects and that portray the resilience level of the islanded microgrid. For example, an indicator that could well represent the connection between the economic investment and the environmental impact of the microgrid operation is the ratio be-

tween the yearly consumption of fossil fuel and the first year investment. This will allow us to see the changes that one design combination entails regarding the reduction of yearly liters of fossil fuel at the expense of a higher investment. Regarding the definition of resilience of the microgrid, instead, we focused our attention on the capacity of the battery storage system, defining the KPI of days of autonomy of the battery and the percentage of critical load to be covered by it. In this way, with the aid of battery storage, we will allow the continuation of the energy supply in the microgrid even in the case of an abrupt event that completely nulls the internal energy generation, for the duration of the days of autonomy requested and supplying the percentage of load that is defined as critical. In general, this will also allow for a more reliable operation of the energy supply of the microgrid. The aim of these kind of indicators is to provide insights on the potential benefit deriving from the change of one parameter. They could show that an increase in the investment cost actually provides a significant improvement on the resilience and environmental impact of the microgrid, that are able to to justify the higher expense. Or, on the other hand, they could even demonstrate that a lower investment is still able to suffice the required level of resilience and CO_2 emissions.

To do so, the software will start from the definition of certain initial inputs inserted by the user to which environmental and reliability reasons, in addition to the economical one, can be easily linked. The software will simulate the yearly operation of the system, considering a typical day for each month, for each possible combination of the above said variables, and portray the consequent results in a comparative way. The variables in question are: the month of the year used for sizing the photovoltaic power to be installed, the days of autonomy required for the battery and the critical load by the same battery. AS, said before, these last two parameters are essential for the definition of the capacity of the battery and the consequent resilience level desired for the microgrid. On the size of the battery installed we rely the reliability of the islanded microgrid in the case of emergency, when the generation is completely lacking. The energy stored in the battery will then need to be sufficient to fulfill the critical loads for the days decided by the user. In particular, the definition of percentage of critical load is not so straightforward. First of all is required the definition of an order of priority be-

tween the loads, which only the designer of the microgrid can define. Furthermore, it depends on many other parameters like the layout of the system, the quality of protection devices, the sizes of load and generators and their specific position on the feeder layout. It is not something that is easily defined and the aid of a software is highly recommended. For this reason, as a first step of this project, we worked on a MATLAB script that is capable of defining the percentage of critical load remaining after a fault has occurred on a specific feeder.

Chapter 2

Critical Load Evaluation Code

One of the most relevant advantages of microgrids is their ability to not be affected by energy distribution network blackouts, by being able to work in island mode and supply their load requirements with their own generation. But this can be done only if the generation is sufficient to cover the entire demand of the microgrid customers. Resilience defines the ability of the microgrid to withstand those interruptions, but then during the emergency state, we should take into account the reliability of supply. Therefore, it is essential to carefully study the role of reliability in the electrical design of a microgrid. This task is particularly difficult, as reliability depends on many different parameters, such as feeder routing, protection devices, and grid layout, i.e. the connections of loads and generators to specific feeders. Thus, it is of the greatest importance to define concrete methods of reliability evaluation that will help us judge from the start the reliability of the microgrid, in order to set a sufficient level of it and so make the acceptable choices regarding the microgrid design to reach it. Providing a satisfactory level of reliability is one of the core efforts to increase the resilience of the system; since these two concepts are highly interconnected, the application of one greatly helps the strengthening of the other.

In the reliability study of the national distribution network the indicators used are SAIFI (System Average Interruption Frequency Index) and SAIDI (System Average Interruption Duration Index). At the start of the design process of a microgrid, it would be impossible to consider the common indexes of SAIFI and SAIDI to evaluate reliability. In fact, SAIFI is defined as ratio between the interruptions of energy supply

that have happened in a specified time horizon and the total number of customers in the system, while SAIDI considers at the numerator the sum of the duration of all customers interruptions, so the overall period of time in which the energy supply was missing.

$$SAIFI = \frac{\text{number of customer interruptions}}{\text{total customers in the system}} \tag{2.1}$$

$$SAIDI = \frac{\text{sum of durations of customer interruptions}}{\text{total customers in the system}} \tag{2.2}$$

These parameters are not particularly useful in the process of designing a microgrid because they are based on measured quantities. In fact, these quantities are strictly peculiar to the specific configuration of the grid that is taken into account, because they depend on many parameters that are very difficult to approximate, like feeder layout, users connections and protection device positions on feeders, and therefore they could determine not very precise results. Furthermore, these indicators have another intrinsic disadvantage: they treat every user interruption equally. In the case of a microgrid, where the generation comes only from the sources that are part of it, this is not particularly helpful, since we might find ourselves in a situation in which there is still some generation remaining after a fault, but it is not enough to fulfill the entire demand. In that case, to avoid the total loss of supply, some choices need to be made in order to distinguish the different users or the different activities; this will ensure at least a partial supply of energy.

The equal approach of SAIDI and SAIFI is what qualifies them as better suited indexes for the national network reliability evaluation, but since a microgrid has its core feature in the independence from the main grid, wether we are talking for a completely islanded microgrid or just one that can work in that operational mode, the study for an increased reliability needs to focus on the ability of supplying those loads that are considered as the most important ones, for their peculiar function and necessity inside the microgrid.

As said before, in the particular case of islanded microgrids, it would be more appropriate to talk about resilience, the ability to withstand abrupt events, such as natural disasters, that could cause interruptions of the energy supply. Even a microgrid

that still presents the connection to the outer network, as mentioned before, lies its strength in its ability to continue to supply the loads even in the absence of the latest and so needs to be comparable to a fully islanded microgrid with its high degree of resilience. Events that could cause the complete lack of generation sources in an islanded microgrid are various. One of the most common applications of islanded microgrids is related to communities located in remote geographic areas that cannot be reached by the distribution system infrastructure. It could easily happen that, due to their secluded location, the delivery of fossil fuel would be interrupted, leaving the microgrid without its only source of programmable generation. In the event of such a situation, we would find ourselves in a condition in which the level of resilience of the microgrid would make the difference in its customer satisfaction. If the size of the battery storage system were enough to cover a certain amount of load, the damage to the microgrid users following this abrupt event would not be as impactful. Of course, this battery charge has a cost, especially if we consider the extreme case of completely lacking any kind of generation, even the renewable one, which is something that is done to cover all possible scenarios, even the worst one, assuring the greatest quality of design. This is another reason that shows the relevance of defining a priority in the loads to be covered. The battery storage will then be sized according to that value, among other criteria, to ensure the reliability of the supply of that specific amount of load even in the case of such an emergency condition.

Resilience in microgrids combines energy reliability, adaptability of energy supply following extreme events, such as covering the most critical loads, and a fast recovery to come back to the ordinary operation mode[17]. The concepts of resilience and reliability in an islanded microgrid are strictly associated to one another, since the microgrid itself is the only one in charge of providing any kind of possible generation, this operation is strictly connected to its correct functioning, and this is why studying the reliability of the system also gives us an indication on its resilience and vice versa.

The definition of a priority in the loads to be supplied is what is needed to enhance the most correct reliability definition for a microgrid operation, that will help in reaching its highest value.

For a correct reliability evaluation, we should take into account many criteria, but

the most relevant of which is definitely the layout of the system. Based on the position of loads and generators, in fact, we can understand how a failure on a feeder impacts the overall operation of the microgrid. This evaluation has its strength exactly in the definition of priority for the different loads connected to our system. By selecting the highest priority for a specific load we ensure that in case of a fault, therefore a possible decrease in the production, the demand of that load will be fulfilled, as long as the generation is sufficient and the load is not positioned on the feeder affected by that fault. The remaining generation succeeding a fault will be distributed on the different loads based on their priority, from the highest to the lowest until the generation is enough. The lowest priority load will not be supplied unless the generation is sufficient to fulfill all the remaining loads, so the ones not affected by the feeder failure, with higher priority. We can imagine the relevance of this description when we think about a microgrid which is represented by a hospital. In a hospital we must allow the continuous operation of the most essential devices that regard people health and safety, and to do so we can let those less important services stop in favor of sufficient energy for the most critical demands.

Once the priority of loads ihas been defined we would like to know, on average, which is the critical load that will be remaining after a feeder fault. In fact, this quantity is what will help us decide the sizing of those devices, such as the battery storage, that are at the base of the reliability of the system and that would be the core essence of its resilience.

Since we are studying the design of the microgrid, we will need to base our evaluation on a set of predicted variable values, instead of measured one, that describe the probability of a feeder to be affected by a fault. These data need to be based on statistic calculations of devices and components failure. Once these data are known, we would then be able to improve the system layout by connecting the highest priority load and bigger generators on the feeder that is statistically less likely to fail. This would be a further approach to increase the resilience and reliability. However, what is really of interest for us is the average critical load that is remaining after a fault on a specific feeder. In fact, one of the intrinsic parameters of a microgrid is its meshed distribution of loads and distributed generation. For this reason, a fault on one feeder may

or may not affect the energy distribution that occurs on the other feeders connected to it. That all depends on the power supply that our remaining distributed generators sources are able to provide. That is why our code will only implement the calculation of the percentage of remaining load in our overall system. This will be needed in our Decision Support code to define the most likely percentages of critical load to be taken into consideration in the microgrid battery storage sizing, and it is one parameter that, with the addition of the days of autonomy required for the battery storage, will help us define the level of resilience of our islanded microgrid.

2.1 Input of Data

Taking inspiration from the code of Maleki et al. [18] we based our evaluation on the definition of a Connection Matrix that shows how the different feeders of the system are connected between themselves. Furthermore, we need to know the distributed generation sources output on each feeder and the location of loads on the microgrid's feeders. This is all aimed at getting as a result the Failure Effect Matrix that shows if the different loads are affected by the failure of a feeder or not.

Provided that the generation and the peak demand, that is, when all the loads are working at their maximum power, need to be equal to ensure the energy balance, we will define the different generators and the different loads only as a percentage of how much they contribute in the total sum of their power generated or required.

The definition of these percentages is not so straightforward because of the possible variability in the different loads demand, and also that of the generators. The type of generators is not specified; they could represent any possible technology, from fossil fuel generators to distributed renewable energy sources. The latest, in fact, are particularly affected not only by the seasonability but also by the meteorological conditions and the passing of day and night. These percentages are meant to be an indication of how much the user is aiming to divide the generation between the different sources, taking into consideration how much they are willing to rely on each one of those, and how the demand is spread between the different necessities they require. Therefore, it is advisable to choose average or most statistically probable percentages in order to

have the most appropriate results.

The priority of the different loads needs to be set as follows: the vector that contains the different percentages that represent the power of the single loads with respect to the total demand needs to be written with the percentage regarding the highest priority load in the first position and consequentially decreasing the priority until we reach the last element of the vector that corresponds to the lowest priority load. All the feeders of the system need to be enumerated to be described by a unique number.

The description of the feeder layout needs to be inserted as three different connection matrices:

- **Feeders Connection Matrix:** to show how the different feeders are connected between themselves. The Dimension of the matrix is

$$dim = \text{number of feeders} \times \text{number of feeders} \tag{2.3}$$

- **Loads Connection Matrix:** to show to which feeder the different loads are connected to. The Dimension of the matrix is

$$dim = \text{number of feeders} \times \text{number of loads} \tag{2.4}$$

- **Generators Connection Matrix:** to show to which feeder the different generators are connected to. The Dimension of the matrix is

$$dim = \text{number of feeders} \times \text{number of generators} \tag{2.5}$$

The rows of these matrices represent the feeder described by the row index, while the columns represent the other parameter described. The elements of these matrices will need to be set to one when the connection between the different components is present, and to zero when it is not present. For example, considering the Load Connection Matrix, if the load of column *j* is on the feeder *i* then d_{ij}=1, if not d_{ij}=0.

In particular, for the Feeder Connection Matrix only the direct connections between feeders are represented by the value 1. Furthermore, for the calculations of remaining loads and remaining generators, we will also need the elements on the Feeder Connection Matrix diagonal to be set as 1.

2.2 Code Flowchart

The code is instructed to build the Failure Effect Matrix (FEM). This Matrix has the same dimension as the Load Connection Matrix that explains the relationship between feeders and loads, as seen in equation 2.4. This matrix shows if the load described by the column index is still being supplied when a failure on the feeder marked by the row index happens. If a failure on the feeder *i* occurs and the load of column *j* cannot be supplied then d_{ij}=1, if the load is not affected by the fault d_{ij}=0.

The Flowchart representing the code is shown in Figure 2.1.

To define if a fault does affect or not a load we need to consider the distributed generators output of all the feeders that are connected to the feeder where the load is inserted. If the power generated is enough to supply all higher priority loads and the load being considered at the moment, then d_{ij} is 0. To do so, the code implements a *for loop* that at each iteration considers the fault to happen in the feeder described by the for index. All the loads in the Load Connection Matrix and all the generators in the Generators Connection Matrix that are linked to the failed feeder *i* are now set to zero, because they cannot participate in the energy balance of the system. The code needs then to evaluate the connections between the remaining feeders, recognizing which ones are connected, even when the connection between two different feeders is not a direct one, and calculate the remaining generation and demand. It might happen that the fault in a feeder causes the creation of two different subsystems that need to be evaluated separately, that is because we cannot mix the loads that are present in one system with the generation produced in the other, but we will have to calculate two separate values of remaining load and remaining generation, one for each sub-system. With the value of remaining load we can evaluate if the remaining demand is sufficient to supply it and consequentially build the FEM. After building the FEM we can then evaluate the resulting percentage of load that is been supplied when a fault on feeder *i* has happened. We will obtain as a result a vector of dimension $dim =$ number of feeders $\times 1$ in which each element corresponds to the percentage of remaining load when the feeder described by the row index is affected by a failure. Furthermore, the code gives as a result the average critical load, after considering all possible failures in the system.

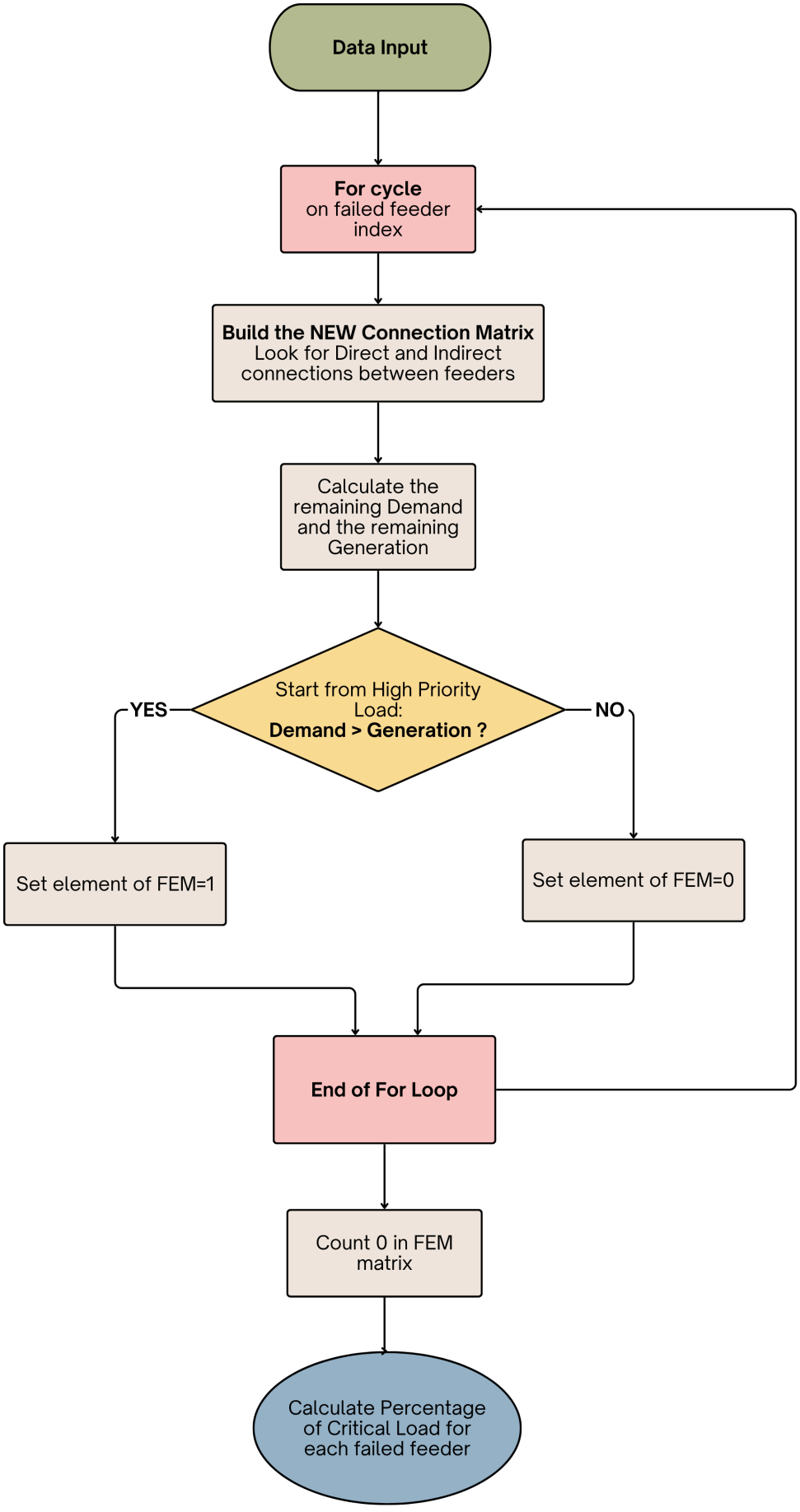


Figure 2.1: *Flowchart of Critical Load Evaluation code.*

2.3 Example and Results

Let us consider the example of the layout of the microgrid shown in Figure 2.2, to which we will apply the code for the evaluation of the critical load. In that figure, we can see the connections between feeders, generators, and loads, where both feeders and generators are numerated, and the loads are numerated from the highest priority to the lowest priority.

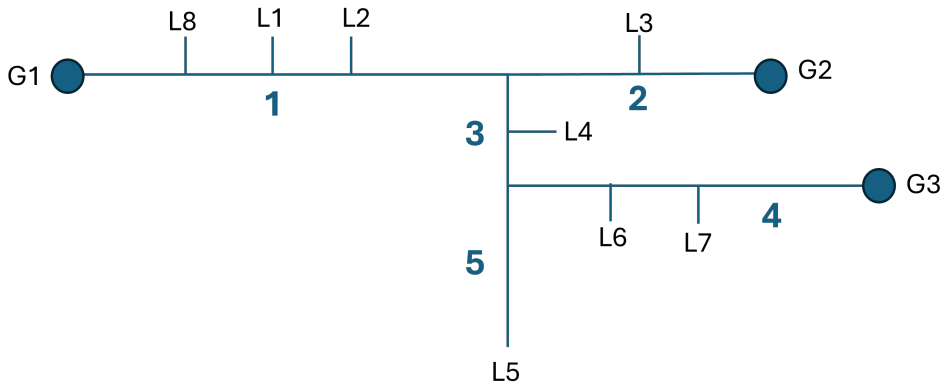


Figure 2.2: *Example of microgrid layout used in the code.*

The blue numbers indicate the different feeders, numerated from 1 to 5. Generators are symbolized by blue dots. We are considering three generators and we will insert as input of the code the different percentage of power provided by each generator with respect to the total generated power. While defining a fixed percentage of these values we must remember that the real operation of the system will not always be set to this distribution of generation but that we are considering an average operation and therefore also the results will be a consequence of that. The values implemented to represent the power distribution between the generators are the following:

$$Generators = [0.3,\ 0.3,\ 0.4] \tag{2.6}$$

We have opted for a nearly unified distribution of power generated between all sources, in order to stay in a very general case and not rely too heavily on a single technology of generation, although giving a slightly higher percentage to the last generation source, having in mind the contribution of fossil fuel generators that, unlike renewable sources, are programmable. On the other hand, the loads are represented by eight

different contributions, and they are written in the Load vector in the order that symbolizes their priority, that is to say, *L1* is the highest priority load and *L8* is the lowest one. The loads are defined as follows:

$$Loads = [0.1,\ 0.2,\ 0.05,\ 0.1,\ 0.15,\ 0.15,\ 0.2,\ 0.05] \tag{2.7}$$

the Connection Matrices that define how the feeders are connected between each other and how the generators and loads are inserted inside the feeders are the following:

$$\textit{Feeders Connection Matrix} = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \end{bmatrix} \tag{2.8}$$

$$\textit{Loads Connection Matrix} = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \tag{2.9}$$

$$\textit{Generators Connection Matrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \tag{2.10}$$

The elements with value equal to 1 underline the presence of a connection, while the value 0 stands for a missing connection.

This particular layout is peculiar because of the presence of feeder 3 that acts as a bridge between the other feeders. When we are considering the fault on that feeder, in fact, we will have to consider two different sub-systems: the one composed by feeder 1 and 2 and the other sub-systems composed by feeder 4 and 5. In this case, even in the presence of an over generation in one sub-system we will not be able to supply

more loads belonging to the other sub-system because of the missing connection between the two. Furthermore, since the Feeders Connection Matrix only stores direct connections, it is necessary to consider all the actual feeders that are still connected in the system after a fault on a specific feeder. For example, let us consider the case in which feeder 2 is affected by a fault. To store the feeders that are actually connected between themselves, the new feeder connection matrix needs to have all zeros in row and column of the fault feeder index, in this case feeder 2. In fact, we must completely disregard the feeder 2, since the fault makes it operationally unavailable. When we are looking for the connection between feeders, then we start from the first feeder and look for the column index of the values equal to 1. We will see the direct connection between feeder 1 and feeder 3, and we will store these indexes in an array. Now we must look, for each of the stored indexes, for the direct connections to those feeders. We will need to skip to the row of the connection matrix the index of which is equal to the index stored in the array, and look for the value 1. We will then store the column index of the element equal to 1 in the array. This operation must be carried out for all the indexes that are stored in the connection array until we have searched for all the feeders in the system connected to them. We will then disregard duplicated number, since it is sufficient for just one feeder to have a direct connection to the other one to be allowed to consider its generators and loads. So, in this example, we will have to look for the direct connections of feeder 3. Feeder 3 is connected to both feeder 4 and feeder 5. Looking then at those rows of the connection matrix we see that ultimately there are no more connections to be considered. Our final system will then be composed by feeders 1, 3, 4 and 5. A visualization of the process of storing indirect connections can be seen in Figure 2.3.

After having stored the remaining connections between feeders following a fault, it is time to calculate the consequent remaining demand and generation, in order to be able to build the Failure Effect Matrix. After all the calculations and all the fault evaluations for each feeder, the software gives the following FEM matrix:

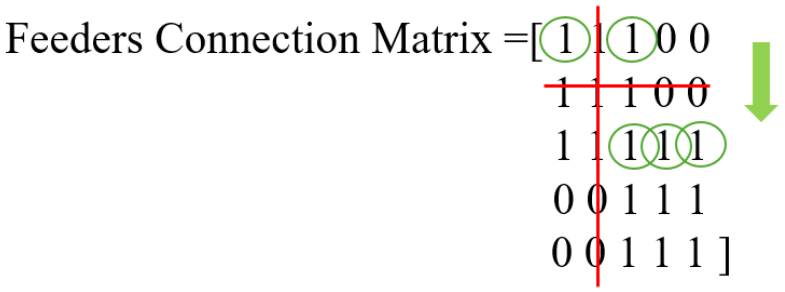


Figure 2.3: *Example of indirect connection storing used in the code.*

$$\textit{Loads Connection Matrix} = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \tag{2.11}$$

Value 1 stands for the impossibility of supplying the load corresponding to that column index because of the lack of sufficient generation or the lack of a connection between feeders. We can immediately see that all the loads that are connected to the feeder marked by the row index we are considering are set to 1, due to the effect of a fault on that feeder. Furthermore, we can see how the columns that present the higher number of elements with value 1 are those characterized by lower priority, therefore Load 7 and Load 8. Having built the Failure Effect Matrix we can now calculate the Critical Load Percentage after a fault on one feeder. This is the resulting vector containing those values:

$$\textit{Critical Load Percentage per fault} = \begin{bmatrix} 0.65 \\ 0.7 \\ 0.7 \\ 0.6 \\ 0.85 \end{bmatrix} \tag{2.12}$$

We can see how the highest critical load remaining is the one associated to a fault on feeder 5. In that case, in fact, since feeder 5 has no generator connected, we simply cannot supply the load that is connected to that feeder, Load 5, characterized by a

percentage on the overall demand of 15%. While, a fault on feeder 4 causes the lowest remaining critical load equal to 60% of the total demand. That is because we are losing not only Load 6 and Load 7 connected to that feeder, but also the generation coming from generator 3, which is the one with the biggest contribution to the total generation. This entails, as it can be seen in the FEM matrix, that lowest priority loads, such as Load 8, will not be supplied. If we compute the Average critical Load, considering all possible feeder faults, we get a percentage equal to 70% of the total load demand. These considerations will be used in the Decision Support Code in order to set reasonable values of critical load to be considered in the sizing of the battery storage system. Of course, these values are not perfectly accurate, since they depend on so many variables that are very difficult to be considered in an early stage of a microgrid design, but can be considered a good approximation on which we can base the consequent observation regarding the reliability and resilience of the system.

Chapter 3

DSS Code

The present work consists in writing a code that will help the designer of a microgrid to make the appropriate choices regarding the sizing of its components; for this reason we will refer to it as Decision Support Software (DSS). To do so, the code will show a vast array of solutions, and each will be characterized by a different combination of components sizes. In this way, the designer will be able to see more clearly not only what each different solution entails, but also how a small change in the design parameter may affect different criteria that regard the overall operation of the system. The code is written in MATLAB and utilizes the Mixed Integer Linear Programming (MILP) optimization algorithm. The software will work by solving the optimal operation of the system for a typical day for each month of the year, and will then show significant key performance indicators that define the solution, such as the investment cost or the liters of fossil fuels used to power the diesel generators. In particular, the MILP problem focuses on minimizing the amount of liters used in a year, providing a benefit both for the environment, the energy independence of the microgrid, allowing the microgrid to be less subject to geo-political tensions, and also on the yearly cost of operation of the system. The parameters that will be varied to construct the different possible configurations are three:

- The month used to size the installed peak power of the photovoltaic production plant;
- The days of autonomy that the battery system needs to be able to withstand in

case of emergency, that is, when the production of power is completely lacking;

- The percentage of critical load, on the overall system demand, that will be covered by the battery in the emergency condition.

The last two variables are the ones that will define the capacity of the battery used in the system. For each of these, the user can insert as many values as they desire, with the only impediment being the computational effort and, therefore, the time required by the software to give a solution. In addition to these values, the user can personalize the code with the appropriate values regarding its components' technology and cost in order to have the most precise evaluation as possible. Furthermore, in association with DSS code, it is possible to evaluate the useful life time of the battery defined by a specific combination of such parameters, through the aid of the Rainflow code. This will provide more insights on the future expenses and environmental impact of the system.

3.1 Input of Data

First, the user needs to provide the load that the microgrid will serve. To have a easier implementation, since the project is supposed to help in the initial design of a microgrid, the format required to insert the typical load is based only on two typical days: one regarding the summer time and one the winter time. The summer time will be used to model the months of April, May, June, July, August and September, while the winter one will model the months of January, February, March, October, November and December. The typical days need to be described by an excel file, saved as "power24", where the different values of the load are written in watt-hours [Wh], the first column will represent summer and the second winter. The number of values that will be inserted for a single day will define the time slice that the program will use to optimize the operation of the system. It is important to remember that this definition of time slice must match the one the user will use to define the irradiance of the geographical position corresponding to where the microgrid will be located, this will allow for the definition of photovoltaic production to serve the load, being based on the same

time slot. The user will then need to insert the details regarding the diesel generators. The sizing of these components is not a prerogative of the software since it is strictly linked to the user load and very straightforward to evaluate. The diesel generators, in fact, need to be able to cover the maximum load required by the load, even considering the total lack of power coming from the battery or the photovoltaic plant. This is done to ensure the reliability of the system, even at the cost of an higher consumption of diesel liters. The input data for the diesel generators is possible through an excel file called "generators", in which each row represents one single generator. The user can insert as many diesel generators as they want. Each generator needs to be described with three parameters: Power in watts [W], the angular coefficient, that is the slope, and the y-intercept that describes the load curve. The last excel file that needs to be created by the user is the one related to the irradiance data. This file, which must be named "irradiance", needs to contain the value of solar irradiance for the geographical spot in which our microgrid will be built, in the format of one typical day for each month, where the unit of data must be written as watt-hour over kilowatt of peak [Wh/kWp] of photovoltaic power and the time slot used must match the one used for the load definition. For this task, the software PVGIS (Photovoltaic Geographical Information System) is particularly helpful. PVGIS is a free software developed by the European Union to retrieve irradiance data based on geographical coordinates all around the globe. In particular, this software is able to give the value of photovoltaic production, so already considering the efficiency of the conversion, for a specific power plant defined by its technology, position and peak power installed. The software is even able to calculate the best azimuth and slope angle for the installation of photovoltaic panels, so it is possible to already consider the best solution possible for the desired installation site. In particular, we must consider the values of photovoltaic production in the arc of the whole year described by a defined time slot. PVGIS already gives the option to retrieve these data on an hourly based description. Therefore, the easiest and more handy implementation of our software is hourly based, considering 24 hourly values for a typical day for each month of the year. This decision also allows us to avoid an excessive computational effort, determining shorter resolution time. Therefore, by selecting then the Hourly Data option and defining the value of Installed Peak Power as

1 kWp, we will be able to retrieve the hourly data for each day of the year in the format of Wh/kWp. An example of the selection of data on the starting page of the software can be seen in Figure3.1. Once again, to avoid an excessive computational effort, we

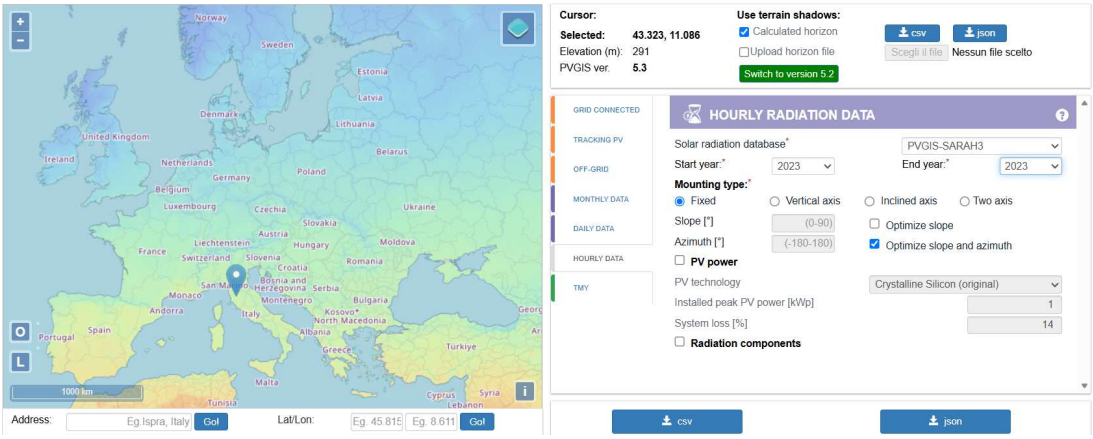


Figure 3.1: *Example of data insertion in the Hourly Data section of PVGIS.*

will consider only a typical day for each month of the year, since the degree of precision that will come from utilizing all the days of the year will be completely useless due to the unpredictability of future weather conditions, an average consideration will suffice. To do so, the user can choose how to select the specific day of the month to use as typical in the computation. A possibility could also be to use an excel pivot table that will calculate the average between all the days of one month and that consider those as typical days. The user can personalize the code by inserting the specific values of price that is required to purchase and install the photovoltaic power plant, the battery storage system, and the cost per liters of fossil fuel. These data should be described in \$/kWp for what regards the photovoltaic plant, \$/Wh for battery storage and \$/L for fossil fuel. The same can be done for the values of equivalent kilograms of CO_2 released in the atmosphere by the use of fossil fuels. This value must be set as $kgCO_2\text{-}eq/\text{L}$ and will then be fundamental in the calculation of the overall quantity of CO_2 emitted by the microgrid each year. Furthermore, the battery that will be taken into consideration can be further customized by the user by defining the maximum and minimum state of charge that they are willing to apply to their battery storage system. These values, described as soc_max_bat and soc_min_bat, can be found in the part of the code regarding the definition of the battery energy capacity. The opera-

tion of the DSS code is based on the evaluation of the different combinations of three parameters: month used to size the photovoltaic power plant, days of autonomy required by the battery and critical load that needs to be covered by the battery in case of emergency. These data must be stored from the lowest to the highest numerically value in the respective vectors: $months_for_sizing[\,]$ where the months must be written as numbers, $days_covered[\,]$ for the number of days that the battery capacity must sustain the defined percentage of critical load, and finally, $critical_load[\,]$ where the percentages must be written in decimal form, where 1 expresses 100% of the total load. These data are completely free to be decided by the user; a suggestion to make the study more compelling would be to work with a low, an average, and a high value for all these parameters. The user will then be able to narrow their decision by choosing other values closer to the one they are more interested in, so that they could expand their understanding of the possible solutions. For example, in the case of the month used for the sizing of the photovoltaic power plant, it could be beneficial to choose the month of the year that receives the lowest irradiance, so that it will determine an highest peak photovoltaic power installed, the highest irradiance, determining the lowest peak photovoltaic power to be installed, and an average one. About the critical load values, instead, we have a wider range of possibilities depending on the interests of the user and the application we are considering. It might be the case that a user wants to always evaluate a critical load which is higher than the base one, to learn about how the benefits of a higher resiliency impact the economic and environmental aspects. In another case, since the critical load is the one that needs to be considered only in states of real emergency, where we are completely lacking the generation sources, the user might just be interested only in lower percentages than the base one, and study then the benefits and possible disadvantages of its downsizing. This is the most customizable part of the DSS code, where the user can insert the values of the main parameters that will determine the outcomes of the different design solutions. The user might even want to start the evaluation of their microgrid considering only the implementation of fossil fuel generators, without the aid of a battery storage system or photovoltaic generation plant. This is possible by setting the parameter of either the days of autonomy or the critical load as zero, to have a null battery capacity, and after that, to have a null

photovoltaic generation, the first element in the vector $months_for_sizing$ should be put equal to zero. This evaluation might be interesting to see more clearly the environmental advantages regarding the emission of CO_2 and also to compare more neatly the differences between the first year investment, due to the possible installation of a photovoltaic power plant and an energy storage system. This, of course, can be just considered as a useful insight on the real application of the DSS code, which is born precisely to study the best way, according to the user's own interest criteria, to integrate the photovoltaic production and the resilience and reliability coming from the installation of a battery storage system, which is able to provide the adequate energy to the islanded microgrid, which cannot rely on an outer distribution network, in case of an emergency. Furthermore, for the calculation of the peak photovoltaic power to be installed, the user is required to insert the percentage of the overall maximum daily load of the year that must be covered by the photovoltaic power plant. In this way, the photovoltaic power plant will be designed to provide a minimum amount of energy in the month of the year specified by the chosen parameter, the one prescribed for the sizing, that will be sufficient to cover that percentage of the maximum load. Even for this parameter, the choice is completely up to the user. One might be interested in maximizing the photovoltaic generation, and therefore choose a high percentage on the yearly maximum load, hoping that this decision will lead to a lower use of fossil fuel, having the battery storage to be mainly charged by the photovoltaic production. However, as a downside, an excessive installation of peak photovoltaic power might lead to higher curtailment, causing an increase in the first year investment that is not then fully justified by the consequent allocation of power which, to maintain the constant balance, might still need the use of fossil fuel generation. The most common choice will be to define a base load on the overall yearly operation of the microgrid and use that to define the percentage on the maximum load. This will cause the photovoltaic generation to be able to fulfill at least a minimum quantity on energy, as much as the weather forecast can allow, for the month used for sizing and, therefore, for all the months that are characterized by a higher irradiance. A lower percentage than the base load one would determine an under-sizing of installed peak photovoltaic power and, therefore, a higher need of relying on fossil fuel, both for balancing the system and charging the

battery, causing a lower first year investment but a higher dependency on fossil fuel and a worse environmental damage. Another possibility would be to decide to have this percentage equal to the most likely critical load remaining in case of emergency, in order to have a good portion of that load covered by the photovoltaic generation. This might be helpful in the event of lack of only fossil fuel generation, where the power balance will entirely be dependent on photovoltaic generation and battery discharge. Ultimately, all these considerations depend entirely on the user's purpose and the implementation of the DSS code to evaluate different scenarios is aimed as help to visualize better what the different configurations entail, making the user more aware of their choices and maybe helping them in finding possible improvements in their initial islanded microgrid design. Having set all these values, the code is now ready to run.

3.2 Code Flowchart

The structure of the DSS code is based on the Mixed Integer Linear Programming (MILP) optimization algorithm, which is applied for each month of the year swiping between all the different combinations of the chosen design parameters. The optimization, which swipes between the twelve months thanks to a for loop, is placed in 3 nested for loops, each one responsible for the change of one single parameter between the month used for sizing the photovoltaic power plant, days of autonomy of the battery and the percentage of critical load. At the end of this procedure, the code is instructed to portray different graphs showing different key indicators that will help the designer in the final evaluation process.

The first for loop to appear in the code is the one related to the swiping between the months used for the sizing of the photovoltaic generation. Inside this for loop, we find the formula used to set the peak photovoltaic power to be installed for each month used for the sizing. These values are contained in the vector $Ppvn$ (nominal photovoltaic power), which has dimension 12x1 and only the elements in the row corresponding to the month used for the sizing are different from zero. The formula used

to calculate such power is the following:

$$Ppvn = load_max \times percentage/Eirr \tag{3.1}$$

Where $load_max$ stands for the maximum daily load in the whole year, $percentage$ is the percentage of the maximum daily load, decided by the user, that must be covered by the photovoltaic generation and $Eirr$ is the total irradiance energy of the typical day for the month chosen for sizing and comes from the irradiance data downloaded from PVGIS and selected by the user. From this formula, we retrieve the value of kilowatts peak [kWp] to be installed, since the load is defined in watt-hours and the irradiance, from the PVGIS initialization, is defined as watt-hour over kilowatt of peak. From this value we can then calculate the effective photovoltaic production in the typical day of each month. To do so, it is simply needed to multiply $Ppvn$ of the specific month we are considering as a sizing unit, and the yearly irradiance of our installation site coming from PVGIS calculation. We will get as a result the matrix Ppv (photovoltaic power) defined in watt-hours with size 12x24 where each row stores the hourly value of photovoltaic production for the typical day studied for that month of the year. After this evaluation, we have the start of the for loop regarding the days of autonomy of the battery and, right after that, the start of the for loop regarding the critical load to be covered in case of emergency. Inside these two nested loops, we find the definition of the battery capacity and the battery maximum power. We have to remember, in fact, the differentiation between energy intensive and power intensive battery storage, and give a definition for both these qualities. The formula used to define them are the following:

$$Pbatt_max = max(load(:)) \times cl \tag{3.2}$$

Where the maximum power that the battery needs to be able to bestow, in the state of emergency, is the maximum hourly value of load power required by the user scaled by the percentage of critical load we are considering (cl), and it is described in watts, while for the energy capacity we have:

$$unadj_ASEmax = doa \times load_max \times cl \tag{3.3}$$

Where doa describes the days of autonomy, $load_max$ is still the maximum daily load of the year, and cl is the percentage of critical load defined in the user parameters.

This value is called $unadj_ASEmax$ because it then needs to consider the maximum and minimum state of charge of the battery that the user is willing to bear; therefore, to finalize the calculation, we must scale by the difference between these two input variables:

$$ASEmax = unadj_ASEmax/(soc_max_bat - soc_min_bat) \tag{3.4}$$

In this way we finally get the battery capacity corrected of max depth of discharge, described in watt-hours. Since the value of $ASEmax$ is depending on both the iteration on the percentage of critical load and the days of autonomy, it will be described as a 3x3 matrix in which the rows represent the different percentage of critical load, and the columns the different days of autonomy. While $Pbatt_max$ changes only for the percentage of critical load covered, but to maintain the same storage description, we defined it as a 3x3 matrix, where the elements of the same row are all equal to each other, allocating some unnecessary memory space, for the sake of a quicker visualization of the specifics of a single battery storage, due to the overall indifference in the raise of the computational effort.

Since the DSS code inserts the battery storage not only as an aid for the balance of power, but also as a device aimed to enhance the resiliency of the system, the choice of capacity is ultimately due to the latest purpose, because is the one that requires the highest capacity. Therefore, we will see as results the need of devices with the ability to reserve very large quantity of energy. This will not be needed in the daily operation of the system and, for this reason, we will expect the battery to work around rather low values of state of charge. A so big reserve of energy, though, is absolutely necessary for the emergency state of the system. We must remember that the DSS code is born to support the design of islanded microgrids and therefore the most critical state of the emergency is the one where every kind of generation is lacking and the supply of the system can only rely on the battery. The code then concentrates on the optimization of the daily operation of the system, because it is considered to be the most common one. The generation sources will not be instructed to recharge completely the battery after a decided time interval to secure the availability in the emergency state, but this is something left to the energy manager of the system to implement, having given them

the possibility to do so by already considering the effect of the installation of such a big energy reserve in the first year investment.

The next step of the DSS code is the for loop responsible for the optimization of the yearly operation of a certain combination of peak photovoltaic power and battery capacity installed. This for loop will asses the power generated from the fossil fuel generators, the curtailed photovoltaic power, the battery power charged and discharged for each month of the year, representing some key performance indicators that will describe the microgrid operation. This optimization aims at minimizing the liters of fossil fuel used to generate power while strictly maintaining the constraint of power balance. To do so, it is necessary to implement some binary variables specifically to enable and disable, according to the need or absence of the fossil fuel generators, the presence of the y-axis interceptor of their characteristic generation curve, to avoid the simultaneously operation of the battery in both charge and discharge mode, and, finally, to consider the curtailment of photovoltaic power only when strictly necessary, that is to say, when the photovoltaic power is higher than the load requirements. This last decision is made exactly to have the use of fossil fuel as low as possible, giving the priority to the photovoltaic generation to supply the loads, gaining a benefit both economically and environmentally. Furthermore, to allow the continuity of the microgrid operation between one day and the other, an additional constraint is defined for the state of charge at the beginning and at the end of the day, which is imposed to be the same. In this way the battery is already set up to work for the next day, without the need for an initial charge or discharge of energy. The flowchart which shows the operation of the DSS code can be visualized in Figure 3.2.

With the optimization results we are able to calculate all the variables of interest, which represent the key indicators for our study, to then finalize the graphs which will be the main tools for our comparative analysis of the results coming from the different combinations of components. Since we want to portray, in the same graph, the results differentiated for all the combinations, the storage of such variables must be done in a way that allows us to recollect to which specific combination that value comes from. Therefore, all the variables which represent key performance indicators are stored in

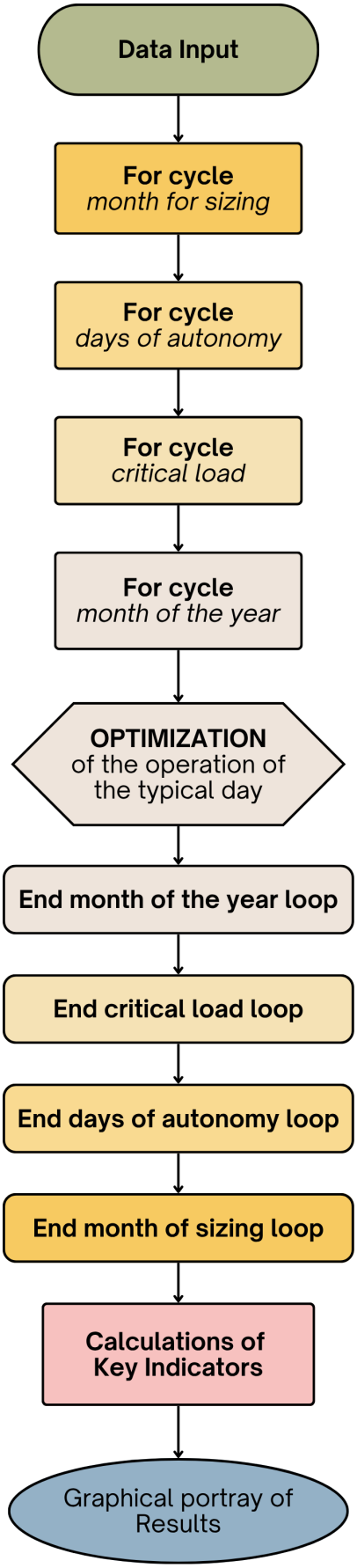


Figure 3.2: *Flowchart of DSS code.*

matrices of dimension equal to:

$$dim = (nmon * ncl) \times ndoa \tag{3.5}$$

Where $nmon$ is the number of months selected by the user to size the photovoltaic power plant, $ndoa$ the number of different evaluations of days of autonomy required by the user and ncl the number of critical load percentages to be considered. If we consider, for example, that the user has chosen three different months to evaluate the photovoltaic sizing, three different values for days of autonomy to be studied and three critical load percentages to be covered we can visualize the storage of such matrices in Figure 3.3. Variables that must be stored in such a way include: the number of

				ndoa		
				doa1	doa2	doa3
nmon	mon1	ncl	cl1			
			cl2			
			cl3			
	mon2	ncl	cl1			
			cl2			
			cl3			
	mon3	ncl	cl1			
			cl2			
			cl3			

Figure 3.3: *Storage of key indicators matrices to differentiate the different combinations*

liters consumed in a year, the first year investment, the kilograms of CO_2 emitted, the percentage of curtailment on the overall photovoltaic production and the share of how the load is covered, what comes from the photovoltaic production, what from the battery discharge and what from the fossil fuel generators, analogously how the overall photovoltaic production is divided between load, curtailment and battery charge.

About the kilograms of CO_2 emitted, this value considers one year of operation of the system, where the specific data related to the photovoltaic and the battery emission are considered to be life cycle emissions or carbon footprint data that relate to the

kilowatt-hours of production, or in case of the battery storage, to the energy stored in the component. To these calculations the effect of the fuel consumption will be added and the user will be required to insert the value of kilograms of CO_2 per liter emitted by the fossil fuel used for the generators.

Another key indicator that will be interesting to study is the ratio between the yearly liters of fuel and the first year investment. This variable will help the user to see if an higher investment is actually worth to be pursued since it causes a sensible reduction of the yearly liters of fuel. In fact, the smaller this ratio the higher the investment and the smaller the number of liters used in a year. While, the higher is that ratio, the higher is the dependency on the fossil fuel generators. What helps the designer evaluation to be even easier is the comparison between a specific combination which can be fixed by the user. This is done by portraying the difference between the ratio of yearly liters over investment for all the combinations and the same ratio of the fixed combination. In this way we will have negative values when the fixed combination determines an higher dependency on fossil fuels, making the combination that we are considering in that moment more environmental-friendly and more energy independent, at the possible expense of a higher first year investment.

To have a simpler comprehension of the data output of the optimization, the DSS code provides different types of graphs to help the user in visualizing the results and comparing them with each other. The first topology of graph used is the scatter type: this graph presents dots the y coordinate of which symbolizes the values to be portrayed. Since it is essential to differentiate the three distinct parameters that made up the combinations, to make every dot unique and easily corresponding to one specific design combination, the dots change in size, in color and in position on the x axis to portray the differences in the three choice parameters. So one parameter will be associated to the x coordinate, one to the color of the dot and the last one to the dot dimension. The specific correspondences will be shown in the legend of the graph. The first key indicator to be portrayed is the ratio between the yearly liters consumption over the first year investment. This key indicator is depicted in the following different graphs:

- **Scatter graph**: where on the x axis is portrayed the month used for the sizing of

the photovoltaic plant, the different colors of dots represent the diverse values of days of autonomy of the battery storage while, and their dimension represents the percentage of critical load that must be covered in emergency state.

- **Three scatter graphs, portrayed in one grid, differentiated by the percentage of critical load**: for each one of the graph the values of the variable yearly liters over first year investment that refer to the same percentage of critical load that must be covered are portrayed together, differentiated only by the month used for the sizing of the photovoltaic plant on the x coordinate and by the days of autonomy of the battery storage with different color dots.

- **Three scatter graphs, portrayed in one grid, differentiated by the days of autonomy of the battery**: for each one of the graph the values of the variable yearly liters over first year investment that refer to the same value of days of autonomy that the battery can sustain are portrayed together, differentiated only by the month used for the sizing of the photovoltaic plant on the x coordinate and by the percentage of critical load that must be covered with different color dots.

Even the key indicator regarding the CO_2 emissions is portrayed with the same simple scatter graph used for the ratio between yearly liters and investment. While for the key indicator that represents the difference between the ratio belonging to two different combination, so the delta yearly liters over the delta investment, is portrayed with two scatter graphs:

- **One scatter graph with months used for sizing the photovoltaic plant on the x coordinate**: the different colors of dots represent the diverse values of days of autonomy of the battery storage while, their dimension, represents the percentage of critical load that must be covered in emergency state.

- **One scatter graph with days of autonomy of the battery storage on the x coordinate**: the different colors of dots represent the diverse months used for the sizing of the photovoltaic plant while, their dimension, represents the percentage of critical load that must be covered in emergency state.

Finally, the last graphs shown by the DSS code are pie charts. In particular, these pie charts will be placed inside three different windows that portray three peculiar combinations:

- **The cheapest solution**: the combination that provides the lowest first year investment.
- **The most reliable solution**: the combination that allows for the highest nominal photovoltaic power to be installed, the one related to the worst month of irradiance, the highest number of days of autonomy of the battery storage, and the highest percentage of critical load covered in emergency state.
- **The most sustainable solution**: the one that provides the lowest value of kilograms of CO_2 emitted in the atmosphere.

For each graph produced we will be able to visualize the values of the parameters that made up that specific combination, in order to know to which design solution these title refers to. For each scenario, three different pie charts will be portrayed:

- **Load Supply**: shows how the load is covered between the different percentages of photovoltaic power, fossil fuel generation, and battery discharge.
- **Distribution of PV production**: shows how the photovoltaic generation is divided between the load, which has the priority, the battery charge and the quantity that is affected by curtailment, if present.
- **BESS Charging**: shows how the battery storage system is charged, differentiating the percentage of energy coming from the photovoltaic production and the fossil fuel generation.

3.3 Rainflow Code

Another code that can be integrated in the use of the DSS code is the Rainflow code. This code is instructed to calculate the useful life time of the battery storage defined by a specific combination of parameters, and therefore, by a specific operational mode

which is the result of the MILP optimization, through the Rainflow method. In the Rainflow algorithm each charging cycle is paired with a discharge cycle in order to determine the total duration of that cycle. With the sum of all the cycles that the battery undergoes, we are then able to calculate the damage suffered by the battery [19]. The combination taken into account can be changed by the user in the DSS code within the section regarding the Rainflow reference variables that can be found at the begining of the script, while the actual calculation and storage of the needed variables is placed within the for loop of the monthly optimization of the system operation. The Rainflow code must be run after the run of the DSS code and it will study the damage on the battery, considering all the year long operation. After calculating the damage for the typical day of each month of the year, that damage will be weighted by the number of days present in that month and, by summing them all together, the total yearly damage will be calculated. The useful life of the battery will then be obtained with the following formula:

$$useful_lifetime = ceil(1/total_annual_damage) \tag{3.6}$$

Where the output is expressed in days as the smallest integer greater than or equal to the reciprocal of the total annual damage. This operation is extremely interesting for calculating the overall expenses of the installation of the islanded microgrid. In fact, by knowing the days of useful operation of the battery storage, we can predict how many times, in the overall lifetime of the project, it will be necessary to substitute such component. With these calculation we can then have a more deep understanding, not only of the operation of our system, but also of its environmental consequences and future expenses.

Chapter 4

Case Study

To test the DSS code on a real life application, we used the load hourly data from Kamal Adwan Hospital located in Gaza. As discussed before, a hospital is the perfect example of a microgrid: continuation of service must be allowed at anytime, independently from the operational state of the outer distribution network. It is particularly easy to associate the idea of a percentage of critical load to a hospital as well; in case of emergency, only life-saving equipment has the urgency of being supplied, while other customer satisfaction services can be put on hold without the risk of hurting people. Considering the current geopolitical state of that area, it is, in no possible way, assured to provide a completely adequate level of resilience, but the implementation of a microgrid might be able to provide at least the energy independence of the building, thanks to photovoltaic generation and the installation of a battery storage system, making the hospital less dependent on fossil fuel consumption.

4.1 Data Input

The load hourly data of the hospital is divided in two typical days, one for the summer period, considering the months of April, May, June, July, August, and September, and one for the winter period for the remaining months of the year. These two typical days are taken from the report of the United Nations Development Programme (UNDP) on the Solar Electrification of the Health System in the Gaza Strip [2] and are written down, in this order, in an excel file where the hourly load is described in

watt-hours. The load data used are shown in Table 4.2.

Hour	Summer load	Winter load
1	165300	85200
2	162400	83700
3	154000	79400
4	152000	78400
5	162500	83800
6	161900	83500
7	144500	74500
8	161000	83000
9	150900	77800
10	158900	81900
11	194700	100400
12	202500	104400
13	186000	95900
14	181600	93600
15	191700	98800
16	177300	91400
17	182600	94100
18	201700	104000
19	211400	109000
20	186700	96200
21	167200	86200
22	168100	86600
23	166200	85700
24	162800	83900

Table 4.1: *Gaza Hospital hourly data in watt-hours [Wh]*

To ensure the continuity of the service, as much as possible, two diesel generators are considered, in order to have at least one as a backup in case of the malfunction of

the other. To decide on the size of the two diesel generators, it is necessary to look at the values of the daily load. The idea would be to define the power of a diesel generator to be equal to the base load, that is to say, the minimum amount of energy that must be supplied, in the normal operation of the microgrid, each day of the year. In this way, that generator will work in full load operation as much as possible, so at the best possible generation efficiency. In our case, to comply with market standard sizing, this generator will be sized with power equal to 80 kW. The other generator, instead, must be sized so that the sum of the power of the two diesel generators will be sufficient to fulfill the highest load requirement. This is done to guarantee the continuity of the service even in the complete lack of photovoltaic generation. For this reason, complying with market standard sizing, we will consider a second generator with 140 kW of power. To fulfill the requirements of the code we must insert in the excel sheet about the generators, not only the power in watts, but also the angular coefficient, which we will call m, and the y-intercept, which we will call q, that describe the load curve. To calculate the load curve, we searched for the hourly liters consumption of diesel generators of similar sizes based on the load factor, and linearized that behavior. These data are taken from the web [20] and refer to a diesel generator with 75 kW power to symbolize the 80 kW one, and one with 150 kW to symbolize the 140 kW one. Their linearization was studied with an excel file and can be visualized in Figure 4.1. From the lines that linearize the behavior of the load curve, we can extract the angular coefficient and the y-intercept and save them in the appropriate excel file that will be used in the optimization. The final table which will work as input of the DSS code regarding the chosen generators is the following:

Nominal Power [W]	**m**	**q**
80000	4.6556	3.9743
140000	9.2354	4.1635

Table 4.2: *Diesel Generators data*

After the generator initialization, it is now time to insert the irradiance data relative to our site of installation. To retrieve the irradiance data we will use PVGIS software.

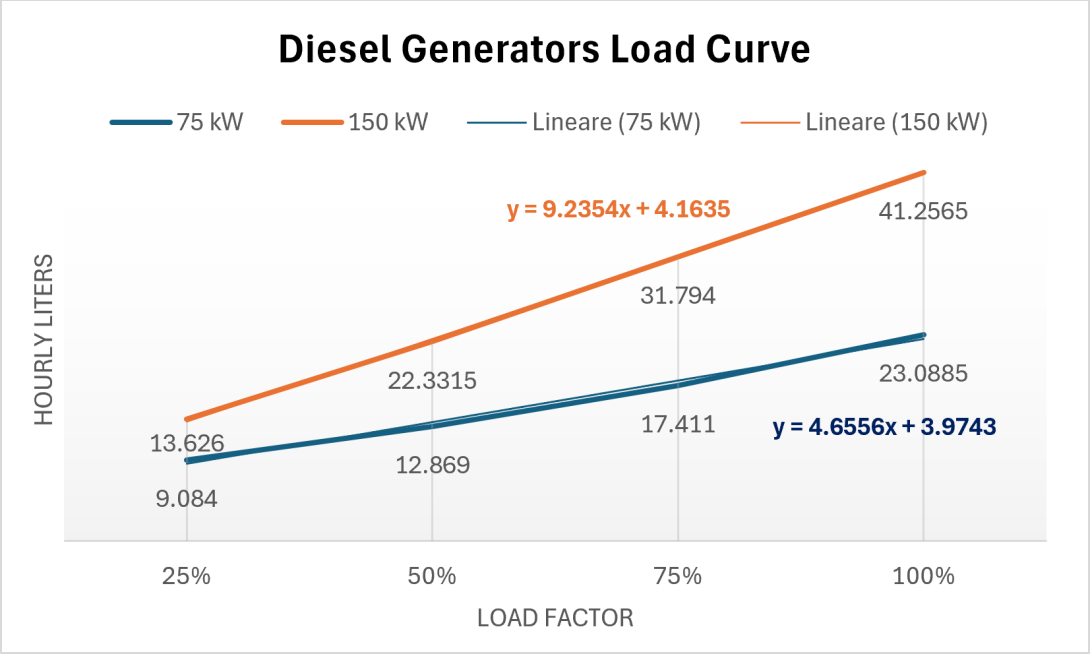


Figure 4.1: *Diesel generators load curves and their linearization.*

To download the irradiance data, we need to select the hourly data section from the PVGIS main page and insert the geographical coordinates of our microgrid. Since the precise position of our hospital is unknown, we used plausible coordinates that could well represent our installation site. The PVGIS irradiance data, therefore, correspond to the geographical location described by a latitude of 31.522561 and longitude of 34.453593, which corresponds to a position in the center of Gaza City. Not using the exact position will not cause a high level of imprecision since the meteorological data regarding irradiance will not change as much; it is important, though, that anywhere the photovoltaic panels will be installed will not be shaded by taller structures, so the designer must be aware of eventual obstacles. We prescribed the software to work with fixed mounted panels and to optimize their slope and azimuth angle. We will insert a nominal power of 1 kWp, so that we can then easily calculate the true photovoltaic generation once the code has assessed the nominal power to be installed. We selected the photovoltaic panel technology as crystalline silicon, since it is the most common one available on the market, and we selected a generic loss value, suggested by PVGIS, of 14% to directly consider the electrical generation resulting from the photovoltaic transformation. The PVGIS page initialized in this way can be seen in Figure

4.2.

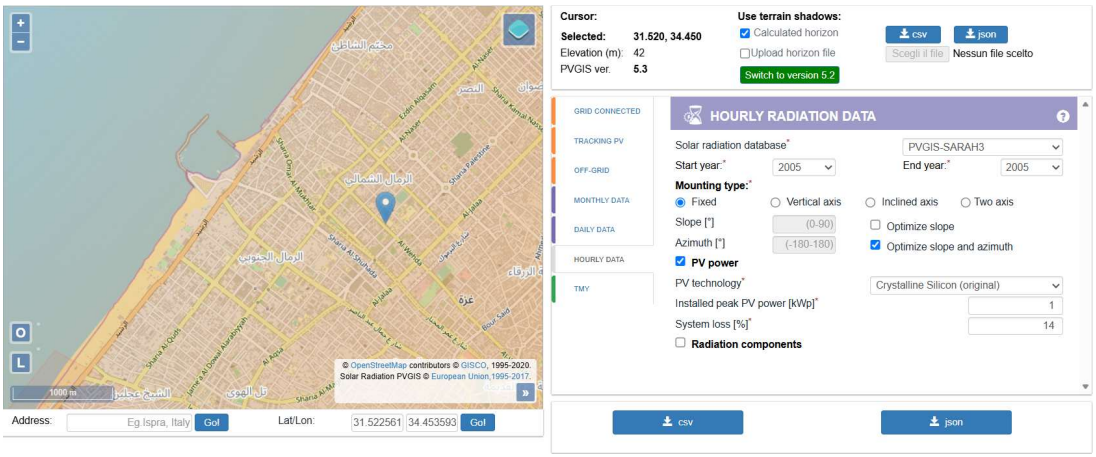


Figure 4.2: *PVGIS page inizialized with the study case data.*

After this procedure, we are ready to download the data. The next step is to reorganize the hourly irradiance data for the entire year to be able to select just one typical day for each month. In order not to be influenced by the meteorological data of one specific date, we decided to use an excel pivot table to calculate the average between the specific hour of that specific month, in order to build 12 typical days, one for each month, that are the average of all the days present in that month. Initially, for the sake of simplicity of data manipulation, we thought of considering a fixed day for each month, but that information would have altered the real classification of the irradiance of the different month, putting as the lowest irradiance month simply the one with cloudiest weather on that specific day. The irradiance data, defined hourly and already in electrical watt-hours, for each typical day of the month, can be seen in Figure 4.3.

In order to have a complete economical analysis we must insert the data relative to the cost, comprehensive of the installation cost, of our components. While, to complete the environmental analysis regarding the emissions of CO_2, we must define the kilograms per liter emitted by the fossil fuel used in the traditional generation. We can also add the data relative to the equivalent kilograms of CO_2 from the photovoltaic and battery technologies, in the form of Life Cycle Emissions (LCE). In particular, for the data related to photovoltaic production, we consider the carbon footprint of the photovoltaic panels as prescribed by the European commission in their technical re-

Hour	January	February	March	April	May	June	July	August	September	October	November	December
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	1.065806	2.892333	0.675161	0	0	0	0	0
5	0	0	2.575484	31.45667	58.15258	55.556	44.9929	28.07774	30.46633	5.812258	0	0
6	33.60806	59.11429	120.6135	175.9313	203.8948	204.9387	182.8584	150.2958	193.0477	136.7784	110.2677	56.96387
7	201.2845	251.48	296.6387	337.51	373.1716	366.6223	362.7326	326.63	380.9273	317.2571	292.292	264.0139
8	352.1361	382.8404	431.9426	497.8097	515.5548	473.82	503.3045	481.5065	533.5777	483.4003	452.4763	411.7626
9	539.251	502.6004	580.7352	631.9527	636.8739	592.0803	637.3461	611.1958	652.4063	551.7981	534.5747	528.7184
10	575.7613	587.2275	627.469	708.2853	711.6148	632.246	702.0058	690.3416	707.109	631.1506	578.4	568.4681
11	573.0174	561.3229	685.2494	719.059	714.8835	679.24	722.7274	709.7565	726.526	598.9906	556.418	557.9129
12	569.0935	577.0518	651.1139	722.4047	687.3016	614.7903	691.7787	677.0042	689.2713	560.2948	539.3847	528.1042
13	507.5613	486.0554	564.6068	609.309	595.9584	583.049	616.9477	589.389	564.1643	470.7371	440.6987	413.6813
14	362.3971	387.7739	467.0455	463.7977	454.3555	455.058	491.4484	454.7287	443.2893	339.5635	298.7407	249.2529
15	166.4823	211.265	255.8368	290.7263	276.6106	289.6417	324.2287	297.281	253.8773	123.5535	67.66667	68.99097
16	0	12.01286	60.32516	89.64667	105.5768	121.1443	134.899	106.6155	51.182	0.444839	0	0
17	0	0	0	0	4.026129	16.184	17.2071	3.393871	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0

Figure 4.3: *irradiance hourly data in electrical watt-hours [Wh].*

port of 2025 [21]. These values change consistently from the site of production of the panels and the transportation to their final installation site, so, to get a general result, since the data related to our system are not available, we decided to consider the worst possible scenario. In this section, due to the specific data inserted by the user, we can define the technology of the battery storage system we are going to use. In our case, we have opted for the Lead-Acid type. Lead-Acid batteries are widely used for large scale microgrid applications, due to their good charge retention, their excellent energy density, their fast rate of response and a generally large calendric life span of around 15 years; although they are also characterized by a shorter life cycle, so they can sustain a small number of charging/discharging cycles (around 2000), and require regular maintenance [22]. To use as a generic plausible cost, we considered the data relative to the installation of the photovoltaic power plant and the battery storage system, found in various article in literature or on the web. The same is done for the data related to the CO_2 emissions of the battery storage. While, for the cost of diesel, we used the price found online updated to the date of the simulation of the study case. In the absence of data relative to the precise country in which our microgrid will rise, we used the price of the nearest country that was available. These values and their reference can be seen

in Table 4.3. It is strictly necessary to use the defined unit of measure to allow the DSS code to do the correct calculations.

Cost PV [$/kWp]	1510 [1]	[23]
Cost Lead-Acid BESS [$/Wh]	0.22	[11]
Cost Diesel liters [$/L]	1.22 [2]	[24]
CO_2 **emission from diesel [kg/L]**	2.7	[25]
CO_2 **emission from PV production [kg/kWh]** [3]	0.044	[21]
CO_2 **emission from stored energy in BESS [kg/kWh]** [4]	0.028	[26]

Table 4.3: *Cost of components and CO_2 emission data.*

To consider a correct use of the Lead-Acid battery storage we defined a maximum depth of discharge possible by restricting the state of charge to a minimum of 0.2, keeping as maximum the rated capacity. This is done to preserve the battery, not letting it go under the minimum state of charge, in fact, allows for a better operation and longer lifetime of the storage component.

The choice of the percentage of the total maximum load, that is, the percentage of maximum load that must be covered by the photovoltaic production during the month specified by the user, is needed to size of the peak photovoltaic power to be installed. The month, whose irradiance is used for the photovoltaic sizing, is chosen by the user in the vector regarding such parameter and it is responsible for the iteration of one of the three for loops, determining a different value of peak photovoltaic power for each month inserted in that array. While, to define the percentage of load to be covered, we considered the load hourly values for the typical day of the two different seasons, and choose the percentage of the maximum load that represents a yearly base load. In order to do so, we need to consider the minimum amount of load required by the user in the overall year, multiply that hourly value by 24 to consider its extension on the whole day, and compare it to the maximum load day that we have. Having done these

[1] price updated to year 2025
[2] price relative to Jordan
[3] Carbon Footprint
[4] LCE - Life Cycle Emissions

calculations in an excel file we get that the minimum load determines a base load the percentage of which on the maximum load day is equal to 40%. The reasons behind this decision are based on the desire to compromise the highest possible photovoltaic production, benefiting the environment, while avoid as much as possible the need of curtailment, causing an unjustified investment in components the production of which will not be entirely used. These calculations are completely dependent on the user evaluations and reasoning; another designer might choose a different strategy to size the photovoltaic plant, for example, one that aims at maximizing the peak photovoltaic power installed, to cover a higher percentage of load in the daily operation of even the lower requirement load day.

The last values that the user needs to insert in the DSS code are the choice parameters on which the different combinations of component sizing are based. The whole code is centered on the evaluation of these specific situations, so it is important that the user chooses them accordingly to their main interests regarding the aim and needs of the microgrid. For our simulation, the values chosen for these parameters are the following:

- **Months used to size the peak photovoltaic power to be installed**:

$$months\ for\ sizing = [\quad 3 \quad 7 \quad 12 \quad] \tag{4.1}$$

  To choose the months to evaluate the nominal power of the photovoltaic production, we focused on the value of irradiance, coming from PVGIS data, that characterizes the typical day used to describe that month. We considered the worst month regarding the value of received irradiance, which is December, the best one, so the month with the highest irradiance value, which is July, and an average month, such as March.

- **Days of autonomy of the battery system in the emergency state**:

$$doa = [\quad 1 \quad 4 \quad 7 \quad] \tag{4.2}$$

  These values are chosen as a supposition of the plausible duration of the emergency state, from a quickly repairable interruption of 1 day, to a mild one of 4

days until an extreme interruption of generation lasting a week. The causes that could determine a state of emergency are various, from the interruption of the provision of fossil fuels, in the case of remote islanded microgrids that could be impacted by street work or other kind of damage from natural disasters, to the breakdown of a component, whether it be the fossil fuels generators, feeders, or the inverter or other devices that cause the disconnection of the photovoltaic plant. Therefore, these values can change a lot between different types of microgrids and only the designer can predict their duration more appropriately.

- **Critical Load percentage to be covered in the emergency state**:

$$\textit{critical load} = \begin{bmatrix} 0.5 & 0.7 & 1 \end{bmatrix} \tag{4.3}$$

The percentage of critical load to be covered by the battery storage system during the emergency state is chosen thanks to the Critical Load Evaluation code. The results of that code showed that the most probable percentage of remaining load after a feeder fault is 70%; therefore, we will use that as one of the values to evaluate. The other parameter that would make for an interesting observation is the ability to cover the entirety of the load, so a percentage equal to 100%. The last value we will consider, since we decided to go for 100%, so a higher percentage than the most probable one, is a lower value, like 50%, to have a broader variability in the results and therefore a more unique comprehension of the various possibilities of results in our simulation. Furthermore, it is interesting to see how this value of minimum amount of critical load considered for our system is very similar to the percentage of load used to size the photovoltaic power to be installed (40%), meaning that the photovoltaic production was sized taking into consideration a good portion of the minimum possible amount of critical load.

Now that we have set all the parameters, the DSS code is ready to run and show its results in MATLAB windows.

4.2 Results

The graphical portrayal of the DSS code results is an essential part of the project, since the aim of it is to be easily understandable by anyone interested in the foundation of a microgrid. In fact, designers could use the resulting graphs of the code to justify their choices in front of the actual customers of the microgrid, who have to be able to understand it whatever their cultural background may be. First of all, it is interesting to show the results regarding the sizing of the different components due to the different combinations of the parameter values chosen by the user. Table 4.4 contains the results concerning the peak photovoltaic power installed, while Table 4.5 the ones relative to the battery capacity. Since a battery is described not only for its energy storage but also for the maximum power they are able to store or discharge, we must define also this value that describe its power intensity quality. To define it we will consider only the percentage of critical load prescribed for that specific combination and multiply it by the highest hourly load required by the microgrid. The final results for the battery power can be seen in Table 4.6.

Month used for PV sizing	**Ppvn [kWp]**
March	350.2333
July	305.8188
December	455.4878

Table 4.4: *Peak photovoltaic power to be installed resulting from changing the value of irradiance, using the different months prescribed for sizing.*

As expected, the month of December, characterized by a low value of daily irradiance, is the one that requires the highest value of peak photovoltaic power to cover the percentage of load required by the user. This will definitely be one of the reasons that will determine a high first year investment for the combinations described by this month for the sizing of the photovoltaic power plant. The installed peak power is significantly lower for July, which is the month of the year with the highest daily irradiance value, while the average month for irradiance value, March, is much closer to July than to December. Therefore, it is plausible that the month of December is one of the

Battery Capacity [Wh]				
		Days of autonomy		
Critical load	50%	2596187.50	10384750	18173313
	70%	3634662.50	14538650	25442638
	100%	5192375	20769500	36346625

Table 4.5: *Battery capacity according to the different combinations of days of autonomy and critical load percentage to be covered in emergency state.*

Battery Power [W]				
		Days of autonomy		
Critical load	50%	105700	105700	105700
	70%	147980	147980	147980
	100%	211400	211400	211400

Table 4.6: *Battery power according to the different critical load percentage applied to the maximum hourly load to be covered in emergency state.*

few exceptions in the overall year, and a sizing like the one deducted from the month of March would generally be sufficient to provide an acceptable quantity of photovoltaic production. The sizing of the battery, on the other hand, prescribes very big capacities of the order of megawatt-hours, reaching up to tens of megawatt-hours when the days of autonomy increase from the base value 1. It is important to remember that these values of capacity are required only in the event of an emergency, in the normal operation of the microgrid these quantities of stored energy would never be reached and the capacity of the battery storage will be underutilized. In fact, to be able to completely charge this capacity, a very high number of fossil fuel liters will be needed, but

the aim of the day-to-day operation is to minimize this quantity. For the resilience of the system, it is although fundamental to allocate these capacities, otherwise we would completely lose the ability of supplying the system during an emergency state in which the generation is completely lacking. The maximum power that the battery can bestow or store changes significantly between one percentage of critical load and the other, arriving to double itself, as expected, when moving from 50% of critical load percentage to 100%. This difference will be responsible for the definition of curtailed photovoltaic power during the optimization of the yearly operation of the microgrid.

Some key indicators that are not directly portrayed in a graph, but that can still be found in the code, are the yearly liters of fossil fuel used and the first year investment of a specific combination. These values, in fact, can be found in the code under the matrices of name *yearly_liters* and *investment* and are reported in Figure 4.4 and Figure 4.5.

				Days of autonomy		
				1	4	7
Months for sizing	March	critical load	50%	55256.19	55253.18	55253.18
			70%	55746.31	55761.50	55528.50
			100%	54720.36	54670.17	54337.41
	July	critical load	50%	61858.83	61932.48	61575.41
			70%	62784.71	63268.33	63315.27
			100%	61513.21	61578.59	61581.94
	December	critical load	50%	44695.56	45004.01	45196.81
			70%	41240.97	41090.12	41065.29
			100%	36770.56	36587.04	36561.90

Figure 4.4: *Liters of fossil fuel used in a year [L].*

As we were anticipating, the month of December that leads to an higher installation of peak photovoltaic power is the one that consumes the lowest number of liters in the yearly operation. In particular, in this month we can notice the high difference of around 5000 liters between the combinations that consider 50% of critical load and the ones that consider 70%, the same difference is visible between the combinations with 70% of critical load and 100%. However, this difference cannot be seen if we focus only on the increase of the capacity due to the increase of days of autonomy. The designer

				Days of autonomy		
				1	4	7
Months for sizing	March	critical load	50%	$1,100,013.54	$2,813,497.29	$4,526,981.04
			70%	$1,328,478.04	$3,727,355.29	$6,126,232.54
			100%	$1,671,174.79	$5,098,142.29	$8,525,109.79
	July	critical load	50%	$1,032,947.58	$2,746,431.33	$4,459,915.08
			70%	$1,261,412.08	$3,660,289.33	$6,059,166.58
			100%	$1,604,108.83	$5,031,076.33	$8,458,043.83
	December	critical load	50%	$1,258,947.89	$2,972,431.64	$4,685,915.39
			70%	$1,487,412.39	$3,886,289.64	$6,285,166.89
			100%	$1,830,109.14	$5,257,076.64	$8,684,044.14

Figure 4.5: *Cost of first year investment for the installation of photovoltaic power plant and battery storage system[$].*

who is mainly concerned about the reduction of the yearly liters of fossil fuels might decide to go for an increase of the percentage of critical load, rather than the days of autonomy, to enlarge the battery since this has a higher impact on the daily operation of the microgrid. This decision will help in the resilience of the system, but only if we actually care about supplying a higher share of loads, so if we want to consider more loads as critical. If the designer wants to truly enhance the resilience of their system for the already specified critical loads, for example 50%, they must accept a higher consumption of fuel liters. This decrease of diesel consumption due to the increase of the percentage of critical load is not as consistent as in the other months used for the sizing of the photovoltaic plant, where, in fact, having fixed the month and the days of autonomy, moving from 50% of critical load to 70% increases the value of yearly liters. This is probably due to the constraint on the battery storage system to return to the same state of charge at the beginning and at end of day, to ensure the continuity of the system. Having a larger capacity, the optimization must utilize some liters to fulfill this constraint. Furthermore, we see how the month of July which, because of the high level of irradiance, prescribes the lowest peak photovoltaic power installed, is also the one that needs the greatest amount of diesel liters to operate: this is due to the lower photovoltaic production in the other months of the year since it can rely on a lower nominal photovoltaic power. An average behavior can be seen in the month of March. Whatever the month of sizing and the percentage of critical load, the increase

of days of autonomy do not affect much the number of liters consumed in the year. On the contrary, we often find a lower value of yearly liters when the days of autonomy are increased to 7 compared to when they were 4. Since these results are connected to the optimization of the microgrid operation, and one of the constraint of optimization is the continuity of the state of charge between the end of a day and the beginning of another, we can suppose that the battery with the higher capacity allows for an easier operation in that regard, organizing its charge and discharge cycles in a way that requires less fossil fuel generation to reach the initial state of charge.

Regarding the first year investment we can see, as predicted, a consistent increase due to the size of the battery. The difference between the same combinations for different months for sizing is not so relevant, meaning that the increase of investment cost is mainly driven by the battery storage system and not by the photovoltaic power plant. This is also to be expected due to the larger variety present in the sizes of the batteries, while the dimensions of the photovoltaic plant are not so significantly different between the different months used for sizing. Another interesting indicator is the yearly percentage of curtailed photovoltaic power over the whole photovoltaic production. As for the yearly liters and the first year investment, the percentage of curtailed power is not directly depicted in a graph, but its matrix can be found in the code under the name *yearly_perc_Pcur* and it is reported in Figure 4.6.

				Days of autonomy		
				1	4	7
Months for sizing	March	critical load	50%	1.1336%	1.1336%	1.1336%
			70%	0%	0%	0%
			100%	0%	0%	0%
	July	critical load	50%	0.0785%	0.0785%	0.0785%
			70%	0%	0%	0%
			100%	0%	0%	0%
	December	critical load	50%	9.4104%	9.4104%	9.4104%
			70%	2.4928%	2.4928%	2.4928%
			100%	0.0781%	0.0781%	0.0781%

Figure 4.6: *Yearly percentage of curtailed photovoltaic power with respect to the overall photovoltaic production.*

Predictably, the highest percentages of curtailed power are found in the month of December, where we have installed the highest peak photovoltaic power. The increase in battery storage capacity, thanks to the increase in the percentage of critical load to be covered, helps to reduce the curtailed power, whatever the month used for the sizing of the photovoltaic power plant, but this does not happen when we increase the battery capacity by increasing the days of autonomy. That is because the maximum power of the battery changes uniquely due to the percentage of critical load, and the maximum power of the battery is, in fact, what enters in the optimization of the microgrid operation. The curtailment of photovoltaic power is strictly connected to the time of its production during the day and the value of demand to be covered at that time. It might be impossible for the battery to store in such a small amount of time that power, due to its technological characteristic and the state of charge of the battery. The month of July is the one characterized by the lowest value of curtailed power. That is due to the small peak photovoltaic power installed, that causes a lower amount of photovoltaic generation during the day and therefore a higher probability for it to be utilized in the energy balance. Also the average month of March has a low quantity of curtailed power, making it a reasonable month for the sizing of the photovoltaic power plant, especially because, as for the best irradiance month, the combinations with the percentage of critical load higher than 50% entail a null amount of curtailed power, providing for the maximum utilization of the photovoltaic generation, completely justifying its installation.

Having described the key indicators that can be found in the code, it is now time to evaluate the ones which are presented graphically. We will undergo all the graphs elaborated by the code and make some considerations about the results found, what they suggest about the optimal sizing of the microgrid and their operational outcomes.

The first graph proposed by the DSS code shows the key indicator of the ratio between the liters of fuel consumed in a year and the first year investment. In order to do so, it uses a scatter graph where the x axis symbolizes the month used for the sizing of the photovoltaic plant, while the diverse values of days of autonomy of the battery storage are represented by different colors of dots and the different dot dimensions represent the percentage of critical load that must be covered in emergency state. This

graph is shown in Figure 4.7.

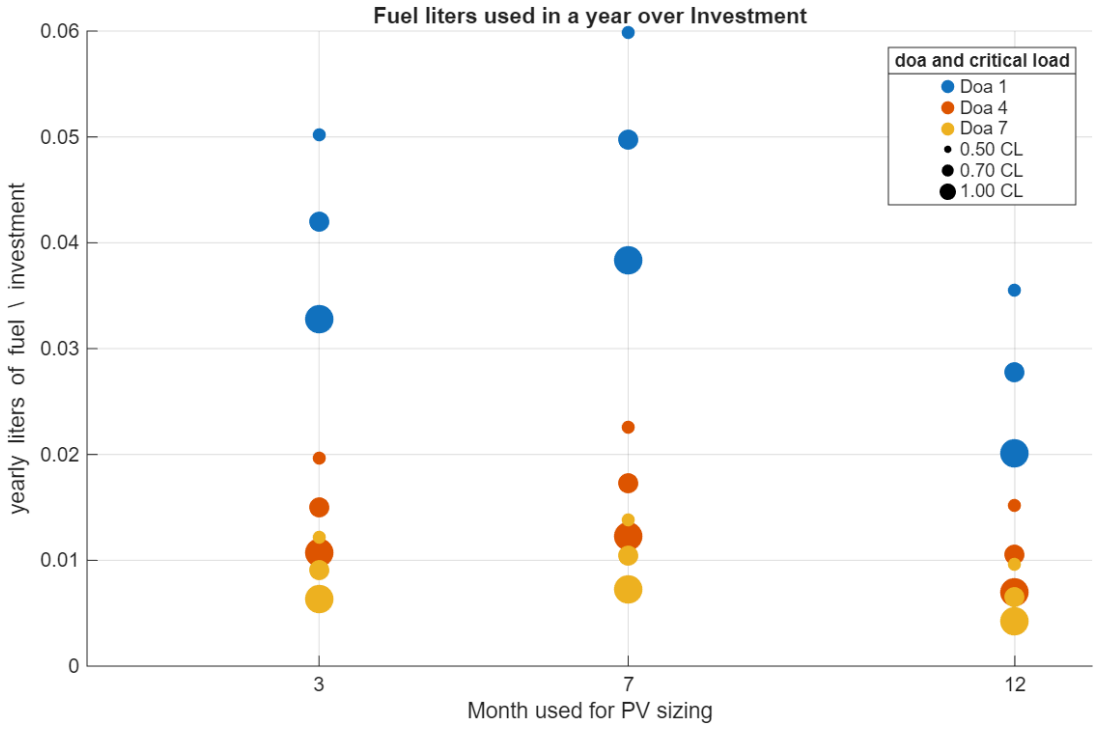


Figure 4.7: *Ratio between yearly liters of fuel over first year investment [L/$].*

We can immediately notice the big gap between the blue dots, that refer to the combinations characterized by 1 day of autonomy of the battery, and the others. In these cases, we have a much higher ratio due to the lower value of investment, since the battery has a much lower capacity, and to the higher consumption of fossil fuel liters. The dimension of the battery capacity, and its consequence on the investment value, also explains the progressively lower values of this key indicator for the combinations defined by a fixed number of days of autonomy and an increasing value of percentage of critical load, since also this parameter causes an increase in the battery capacity and therefore in the investment. Furthermore, we must remember that an increase in the battery storage also defines a lower consumption of fossil fuel liters, since the system can better exploit the photovoltaic production thanks to the battery time-shifting quality. Between all months, July is the one with the highest ratios. This is due to the lower investment in the photovoltaic power plant and the consequent higher consumption of diesel liters, in fact, July determines the lowest peak power installed due to its higher irradiance and, therefore, a smaller photovoltaic production. Regarding

the month used for photovoltaic sizing, it is clearly visible the great distance between the values of the combinations with one day of autonomy of the months of March and July and those of the month of December. In fact, this last month, having a lower irradiance value, determines a higher installed peak photovoltaic power and a higher investment so a lower need for fossil fuel energy production. This situation quickly allows us to understand how a little increase in the investment can actually entail a great energy independence of the system. In addition to that, the combination described by the month of December, one day of autonomy, and 100% of critical load covered by the battery, has a ratio value which is very comparable to the ones of the combinations of the months of March and July characterized by 4 days of autonomy of the battery and 50% of critical load covered, which actually determines a much higher investment cost, meaning that the reduction in the consumed diesel liters is so decreased by the higher photovoltaic production to actually reach the same ratio even with a much smaller investment. This is something that without the aid of this key indicator would have been very difficult to find out. It is interesting to note that generally the higher the battery capacity, the lower is the difference between the combinations that differ only for the month of photovoltaic sizing, meaning that what drives the investment is the battery and not the photovoltaic power installed. A designer strictly concerned about the first year investment should consider one of the combinations with the battery characterized by a single day of autonomy, but, looking at this graph, they might be willing to pay a little more attention to the number of liters consumed in a year and not choose directly the lowest investment combination, maybe opting for a different month for the photovoltaic sizing or a different percentage of critical load. While a designer that is more interested in the environmental impact or the energy independence of the system will consider mostly the configuration with a lower ratio, so the ones with 4 days of autonomy of the battery, and especially the ones with 7 days of autonomy. A peculiarity of this graph is its ability to quickly show those combinations that, although made up of different design parameters, allow for very close values of this key indicator. Thanks to the similarity in values, the designer might decide to choose a different solution from the one they were initially considering, changing one design parameter, in order to select that different combination that guarantees an improvement in another

quality of the system, for example, the resilience, by changing the days of autonomy of the battery, without damaging this key indicator.

To better evaluate the environmental impact of the system, we can look at the second graph, shown in Figure 4.8, that plots the equivalent kilograms of CO_2 emitted.

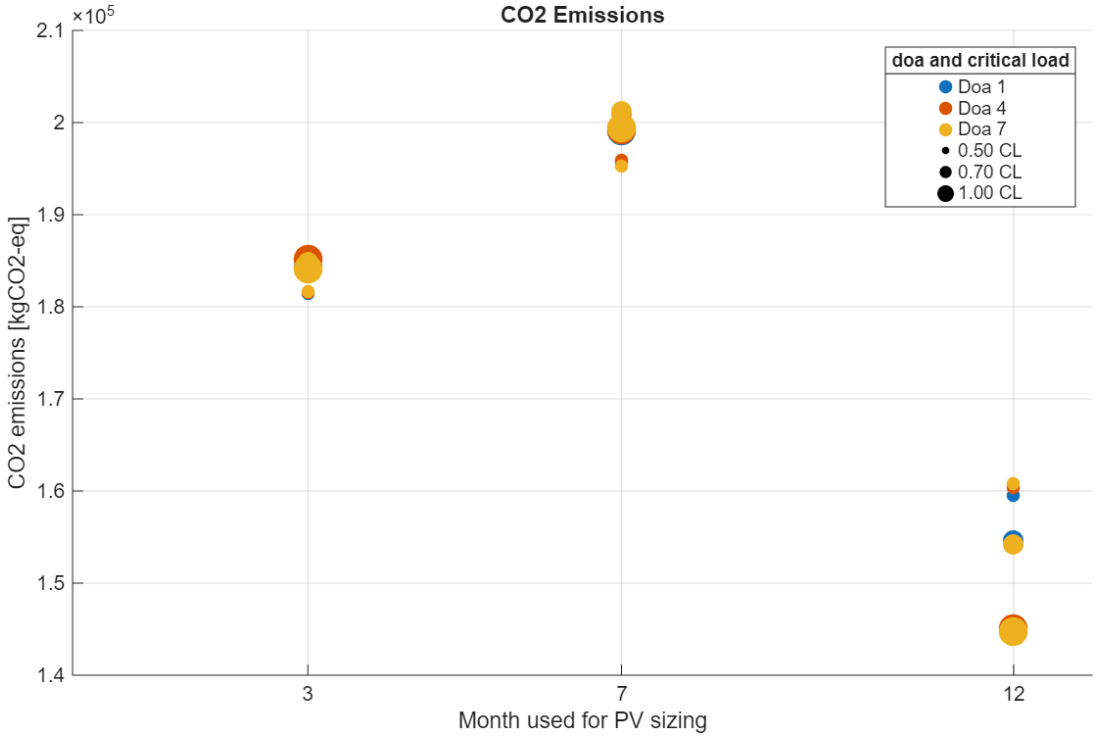


Figure 4.8: *Equivalent kilograms of CO_2 emitted yearly [$kgCO_2$-eq].*

Intuitively, we could have predicted the combinations described by the month of July, which provides the lowest peak photovoltaic power to be installed, to be the most polluting ones, since they entail the highest number of diesel liters consumed yearly. The consequent behaviors for the combinations described by March to be found in an average position and the ones describe by December resulting as the lower emitting ones are also very reasonable for the correlation to the photovoltaic power installed. What is surprising is that the values of emissions tend to overlap one another, and for the combinations described by the month of July and March, the highest values can be found for the combinations described by a high number of days of autonomy. We might be led to believe that this result entails a high influence of the energy stored in the battery in the total CO_2 emissions, but actually, if we focus on the yearly consumption of liters, we see that those results are highly comparable and, therefore, due to the high

emitting propriety of diesel, we can assess that the emissions are a direct consequence of the fuel consumption. We can see the comparison of this two quantities thanks to the conditional graduation propriety of excel shown in Figure 4.9.

				Yearly liters [L]			CO2 emissions [kgCO2-eq]		
				Days of autonomy			Days of autonomy		
				1	4	7	1	4	7
Months for sizing	March	critical load	50%	55256.19	55253.18	55253.18	181468	181576	181603
			70%	55746.31	55761.50	55528.50	185236	185416	184849
			100%	54720.36	54670.17	54337.41	184269	185157	184081
	July	critical load	50%	61858.83	61932.48	61575.41	195676	195853	195226
			70%	62784.71	63268.33	63315.27	199868	201009	201204
			100%	61513.21	61578.59	61581.94	199149	199202	199375
	December	critical load	50%	44695.56	45004.01	45196.81	159502	160374	160804
			70%	41240.97	41090.12	41065.29	154650	154232	154190
			100%	36770.56	36587.04	36561.90	145013	145097	144682

Figure 4.9: *Table with the values of kilograms of CO_2 emitted yearly [$kgCO_2$-eq].*

The overlapping of the dots is fundamentally due to the small difference in the liters of diesel consumed yearly for those combinations. The fact that higher battery storage requires a higher consumption of liters is linked to the operational mode of the micro-grid, particularly to the constraint of continuity of the state of charge at the beginning and at the end of the day of operation. Only the design combinations where the month of December is used for the photovoltaic sizing seem to differ significantly between different percentage of critical load covered, but not between the days of autonomy of the battery storage, and this can be easily seen from the values of emissions shown in Figure 4.9.

In the case that a designer has already defined one parameter as a prerogative of the system, such as a certain percentage of critical load or a defined value of days of autonomy for the battery, the DSS code allows to compare the key indicator of yearly liters over investment of those particular conditions through the graphs shown in Figure 4.10 and Figure 4.11.

In Figure 4.10 the combinations are separated by the percentage of critical load the battery will cover in case of emergency. For each graph described by a chosen percentage of critical load, we can immediately see the difference between the combinations of one day of autonomy for the battery system, while other combinations present more similar values between each other, independently of their design parameters. This is

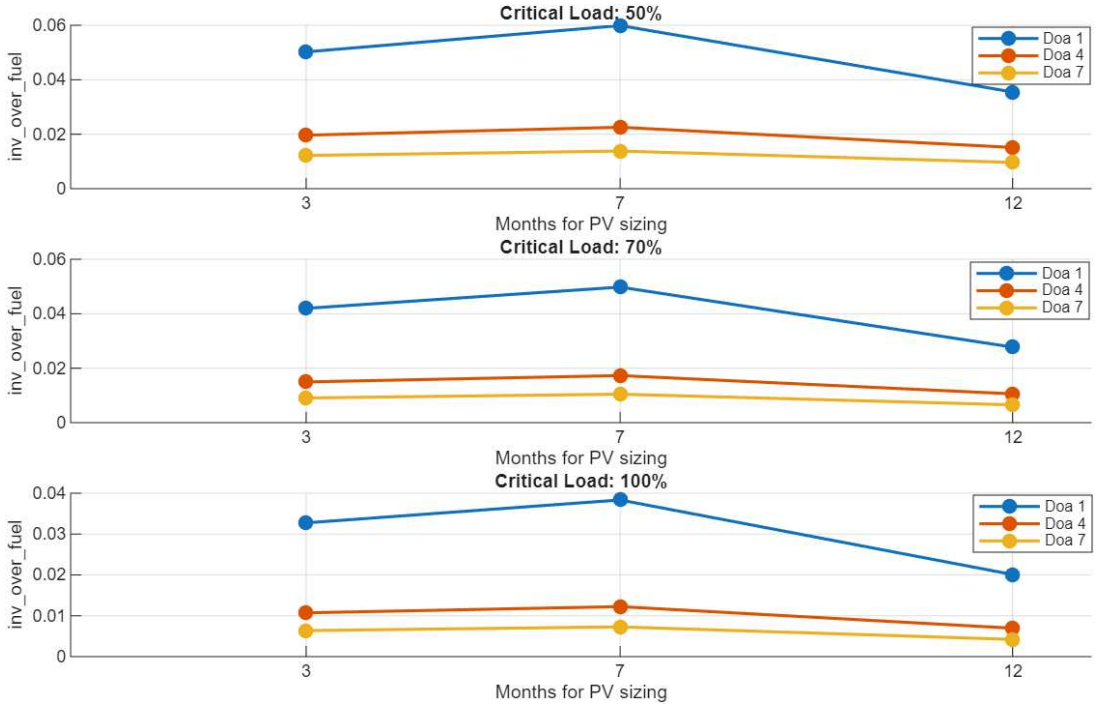


Figure 4.10: *Key indicator of yearly liters of fuel over first year investment separated by critical load percentages [L/$].*

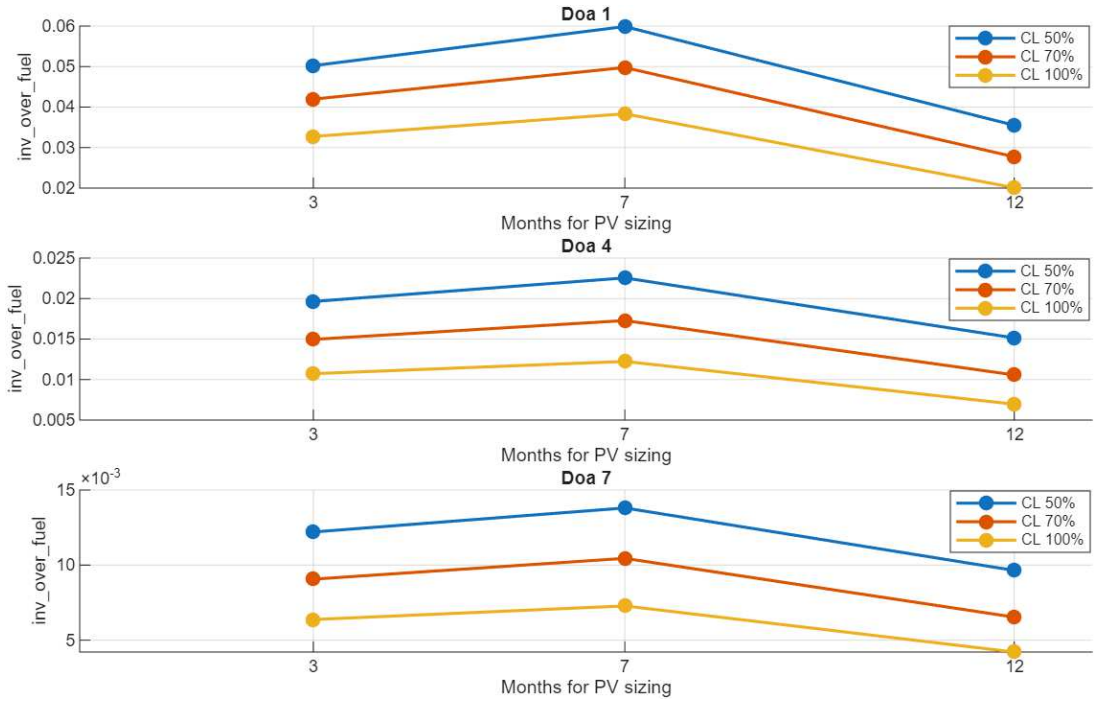


Figure 4.11: *Key indicator of yearly liters of fuel over first year investment separated by days of autonomy [L/$].*

a confirmation of the great impact that the days of autonomy of the battery have on the ratio between fuel liters and investment, particularly in increasing the investment cost and, therefore, decreasing the ratio. In fact, if we now concentrate on the graph in Figure 4.11 we can see how, having divided the combinations by different days of autonomy, the values of the ratio do not differ having fixed a second parameter and changing the third, but the difference stays more or less constant, without big gaps between two different combinations. For example this can be seen if we focus on a fixed number of days of autonomy, for the same month of photovoltaic sizing, at the changing of increasingly higher percentages of critical load, the difference in the ratio values seems nearly constant, or at least very close in value. This is due to the small difference both in the yearly fossil fuel consumption and in the first year investment, proving once again that one of the main characteristics that drives the investment cost is the number of days of autonomy of the battery.

For an easier comparison between different solutions, we can look at the graphs that show the difference between the KPI of yearly liters over investment for all combinations and the same ratio of a fixed combination. To better evaluate the extremes of the microgrid design, we chose as a reference the combination described by the month of March, which is characterized by an average value of daily irradiance, and therefore, an average peak photovoltaic power installed, one day of autonomy and 100% of load covered in the emergency state. In this way we can simulate an average battery capacity that concentrates on fulfilling the entire load even if for a smaller amount of time. In the graph shown in Figure 4.12 we can see these comparisons differentiated by the month used for the photovoltaic sizing on the x axis, while in Figure 4.13 the values are portrayed with the days of autonomy of the battery on the x axis. In both graphs the chosen reference combination is marked by a green outline.

The negative values obtained in the graph show when the fixed combination determines a higher dependence on fossil fuels, making the combination that we are considering in that moment more environmental-friendly and more energy independent, at the possible expense of a higher first year investment. In this way, we can immediately see all the combinations that grant a lower environmental impact, in addition with the information regarding the investment and the consumption of fuel. This is the case

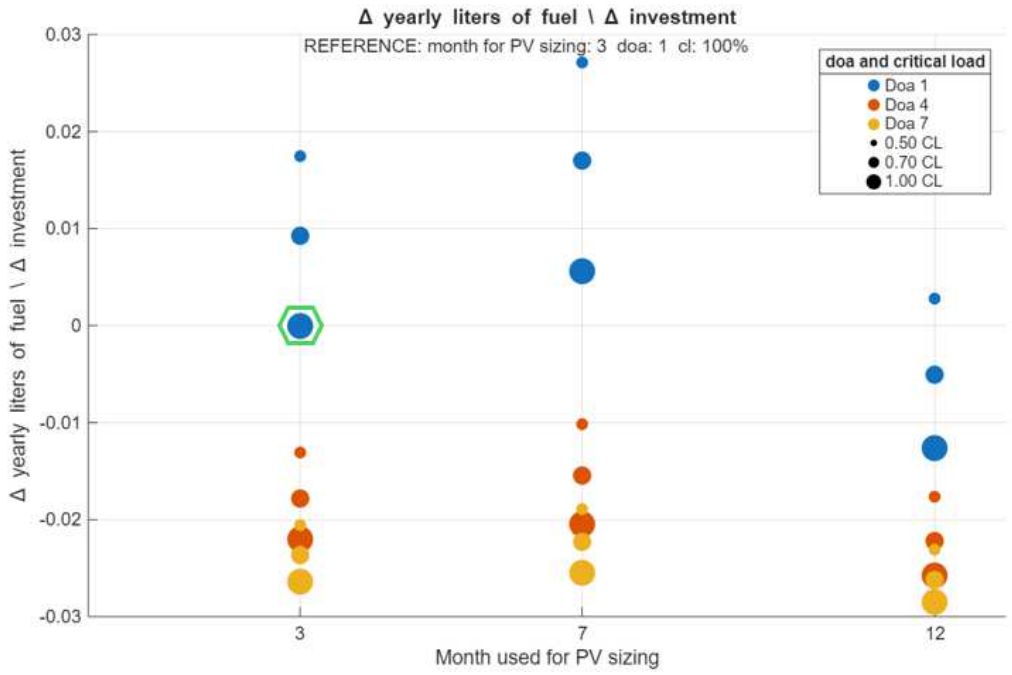


Figure 4.12: *Key indicator of delta yearly liters of fuel over delta investment, with the months used for the photovoltaic sizing on the x axis, with reference the combination described by the month of March, 1 day of autonomy of the battery and 100% of critical load covered in emergency [L/$].*

for all the combinations characterized by a number of days of autonomy greater than one, which enable a lower consumption of fuel at the expense of a higher investment. In particular we can asses a region in which those combinations stabilize around the same value of difference between the ratios, around -0.02, making different combinations very comparable to each other. This behavior might help the designer to see which combinations, with respect to the one they initially chose, allow for an improvement regarding this key indicator, leading them to consider that change in that design parameter to provide the other benefits, for example, a lower investment.

What was said before can be seen clearly also in the graph in Figure 4.13, where the combinations are separated on the x axis by the days of autonomy of the battery. Here we can see a higher sparsity between the dots related to 1 day of autonomy while, for the other values of days of autonomy, the distance between the dots gets increasingly lower, until the biggest value of days of autonomy on the x axis is reached and the dots tend to overlap each other. Now the colors of the dots symbolize the month used

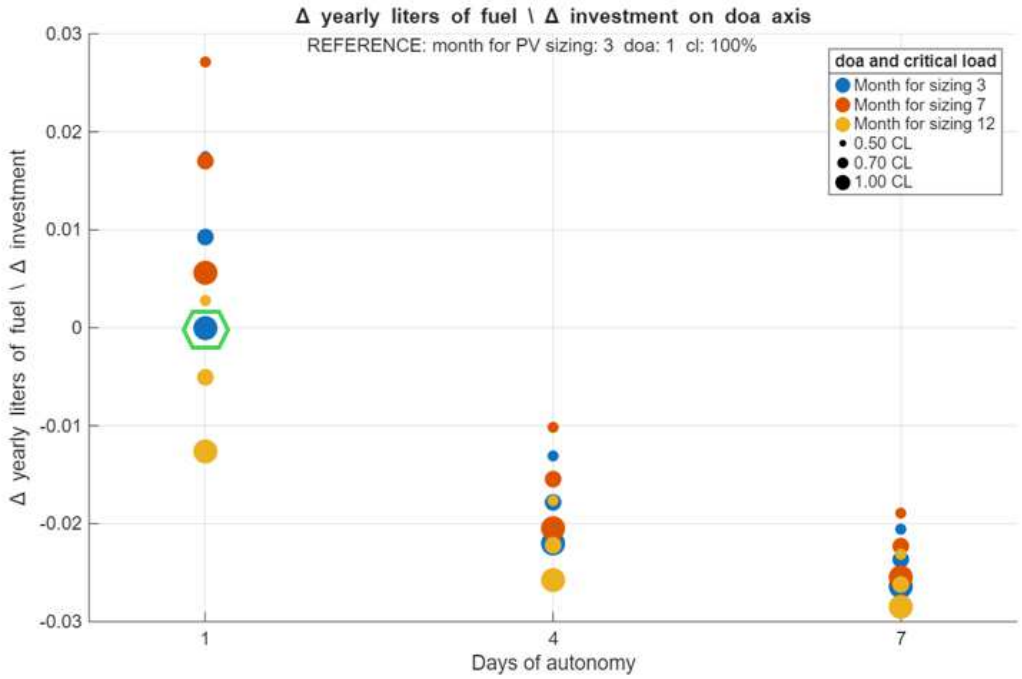


Figure 4.13: *Key indicator of delta yearly liters of fuel over delta investment, with the number of days of autonomy of the battery on the x axis, with reference the combination described by the month of March used for the photovoltaic sizing, 1 day of autonomy and 100% of critical load covered in emergency [L/$].*

for the sizing of the photovoltaic plant, and it is therefore logical that those that define a lower value of this KPI are the yellow dots, so the ones defined by December, the worst irradiance month, so with the highest peak photovoltaic power required and a higher investment. This graph allows to see the lower impact of the sizing of the photovoltaic plant once we fixed the days of autonomy of the battery, as shown by the overlapping of the dots in the column that describes the combinations with 7 days of battery autonomy. This graph, in addition to all the others seen before, allows to compare very different combinations and their impact on the key indicator. Ultimately, all of this is done for the designer to choose which solution, with the benefits that it provides, is the best one of their specific application.

The feature of these last two graphs of providing a way to compare different solutions is just the beginning of many possible solutions. Another interesting possibility would be to fix two design parameters as reference and study the differences in the design combinations regarding only the change of the last parameter. This evaluation

would enable the designer to make the final comments on the design parameter they are most uncertain on, having already decided the others. For example, keeping fixed the month used for the photovoltaic sizing and the percentage of critical load to be covered in emergency, we could study the change in the number of days if autonomy of the battery storage, and see what these solutions entail, since the battery capacity has such an important role in both the investment cost and the resilience of the system.

The last graphs shown by the DSS code refer to specific solutions that embody a particular quality. In this way the designer can immediately asses which combination provides that certain benefit, defining them as the extreme of that quality. The qualities that will be studied are: the cheapest solution, shown in Figure 4.14, the most reliable solution, shown in Figure 4.15, and the most sustainable one, so the one that determines the lowest emission of CO_2, shown in Figure 4.16. In addition to that, thanks to these graphs, we can also evaluate other sensible information about the operation of the microgrid. They show how the load is covered, specifying the different percentages of photovoltaic power, fossil fuel generation and battery discharge, how the photovoltaic generation is divided between load, the charging of the battery, and curtailment, and finally, how the battery storage system is charged, how much comes from photovoltaic production and how much from the diesel generators. These information represent other possible KPI that can be found in the code for any design combination studied.

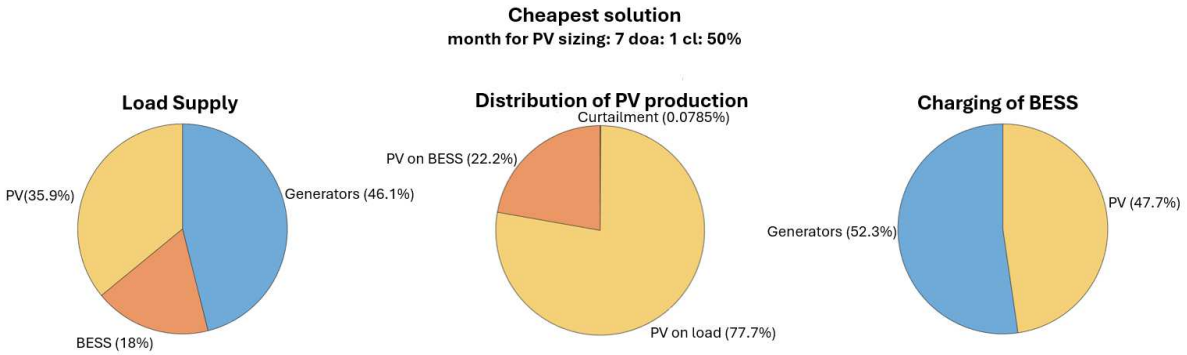


Figure 4.14: *Cheapest solution.*

The first graph reported in Figure 4.14 illustrates the cheapest solution, so the one that provides the lowest first year investment. In our simulation this solution is the

one that considers July as the month used for sizing the photovoltaic plant, 1 day of autonomy of the battery and 50% of critical load to be covered in emergency. It is clear that this is the cheapest possible solution since it is the one that prescribes the lowest peak photovoltaic power to be installed and the smallest battery capacity. For all these reasons, it is to be expected that the highest percentage regarding the supply of the load is the one that refers to the fossil fuel generation. On the other hand, the nearly null yearly photovoltaic curtailment percentage is due to the low peak photovoltaic power installed, that is also the cause for the nearly half shared charging of the battery between photovoltaic and diesel production. This is not a very favorable behavior since we would expect for the battery charging to be nearly a prerogative to the photovoltaic production, maximizing its consumption through time shifting methods, but the software probably implemented this solution because of the need of the diesel generators to work at the highest load factor, maximizing their efficiency and, therefore, minimizing the liter consumption.

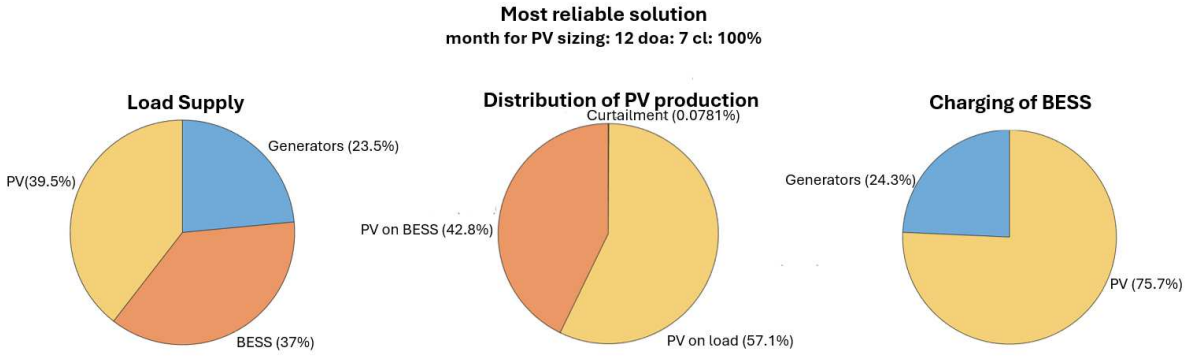


Figure 4.15: *Most reliable solution.*

A different behavior can be found in the second solution portrayed, the most reliable one, shown in Figure 4.15, where nearly the 76% of the battery is charged with the photovoltaic production. This is due to the increase in the peak photovoltaic power installed, in fact, this solution is described with the month of December, the one with the worst daily irradiance value, to size the photovoltaic plant. Furthermore, in order to allow for the highest level of reliability in the state of emergency, battery storage is the one prescribed by 7 days of autonomy and a percentage of critical load that covers entirely the load requirements of the microgrid. Therefore, the most reliable solution,

the one that provides the highest level of resilience, thanks to the largest capacity storage and installed peak photovoltaic power, is also the most expensive. In our code we proposed fixed values as cost indicators for the different technologies, but if we were to consider multiple values of cost, to provide a sensitivity analysis regarding the economic expenses, we would still find that this solution is the most expensive one. This is due to our definition of resilience of the system based on the battery storage system capacity, so on the days of autonomy and the percentage of critical load covered. Furthermore we decided, to provide for the highest reliability, considering any possible event, that also the photovoltaic power should be maximized in this solution; this will allow, a higher reliability in the periods in which we have a malfunctioning of the diesel generators. However, even with the biggest battery capacity, we still present, although nearly close to zero, a curtailment of photovoltaic power. This is entirely to be ascribable to the optimal operation of the microgrid. Having an excess of photovoltaic production, it is necessary to curtail that power, although being subject to a penalty, a constraint inserted to minimize as much as possible the photovoltaic curtailment to have a lower environmental impact, because of the constraints on power balance and on the state of charge of the battery. The benefit of the combination between a higher battery storage and a bigger photovoltaic power installed, can be seen in the supply of the load, where only 24% of it is covered by the diesel generators, compared to the 46% of the previous solution.

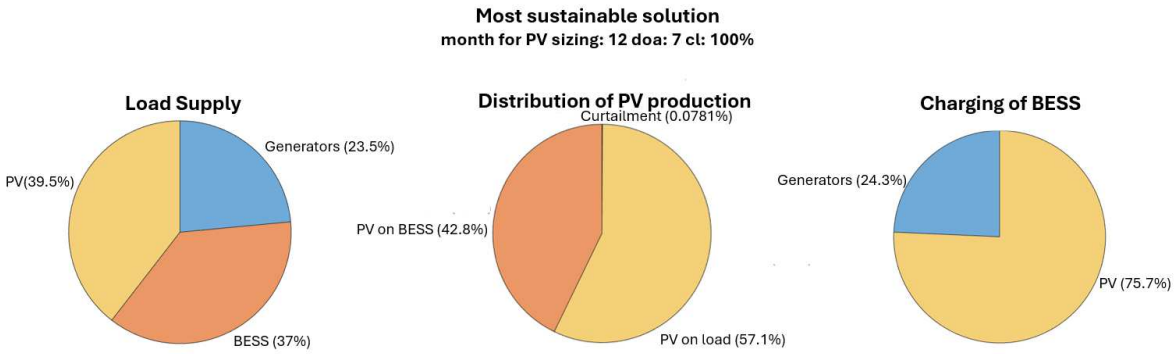


Figure 4.16: *Most sustainable solution (minimum CO_2 emissions).*

Finally, the code portrays the pie charts for the most sustainable solution, which is reported in Figure 4.16. This solution is the one that produces the lowest amount of

kilograms of CO_2 emitted in a year, considering the consumption of diesel and also the carbon footprint of photovoltaic production and the energy stored in the battery system. In this particular case, we found that the most reliable solution is also the most sustainable one. In fact, the combination between the highest battery storage and photovoltaic production is also the one that determines the lowest consumption of diesel liters, which has the greatest impact on the emission of CO_2. Although we have found this peculiar solution, that is not generally true. The emissions of the microgrid highly rely on its operation, and therefore on the constraints regarding its optimization. Having the biggest possible battery storage does not immediately define the lowest amount of CO_2 emissions. We can see an example of that if, by looking at the table with CO_2 emissions in Figure 4.9, we focus on the case of the combinations characterized by the month of July for the photovoltaic sizing and a percentage of critical load of 70%. With increasing days of autonomy, the battery storage increases, but so do the liters of diesel consumed, and the same happens if we considered, for the same month, the percentage of critical load equal to 100%. Even if this combination is also the most expensive one, that is not necessarily the case. As said before, the dimension of the battery storage does not directly determine a lower CO_2 emissions, and therefore the designer might still be required to choose between the two extreme criteria of most reliable and most sustainable. Nevertheless this configuration is the one, between those seen before, with the highest percentage of battery charging from the photovoltaic production, meaning that the time-shifting approach is vastly utilized, and is definitely one of the main reasons for the lowest consumption of fuel.

4.3 Rainflow Results

Now that we have analyzed all the outputs of the DSS code, we can now run the Rainflow code and study the useful lifetime of the battery defined by a specific combination. In our case, we will consider a lead acid battery so the Rainflow code is appropriately written with the formula for the battery cycles calculation that correspond to that technology. Therefore, in the DSS code, in the section prescribed for the data storage regarding the charging and discharging of the battery, the user can select the

design combination they aim to implement in order to receive the required information useful for the definition of a more complete business plan that considers also the substitution cost of the battery storage. For example, in our case, we decided to set the simulation of the useful lifetime of the battery considering the combination described by:

- **Month used for photovoltaic sizing**: March
- **Days of autonomy of battery storage**: 1
- **percentage of critical load to be covered in emergency state**: 50%

We chose this combination as a standard one, being characterized by the average month for irradiance and the minimum requirements for the battery capacity. After running the Rainflow we receive as a useful lifetime of the battery 657 days, which corresponds to approximately 2 years (1.8). Having a description of this value in days, rather than in number of cycles allowed for the battery, is much more helpful since in the economic analysis of the microgrid the designer can forecast the necessity of the battery substitution and consider its cost in the business plan of the microgrid.

For the sake of our study, we run the code multiple times in order to evaluate the differences between the combinations and operations of microgrid designs. The results are portrayed in Figure 4.17 and show the useful lifetime of the battery set in days for their particular design combination.

As we can see from the picture, the behavior of the useful lifetime of the battery is very difficult to predict, since it relies on so many parameters. Many combinations provide very similar values of useful lifetime, which usually increases slightly with larger battery capacity. This is probably due to the fact that high battery capacities are there for emergency state but are underutilized during the daily operation and, therefore, settle on a very similar behavior that is strictly linked to the microgrid constraints and load demand. It is interesting to notice that there is not a unique pattern that describes the change of the battery operation and its lifetime with the different months used for the photovoltaic sizing. For example, considering a battery that has one day of autonomy, the month of December provides the lowest values of battery lifetime,

				Days of autonomy		
				1	4	7
Months for sizing	March	critical load	50%	657	1815	2338
			70%	689	2193	2935
			100%	838	2375	2974
	July	critical load	50%	719	2089	2339
			70%	805	1612	2443
			100%	861	2372	2884
	December	critical load	50%	502	1883	2504
			70%	527	2638	3446
			100%	727	2652	3370

Figure 4.17: *Useful lifetime of the battery storage system [days].*

probably due to the high utilization of the battery storage following a great photovoltaic production. But this does not happen when we increase the days of autonomy of the battery. In fact, we see that generally, for higher values of days of autonomy, the battery described by the parameter of the month of December has a longer lifetime and, therefore, a more efficient operational mode. This is another demonstration that battery performance is strictly connected to the correct management of energy flows in the microgrid, so on load demand and photovoltaic production. The month of July presents an exception: if generally the useful life time of the battery increases with higher critical load, if we set 4 days of autonomy, we see that moving from a critical load of 50% to one of 70%, actually decreases a lot the battery lifetime, going from 5.7 years to 4.4, to then go back to 6.5 years when we increase the percentage of critical load to 100%. This behavior has no easy explanation; we can just assume that the operating conditions due to that specific photovoltaic production and the energy-intensive and power-intensive qualities of that battery storage cause a quicker deterioration of its technology. The battery providing the longest life time is the one with 7 days of autonomy that covers 70% of the critical load, and with December as the month used for the photovoltaic sizing, arriving to 9.4 years of operation. This is an incredibly high number for a lead acid battery, that is comparable to the calendric lifetime of this technology of battery storage, meaning that it might be necessary to predict an earlier substitution of the battery due to that. Generally, a battery operates better thanks to

smaller depth of discharge values, determining a longer lifetime. Having such a big capacity available in emergency but underutilized in the day to day operation allows for smaller depth of discharge, explaining the long useful lifetime found by the Rainflow code. It is to be assumed that this is the combination that provides for the best battery management, determining a very valuable economic benefit by delaying the substitution of the battery storage system as much as possible.

To study the correlation between system design parameter and battery useful lifetime we took as reference the same combination used for the graphs regarding the key performance indicator of delta liters over delta investment, the one described by March for the photovoltaic sizing, 1 day of autonomy and 50% of critical load covered, and calculate the ratio between the useful lifetime of the other design combination and the reference one. The results can be seen in Figure 4.18.

				Days of autonomy		
				1	4	7
Months for sizing	March	critical load	50%	1.00	2.76	3.56
			70%	1.05	3.34	4.47
			100%	1.28	3.61	4.53
	July	critical load	50%	1.09	3.18	3.56
			70%	1.23	2.45	3.72
			100%	1.31	3.61	4.39
	December	critical load	50%	0.76	2.87	3.81
			70%	0.80	4.02	5.25
			100%	1.11	4.04	5.13

Figure 4.18: *Ratio between useful lifetime of the battery for all the design combinations and the reference one (March, 1 day of autonomy, 50% of critical load).*

This figure quickly helps us to visualize the possible improvements or worsening in the battery lifetime depending on the battery operation and the energy management of the system. From this table we can clearly see that the values do not follow a unique pattern and that, as said before, the increase of some parameters such as the percentage of critical load does not necessarily improve the battery life span; such is the case for the combinations described by the month of July for the photovoltaic sizing and 4 days of autonomy. Furthermore, it is interesting to see the great improvement moving

from 1 day of autonomy to 4, we see that it is much more demure in moving from 4 to 7 days of autonomy, since the operation of the battery storage does not change excessively since these great capacities are allocated only for the emergency state. This study also helps us to see the possible range of the battery lifetime, having considered these design parameters, where, for the longest possible duration of battery lifetime, we are able to quintuplicate the reference value. While, for values that go below our reference duration, we only find two possible solutions in the month of December, bot described by 1 day of autonomy; although it is relevant to notice that these values are not so lower than the reference one, meaning that the chosen reference characterized by average value of photovoltaic sizing and small battery storage is one that defines one of the shortest possible battery lifespans, making it a good starting point to evaluate the possible improvements.

In any case, this operation represents an additional valuable key performance indicator that can help the designer compare the different design solutions with respect to the delay of battery replacement and the consequent economic and environmental impact resulting from it. The change of the reference design combination in fact, can show the designer the possible improvements of this quality with respect to the solution they had previously chosen and allow them to consider possible changes.

Chapter 5

Conclusions and Future Works

The aim of this project was to help the designer of a microgrid in sizing the components that will be at the core of the microgrid operation and functionalities, particularly considering the special difficulties present in the case of islanded microgrids. One of the main objectives of this work was to find a way of sizing the battery storage system considering the specific criterion of resilience of the system through an emergency state. This is pursued thinking about the particular situation of an islanded microgrid which cannot rely on an outer distribution network for the supply of its loads, which, in the case of an abrupt event that will lead to the interruption of the energy supply, could be exposed to great damage to its users if the battery capacity is not sufficient to cover the critical load demand. This is something that is not commonly done in microgrid design tools, where it is often required to select an initial capacity for the battery storage to be considered. In the DSS code the topic of battery sizing is tackled through direct questions regarding the resilience level that the designer thinks sufficient for their specific implementation: they are asked to provide the days they want the battery storage to last and the percentage of the overall load, called critical load, that needs to be covered by the battery in the emergency state, that is to say, when the energy generation is completely lacking. To help the designer in finding reasonable values of critical load to be studied, the Critical Load Evaluation code is provided, so that the designer can see, with respect to connections between feeders, loads and generators, which is the most probable percentage of load that will still be supplied in the event of a fault on a feeder. These values do not demand to be directly the ones consid-

ered by the user since they merely regard how the energy balance will be maintained in the event of a fault, but mixed with the knowledge of the designer of the most important load requirements, can be deemed as a good start to select some base values to be studied with the DSS code. The definition of critical load, in fact, depends on the very specific application that our microgrid serves and ultimately to its customers needs, and so the definition of the percentage of load that has the highest priority of being supplied is highly variable in value between different microgrid applications.

The strength of the DSS code lies on its high customization: the users select directly the parameters, referring to general qualities of the microgrid, that will then determine the sizing of the photovoltaic plant and the storage system to be studied, for only them can actually know which are the most appropriate considerations to be accounted for regarding their specific installation site and microgrid requirements. The DSS code will then help them to see what each solution actually entails, the results that they provide and their comparison to different combinations. In fact, another peculiar characteristic of the DSS code is the display of a vast array of solutions, and not merely a single one, through the aid of appropriately designed graphs generated by the code. Those graphs will portray key performance indicators that describe the qualities of the solutions studied. Some of the most relevant ones are the ratio between the consumption of fuel over the investment and the CO_2 emissions. The first will be able to provide an indication wether the increase of the first year investment would actually be worth regarding the reduction of liters consumption, while the other will help in the real assessment of the CO_2 emissions considering all the components that made up the microgrid, included the renewable generation. This particular choice is made considering the goal of emission reduction by the European Union, laying a basis for the future need of more precise calculations regarding this subject.

The easy representation of said graphs is another main target of this project: they need to be understandable by everyone involved, not only in the design of the microgrid, but also in its operational mode. In this way, the designer can use these graphs to justify their choices to the microgrid customers. We firmly believe in the power of microgrids of strengthening the sense of community derived from being part of it, where demand and generation are both strictly linked to one another by the users'

actions and the proximity of the power plants, in the form of distributed generation, gives the impression to common people, independently of their cultural background, of a higher responsibility in its operation, increasing user awareness, which may lead to daily energy saving actions.

Having considered many combinations of sizing parameters and portraying all of them on the same graph may lead to further advantages. For example, if by considering one specific key performance indicator, the designer sees that there is not much difference between two combinations, but one of them is characterized by a greater benefit regarding one of the qualities desired, after having considered also the other key indicators and provided that they fulfill acceptable conditions, the designer might be willing to swap their initial solution to the one that provides the bigger benefit to the system. This is something that they would not have been able to notice if the solutions had been portrayed and studied singularly, as it is often the case for other software. Through the DSS code, the designer will be able to merge, considering their specific priorities, the quality of sustainability, resilience, and economic investment into their solution.

In our study case regarding the Kamal Adwan Hospital in Gaza, we noticed the fundamental role of the battery storage system in the definition of the different microgrid qualities, making it one of the most important parameter to be studied in the design of the system. The battery storage highly increases the investment but at the same time it is needed in the definition of resilience during an emergency state and it can help, although that is not always the case due to the operational constraint, in the saving of liters of fossil fuel consumed but especially in the avoidance of curtailed photovoltaic power. With the provided graphs, the user will be able to choose which solution is worth to pursue, having considered all the proprieties which that specific design and operational mode entail.

There are many ways in which the DSS code could be improved. Firstly, for what regards the useful lifetime of the battery storage system, the evaluation through the Rainflow code is possible only for one combination at a time. It could be interesting to have the contemporary evaluation, with a single run of the code, of all the different solutions found. This will make it possible to implement a comparison process between

the results to better visualize which combination requires an earlier substitution of the battery storage. By integrating the study of the degradation of energy storage, which affects both its performance and its lifetime, into the feasibility analysis of the system, we would be able to study its impact, not only the efficiency of the operation, but also the future cost of the microgrid. With this knowledge, in fact, we would also be able to implement a more complete business plan that considers, over a fixed lifetime of the microgrid, the cost of the battery storage substitution when needed, to which we could even add the cost for its maintenance and for the one for the photovoltaic power plant. At the moment, what is considered is merely the first year investment. Another improvement could be translating the code into Python, to have a greater computational power that will allow for more independent variables subject to the optimization. This increase will also allow us to introduce the study of wind power and other types of renewable generation, such as wave power, in the optimization of the operational day of the microgrid. Furthermore, the language code of Python would let us implement more sophisticated graphs that are still able to maintain their easiness in interpretation, also expanding in the number of graphical display of results, providing additional tools to help in the decision process. Since the aim of the project is to give the designer the tools to decide the sizing of the components so that they give the right weight to each quality of the microgrid, exactly as the designer intended, it would be useful to implement a priori a way for the user to select these specific weights they want to assign to the properties that the microgrid needs to fulfill. This could be done with the aid of one slider, or more, for example, with as many sliders as the qualities to be considered. Taking into account this project, these sliders would be three: one for sustainability, one for resilience, and one for the economic investment. In this way, the code would be able to automatically select the solution that, among all the ones studied, provides benefits exactly weighed by the user's priority. This could be easily done through the assignment of a score for each quality studied, ordering the different design combinations by the values of their key performance indicators that describe that certain propriety.

Furthermore, This project leaves open many possibilities of research on these subjects. For now, we have only always considered deterministic data, both for load and

renewable generation, it would be interesting to implement a more dynamic approach, for example, with the aid of machine learning methods, to have a continuous forecast of these data in order to be of help not only to the designer of the microgrid but also to the energy manager, so the one that supervises the daily operation of the microgrid. Providing more precise data, in fact, would significantly help in the energy saving sector. Moreover, the DSS code could be used as a base for future integration into existing designer software tools, to have a definition of resilience of islanded microgrids in it, in addition to the preexisting functionalities, and the integration of the key performance indicators that describe it into the final results, as an aid to the decision process.

In any case, the missing validation of resilience-based microgrids makes this area of research vastly open to further work, and the experimentation of other forms of possible definition of resilience and their study on actual microgrids remains one of the most significant challenges of the future.

Regarding the resilience of islanded microgrid, the Critical Load Evaluation code could be a base for the enhancement of grid layout reconfiguration to carry out an adaptive load management control in the event of a fault so that the most critical loads are always covered no matter which feeder has been affected by the fault. The idea would be to provide the position of possible sectionalizing switches that can guarantee the continuity of supply to cover those specific critical loads. The number and position of said sectionalizing switches will help the designer in providing economic assessment of the expense of enlarging the resilience of the system, considering additional components and feeders. Another solution that could be studied to enhance the resilience is the interaction between different microgrids. Two islanded microgrids that are located closely to one another, may share the energy flows in the case of abrupt event that has compromised the operation of one of the two, in order to maintain the supply of the most critical loads with the remaining generation, maybe by putting on hold those customer satisfaction related loads that are not strictly necessary in the functioning microgrid. Furthermore, this interaction could also implement some economical benefit deriving from the share of specific components. For example, if we provide a single battery storage system that is needed in the case of the emergency shared between the two islanded microgrids, the economic investment regarding the

purchase of this component would be halved. To be prepared for the future, it would be interesting to incorporate climate projection models that could help examine possible faults that would require a certain level of resilience. In this way, the design could be studied from the beginning with all the components able to withstand those possible scenarios already included.

Ultimately, the DSS code is born to help the microgrid designer in their job, so another possibility of improvement would be possible by reaching out to microgrid designers and directly asking them what they would like to see in such a tool that would determine a big quality upgrade and an enhance its accessibility.

To conclude, the final scope of this project is the design of a tool that will help to understand and pursue the design criteria that are required in each specific microgrid case, adapting entirely to the different characteristics that describe microgrids all over the world, by defining the size of the components that represent the core of the microgrid and determine its best operational mode. Having a broader understanding of what every single solution entails guarantees that the final decision will be the one, among all studied, that allows for the best implementation of the available technologies, leading to a more aware and responsible use of resources.

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