POLITECNICO DI TORINO

Master of science program in electrical engineering

Master's thesis

Control software for micro energy community management

Supervisor | Candidate

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First of all, I want to thank my family. It seems impossible to think where I would be without all the support they have given to me. Giving me the chance to go living alone in another country, study in a completely different university very far from my family and all my friends it's a very big challenge and all the things I've accomplished wouldn't be possible with the support of my family. I love you so much and I'm grateful for all the things you've done for me.

After this, all the people I'm mentioning are not in any particular order and, for me, they have all contributed to who and where I am. The order was chosen according to my 4.22 am caffeinated brain.

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Moreover, from my home University, seriously, I could name dozens of people and I've been thinking about all of you, but I don't have enough space here to name you all. Specifically, I want to name Juan, Claudio, Samuel, and Mayron from QGGM that have been listening to all my adventures through these months. Also, Turco and Pablo from the Electronauts with whom I shared a lot of electrical adventures. Finally, more people I want to name are Camilo, Seba and Guido. In addition to this, I want to thank all the people from Proyecta and Tutores 2019. These volunteer projects gave me the possibility to grow as a human person and be the person who I am. From these projects I want to at least name Vichin, Javier, Vitoco, Javiera, Vicho and Grachi who had been supporting me from the very first beginning of this adventure.

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Kind regards, Felipe Molina

Set your heart ablaze - 心を燃やせ

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Introduction

During the last decades, international awareness towards climate change and its consequences has been increasing as the global temperatures are rising and its devastating effects are showing. On this line, international efforts are being made to reduce the global carbon dioxide emissions, one of the main causes of climate change, with the objective to contain the global rise temperatures and achieve a carbon neutral economy. Between these efforts are the increment of the share of renewable energies in the generation sector, the enhancement of the energy efficiency on buildings and the involvement of the people in the energy transition.

In this context, the PhotoVoltaic Zero Energy Network (PVZEN) project is developed. PVZEN is an innovative multidisciplinary project that involves three departments of Politecnico di Torino, Energy Department (*Dipartimento di energia DENERG*), Architecture and Design Department (*Dipartimento di Architettura e Design DAD*) and Electronics and Telecommunications Department (*Dipartimento di Elettronica e Telecomunicazioni DET*). This project has the objective of designing and develop a nearly zero energy building (nZEB) characterized for its high energy efficiency. The building has three different users, each one with their own photovoltaic generation, load consumption and storage systems, that can operate both as a single user, a nano-grid, as a whole system by interconnecting each other, a micro-grid. The building is intended to be used by students, so its energy consumption is going to happen during sunlight hours, similar to a tertiary sector consumption, which is a great advantage as it matches the photovoltaic generation. Moreover, another important feature is its electrification of the heating and cooling systems by using heat pumps, this way the energy demand of the system is turned into an electricity-only demand. Finally, the main feature for the elaboration of this thesis is the ability of the users to exchange energy, as this will allow the system to increase its performance as users in deficit can be supplied by users having energy surpluses, consequently, increasing the system's self-sufficiency.

The main objective of this thesis is to develop and test a software capable of controlling the energy exchanges inside the system with the main goal to increase the system's self-sufficiency. The software was developed through MATLAB's App Designer which allows to both elaborate a graphical user interface equipped with different functionalities and to use scripts and functions that will allow to process information. The objective is done by developing a software that follows three main steps: reading, control logic and writing. The reading step consists of reading the measurements of the three users' power profiles by communicating via Modbus with the users' inverters and giving this information to the program. Subsequently, the software takes this information and uses it to generate a power balance, first considering the system operating as three independently users and then, considering the users' situation of surplus or deficit, deciding which configuration the system must operate to make the energy exchanges between users, consequently covering the demand of the users in deficit with the excess power of the users in surplus. Finally, the writing step consists of communicating the decision made by the control logic to the system. This is done by writing into the inverters via Modbus and by communicating the system configuration to a programable logic controller that will physically interconnect the users in the desired configuration. In addition to this, a graphical user interface was developed with the objective of plotting the different power profiles of the three users and their respective battery's state of charge. This way, the user will have a graphical tool to monitor and evaluate the system's behavior.

Finally, the software will be used to simulate and analyze the system's behavior in three different days with different weather conditions. These simulations will be done by using stored data from the power profiles of the three users these three days. The days simulated are the 21st, 22nd and 24th of December 2021, and were chosen because of their different weather conditions, specifically for their different cloudiness conditions as there is a cloudy day, a sunny day and a partly cloudy day. By doing these different simulations it will be addressed how the state of charge of the users' batteries behave and if higher self-sufficiency is achieved by using storage systems.

1 Global action towards climate change

1.1 International efforts

During the last decades, different organizations and countries have been discussing about the actions that have to be taken to minimize the effects of climate change. Since the 1800s, the human activities have been the main driver of climate change, primarily due to burning fossil fuels like coal, oil, and gas. As a result, the earth is now about 1.1°C warmer than it was at pre-industrial levels. [1]

This temperature rise is already affecting the world by melting glaciers and sea ice, shifting precipitation patterns, and setting animals on the move [2]. The number of glaciers has declined to fewer than 30 from more than 150 in 1910. This contributes to sea-level rise, which is already threatening oceanic countries like Tuvalu, that has already two of nine islands on the verge of going under swallowed by sea-rise and coastal erosion [3]. Also, wildlife and their habitats are being affected. One example is the Adélie penguin in Antarctica, where some populations on the western peninsula have collapsed by 90 or more [2].

The effects of the climate change will continue to get more severe if no actions are taken. Sea levels are expected to rise, hurricanes and other storms are likely to get stronger and floods and droughts will become more common. Less freshwater will be available, some diseases will spread, and ecosystems will continue to change [2].

Given the urgency of the situation, different international organizations have been performing diagnosis, creating protocols, and searching solutions to decrease the emission of greenhouse gasses.

1.1.1 CO2 emissions by sector

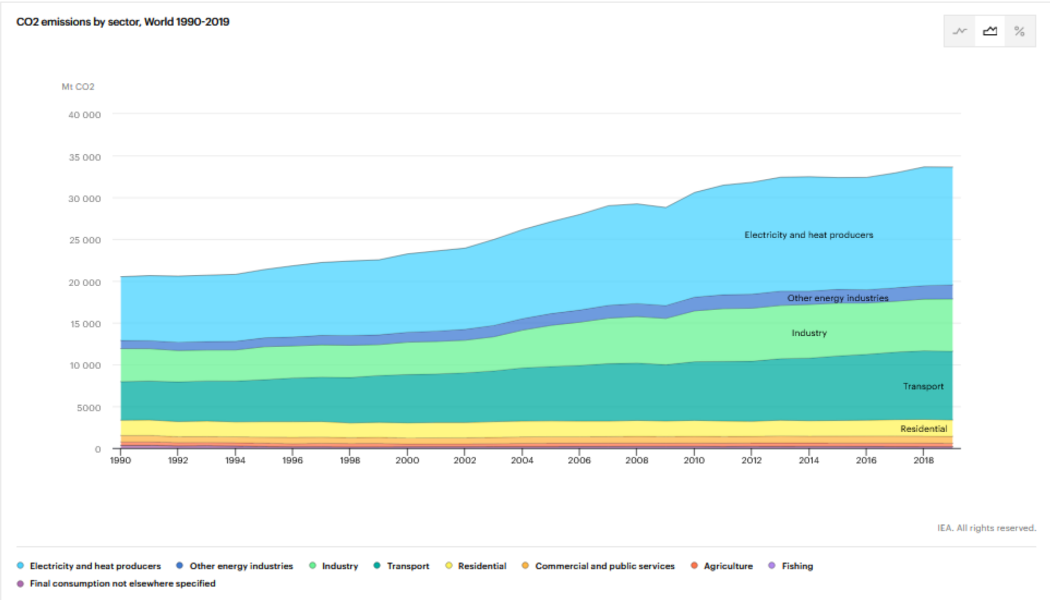

Figure 1-1: CO2 emissions by sector [4]

As seen in the Figure 1-1, one of the sectors that produce the most emissions of carbon dioxide, the primary greenhouse gas emitted through human activities [5], is the energetics-related sector. This is the main reason why different policies made are related to the decarbonization of the electrical and thermal generation and improvements on energy efficiency.

1.1.2 International agreements

The Kyoto Protocol, adopted on 11 December 1997 and entered into force on 16 January 2005, makes operational the United Nations Framework Convention on Climate Change (UNFCC). This convention recognizes that there is a problem, sets the goal to stabilize greenhouse gasses concentrations to levels that don’t interfere with the climate system, incentives developed countries to lead the cutting of emissions and generate new funds to climate change activities in developing countries [6].

The Kyoto Protocol established market-based mechanisms, to encourage to take the most cost-effective ways to cut the greenhouse gasses and a rigorous monitoring, review, and verification system of the emission targets [7].

As years passed and there was more evidence to confirm the human's responsibilities on the climate change and after an extension of the Kyoto Protocol until 2020 at the 18th Conference of the Parties (COP18) there was a reaffirmed compromise to create a new, comprehensive, legally binding climate treaty by 2015. The new treaty would fully replace the Kyoto Protocol [8].

The Paris Agreement is an international treaty which aimed to reduce the emission gasses that contribute to global warming. It sets to improve and replace the Kyoto Protocol. The objective was no less than a binding and universal agreement designed to limit greenhouse gasses emissions to prevent global temperatures from increasing more than 2 degrees Celsius than pre-industrial levels [9].

The key element of this agreement is to reduce de greenhouse gasses to keep the increase in global average temperatures to well below 2 degrees Celsius, but also to limit the increase to 1.5 degrees, which may reduce the risks and impacts of the climate change [10].

The agreement requires the economic and social transformations on countries. Every country must submit their plans for climate action as nationally determined contributions (NDCs). In which they communicate their actions to reduce their greenhouse gas emissions and to build resilience against the rising temperatures [11].

1.2 European Union efforts

The European Union had an important role in the realization of the Paris Agreement and continues being a global leader in the decisions and actions to take to accomplish the objectives proposed by the agreement.

1.2.1 Objectives and strategies

The EU has set its objectives to achieve a climate-neutral condition by 2050. This will permit to achieve the objectives of the Paris Agreement and keep the efforts to limit de increase of the global temperatures to only 1.5°C [12].

By November 2016, to achieve the goals of the Paris Agreement, it was proposed the Clean Energy Package (CEP), a set of eight legislative acts on the energy performance of buildings, renewable energy, energy efficiency, governance, and electricity market design [13].

Furthermore, initially the EU's NDC was to reduce greenhouse gasses by at least 40% by 2030 compared to 1990 under its 2030 climate and energy framework. However, in December 2020 it was updated and committed to reduce the emissions by at least 55% by 2030 [10]. The key targets for 2030 are [14]

- At least 40% cuts in greenhouse gas emissions
- At least 32% share for renewable energy
- At least 32.5% imporvement in energy efficiency

To cover up these objectives, it was approved the 2018/199 regulation on the Governance of the Energy Union and Climate Action. It ensures that the EU's Energy Union Strategy on energy security, energy market, energy efficiency, decarbonization and research, innovation and competitiveness is implemented and coordinated coherently. To achieve this, it is required to member states to produce integrated national energy and climate plans [15].

In the specific case of Italy, the Integrated National Energy and Climate Plan 2030 marks the beginning of an important change on the energetic and environmental policy towards the decarbonization of the country. The plan is structured in 5 guidelines: from decarbonization to the energetic security and efficiency, passing to the internal energy market development, research, innovation, and competitiveness [16]. The table 1-1 summarizes the plan objectives.

	2020 Objectives		**2030 Objectives**	
	EU	**Italy**	**EU**	**Italy (PNIEC)**
Renewable energy sources (RES)				
Share of energy from RES on the gross final consumption of energy	20%	17%	32%	30%
Share of energy from RES on the gross final	10%	10%	14%	22%

consumption of transport energy				
Share of energy from RES on the gross final consumption for heating and cooling			+1,3% annual	+1,3% annual
Energetic efficiency				
Primary energy consumption reduction with respect to PRIMES 2007 scenario	-20%	-24%	-32,5%	-43%
Final consumption savings through mandatory efficient energy regimes	-1,5% annual (without transportation)	-1,5% annual (without transportation)	-0,8% annual (transportation included)	-0,8% (transportation included)
Greenhouse gasses				
GHG reduction vs 2005 for all the plants linked to ETS normative	-21%		-43%	
GHG reduction vs 2005 for all non ETS sectors	-10%	-13%	-30%	-33%
Overall reduction of GHG respect to 1990	-20%		-40%	
Electrical interconnectivity				
Electrical interconnectivity levels	10%	8%	15%	10%
Electrical interconnectivity capacity (MW)		9.285		14.375

Table 1-1: main energy and climate objectives for EU and Italy by 2020 and 2030 [17]

1.2.2 European Green Deal

One of the main measures taken by the European Union is the European Green Deal, an ambitious package of measures that goes from cutting greenhouse emissions to fund research and innovations towards the preservation of Europe's natural environment [18].

The first climate action initiatives are:

- European Climate Law: it writes into law the goal ser out in the European Green Deal for Europe's economy and society to become climate-neutral by 2050. The law also sets to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels [19].
- European Climate Pact: is an EU-wide initiative inviting people, communities and organisations to participate in climate action and build a greener Europe. It invites to connect and share knolwedge, learn about climate change and develop, implement and scale up solutions [20].
- 2030 Climate Target Plan: to cut greenhouse gas emissions by at least 55% by 2030 [21].
- New EU Strategy on Climate Adaptation: a strategy to set out how the EU can adapt to the unavoidable impacts of climate change and become climate resilient by 2050 [22].

1.3 Drivers for the energetic transition

The current energy transition and its challenges make space to create, transform and develop different technologies, frameworks and policies that change the way we see the generation, transport, and consumption of energy.

Moreover, this transition is changing the way electrical energy is produced in a world where "electricity generation and transportation is still largely dominated by centralized structure and centralized systems of thinking" [23] towards a more decentralized and distributed way to produce electricity. It is also projected that the emissions will be reduced due to a "growing electrification of heating and mobility combined with reducing the carbon footprint of electricity". Combining these aspects with energy efficiency gains and increasing direct uses of renewables will allow to reduce even more the final energy demand [24]. Finally, the Clean Energy for all Europeans Package introduces the concept of energy communities, a concept that enables the participation for the citizens in the energy system, taking ownership of their energy consumption [25].

1.3.1 Decentralized systems

The transformation from a centralized-only system towards a more distributed one has caused the development of distributed energy resources (DERs), which can be defined as “technologies and means that can be deployed on the supply side or demand side of the low voltage or medium voltage electric distribution system to meet the energy and reliability needs of the user(s) by that system” [26]. The DERs are composed by distributed generation (DG), demand response (DR), and distributed storage (DS). A type of DG which are very important during the energy transition are the renewable energy sources (RES).

Distributed energy systems can “efficiently increase the resilience of energy systems, improve energy security, empower communities, reduce local and regional CO2 emissions” [27]. The existence of power generation technologies that can be connected at the consumer’s end cause the decentralization of the power system.

1.3.2 Storage systems

On electrical grids characterized of a high renewable energy sources presence energy storage systems could have a big importance, as they give flexibility to the grid and can contribute by participating in ancillary services. Between the benefits of storage systems are their contribution to the resolution of grid congestions, grid reconfiguration in case of faults and non-programmable generation sources variability compensation. [28]

Electrochemical based storage systems are the main way to electrical storage on little to medium scale projects. Nowadays research and innovation are done to achieve higher compactness, affordability, durability, security, and sustainability. The most popular and successful are the lithium-ion batteries. Other type of storage is the based on thermal storage, that can be used for both heating production as for storage system, research is being done to achieve higher energy density options. Finally, the massification of electric vehicles allow the use of them as a storage system for a single user, a micro-grid or for the entire system. It is known as vehicle-to-grid (V2G) when is connected to the grid an behaves as a stationary storage system. [29]

The different energy storage systems can be classified according to their application, as they are characterized of major capability to exchange power or to store energy. In other words, storage systems can be classified as energy-based or power-based [30] [31]

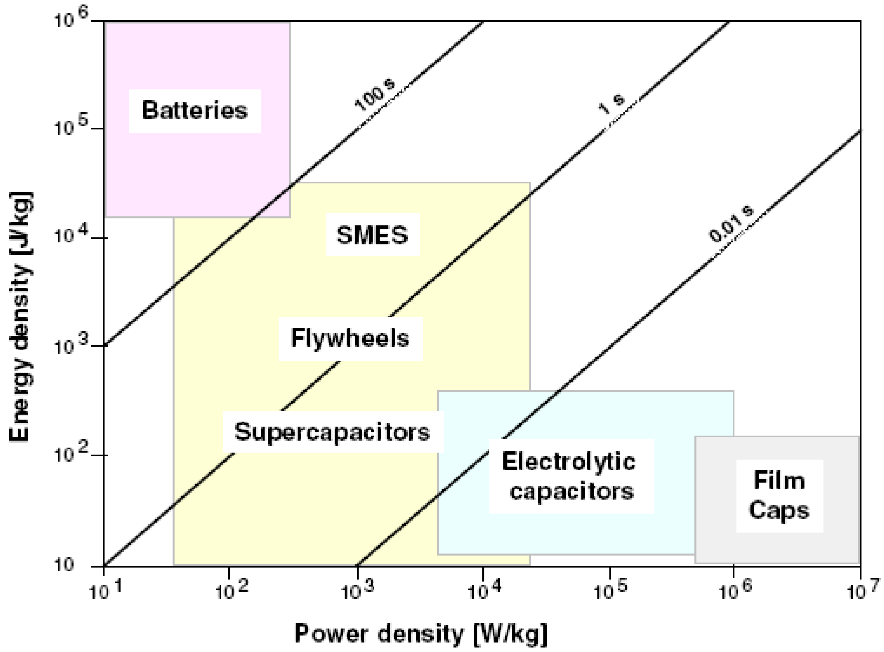

Figure 1-2 Storage systems classified by energy and power density [31]

Some important general storage parameters are: [30]

- State of Charge (SOC): the amount of energy stored in the storage system with respect to the maximum capacity. It can be measured as a percentage.
- Depth of Discharge (DOD): complementary with respect to the SOC $DOD(t) = 1 - SOC(t)$
- Round-Trip Efficiency (RTE): defined as $\eta = \frac{E_{out}}{E_{in}}$ where E_{in} is the energy needed to charge the system and E_{out} the energy remaining afcter a charge-discharge cycle.

1.3.3 Smart grids

Smart grids are defined as "energy networks that can automatically monitor energy flows and adjust to changes in energy supply and demand accordingly." [32] They are very important to the energy transition as they can efficiently integrate the growing amounts of renewable energy sources, and new loads, such as storage systems and electric vehicles. All of this, while maintaining the correct operation of the system in terms of stability and efficiency. [32]

The smartness of an electricity system is composed of two dimensions: communications and elaboration. The communication is achieved thanks to digital technology that allows bidirectional communication between operators and customers, the sensing of the different variables and the ability to actuate different equipment. On the other side, the elaboration is done thanks to different controls, computers, and automations that, with the information received through communication, can respond to quick changes on grid conditions. [33]

A smart grid can be divided into two layers: the power system layer and the communications layer, as shown in the Figure 1-3

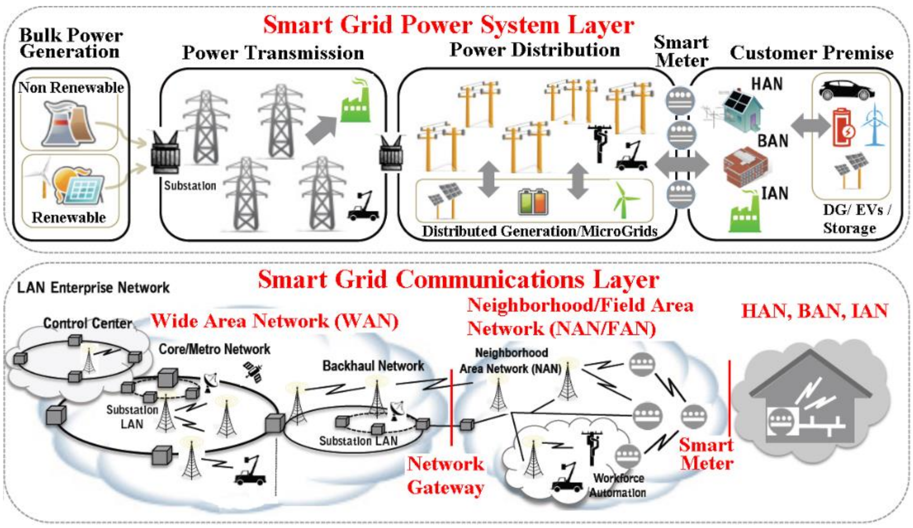

Figure 1-3 Smart grid layers [33]

1.3.4 Electrification of consumption

Electrification can be intended as "the progressive use of electricity from renewable sources in services and activities – like mobility, heating and industrial production- which until now have been mainly powered by fossil fuels, thereby making energy consumption more efficient, widespread and sustainable" [34] It is expected that in areas such as transport, household and industry the overall share of electricity consumption could rise to 46% by 2050, these sectors are considered key as its expected that, due to electrification in those sectors, greenhouse gases will be reduced by 6% by 2050 with respect to 2015 levels. [34]

From the fields mentioned previously, the electrification of household energy is promising as people are choosing to switch to electricity equipment that traditionally were powered by fossil fuels. Some examples are the electric boilers or heating pumps, which is more energy efficient than an oil or gas boiler. [34]

1.3.5 Nearly Zero Energy Buildings (nZEBs)

The concept of nearly zero-energy buildings has been first defined on the 2010/31/UE directive as "a building that has a very high energy performance (…) The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" [35]

The 2010/31/UE directive, also called the Energy Performance of Buildings Directive, also requires that the member states have to ensure that all new buildings were nZEB by the end of 2020 while at the same time all public buildings have to after December 2018. [36]

Regarding the process made in Italy, Decree-Law 192/2005 introduced the energetic efficiency. Moreover, this Decree-Law became a law thanks to the 90/2013 law that incorporated the European directive. Finally, the DM 26 June 2015 defines the minimal requisites for a building to be considered a nZEB and 1st January 2021 it was introduced the obligation of all new buildings or the ones in process of demolition or reconstruction need to be nZEB. [37]

1.3.6 Photovoltaic generation

As the world is continuously transitioning to the use of renewable energy sources to generate electricity it has become their “prime choice for enhancing access to affordable, reliable and cleaner sources of modern energy services” [38] this as a cause of the recent technological advances, the falling costs and new policies that enhance the use of this technologies for power production.

One of the main, and most popular renewable energy sources is the photovoltaic electricity generation. It is a key technology because it is apt for scalability in a short period of time, can be deployed in a modular way and can be deployed in almost every part of the world [39]. It will continue to grow and can be considered as a key technology to achieve a net-zero carbon energy supply as a consequence of its “very low CO2 footprint, its modularity and its ‘no emission no pollution’ function that make it a perfect solution for a dense urban environment” [39]

1.4 Photovoltaic Technology

As said previously, photovoltaic generation systems are one of the main drivers for the energy transition thanks to its massification and low carbon footprint. Therefore, important aspects about photovoltaic technology are going to subsequently be addressed.

1.4.1 Solar cell

The solar cell is the base element for the photovoltaic generation of electricity, in this place the energy that is emitted from the sun its converted into electrical energy through the photoelectric effect. The conversion is achieved thanks to the use of semiconductor materials such as Silicon, a widely used material for electrical applications. There are different kinds of cells, based on their production process, there are crystalline silicon cells (monocrystalline, m-Si or polycrystalline, p-Si) or thin film technologies. [40]

The operation of the cell is explained by the P-N junction, which is a junction of two semiconductor materials that are derogated differently. One layer is doped with trivalent atoms (P-type) and the other with pentavalent atoms (N-Type). This structure causes the diffusion of carriers, and, in consequence, a depletion region is created. For a solar cell, when incident photons reach this region, a current is generated, the photovoltaic current. [41]

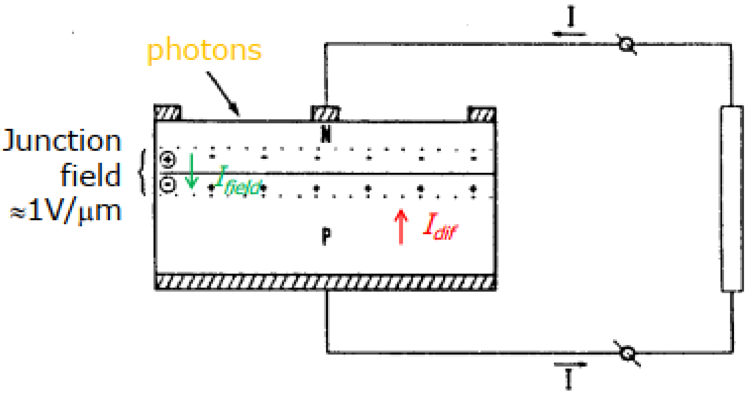

Figure 1-4 Structure of a solar cell [41]

1.4.2 I – U characteristic

The current vs voltage curve of an irradiated cell is strongly non-linear as a cause of its diode-like behavior. This curve it's characterized for a particular irradiance and temperature as its shown in the Figure 1-5

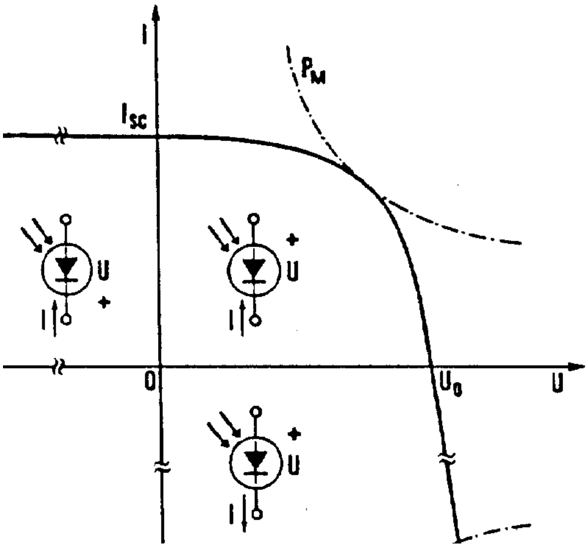

Figure 1-5 Characteristic curve of a solar cell [42]

This curve has some remarkable points such as

- I_{mpp}: maximum power point current
- U_{mpp}: maximum power point voltage
- I_{SC}: short circuit current
- U_{OC}: open circuit voltage

The output power of the cell has a maximum characterized by the value of I_{mpp} and U_{mpp}. In this point, the derivative of the curve is equal to the load conductance. On the other side, the power output goes to zero in both I_{SC} and U_{OC} as, by definition, in both the points the other variable is zero.

One last important parameter is the fill factor (FF), which gives a measure of the proportion the maximum power point voltage and current are with respect to the open circuit voltage and short circuit current, this way it can be determined how near to behaving as an ideal voltage or current source (depending on the point of the curve) the I-U curve is. The formula for the fill factor is

$$FF = \frac{U_{Pmax}}{U_{OC}} \frac{I_{Pmax}}{I_{SC}} \tag{1}$$

1.4.3 Temperature and irradiance dependence

As said previously, the I-U curve depends on the weather conditions, specifically in the level of irradiance (G) and temperature (T). This is important to be known, as the maximum power point will change if any of these parameters change, so it can be took into account when it’s applications are designed and working.

When the irradiance changes, the curve changes. The most sensible parameters to irradiance are the short circuit current I_{SC} and the maximum power point current I_{Pmax}, these parameters change in proportion to the irradiance. On the other side, the parameters related to the voltage (U_{Pmax} and U_{OC}) are less sensible to irradiance variations. This behavior can be seen in Figure 1-6

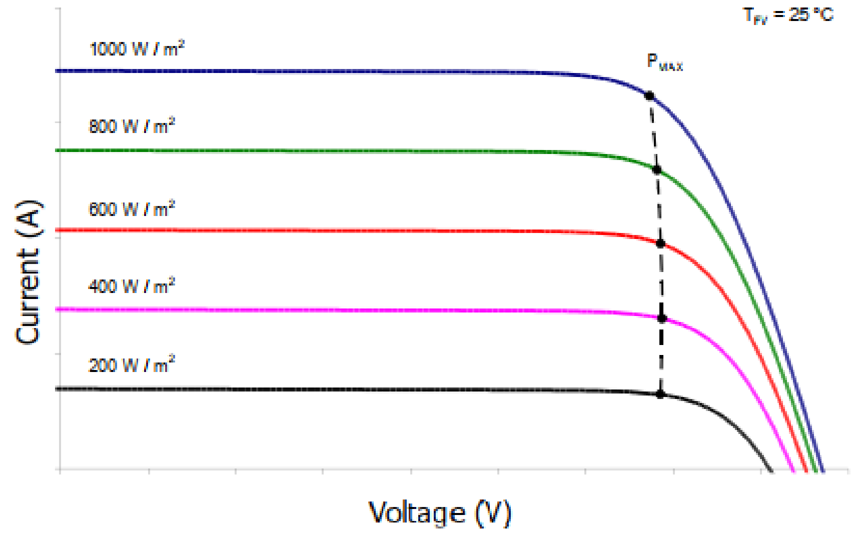

Figure 1-6 Curve dependence on irradiance [42]

On the other side, temperature variations have a different impact on the curve. An increase of temperatures increases the short circuit current but decreases the maximum power point current making little variations on current parameters. On the other hand, the voltage related parameters tend to decrease as it's shown in Figure 1-7

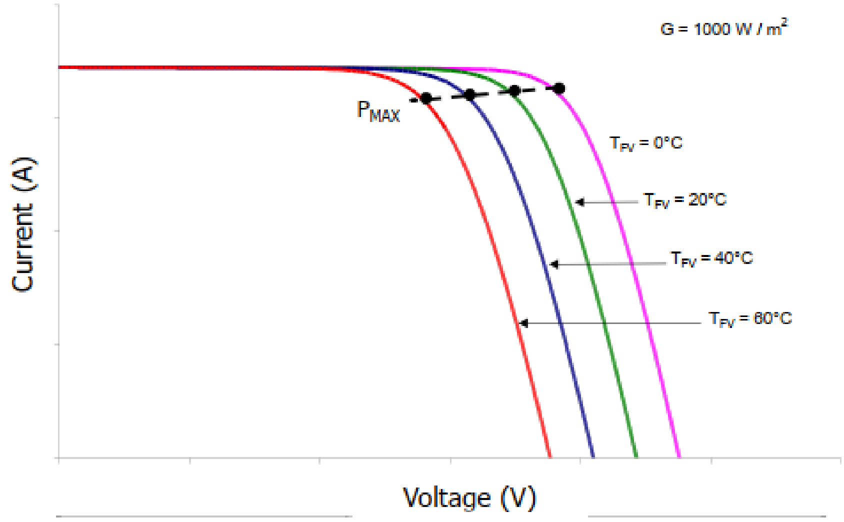

Figure 1-7 Curve dependence on temperature [42]

Given the information, the effect of both irradiance and temperature on the curve can be approximated and, as a consequence, the short circuit current can be considered only as irradiance dependent and the open circuit voltage as only temperature dependent. [42]

1.4.4 Losses in the solar cell

The conversion inside the cell from the sunlight to electrical energy is accompanied by inevitable losses produced by the following factors [41] [43]

- Reflection: not all the photons that reach the cell penetrate into it, part of them are reflected and others are blocked by the frontal electrode. To reduce the reflection losses anti-reflection treatments are applied and the frontal electrode's surface is minimized.
- Excess of energy: the photons that have more energy than the one needed to produce the photoelectric effect transform this excess of energy into heat.
- Missing energy: if a photon does not have enough energy to produce the photoelectric effect, this energy is degraded into heat.
- Recombination: electron-hole pairs are not mantained separated from the junction's electric field as some of the pairs are recombined liberating heat in the process.
- Fill factor: internal resistances due to the structure of the cell produce energy dissipation on them during its operation. These resistances are produced by the electrodes, non-ideal isolation and other constructive factors.

1.4.5 Efficiency of the solar cell

It's important to see how the efficiency of the cell behaves. It can be defined as

$$\eta = \frac{P_{MAX}}{P_i} \tag{2}$$

Where P_{MAX} is the maximum power the cell can produce and P_i is the incident power on a surface. Given a certain irradiance G and surface A, it's calculated $P_i =$

$G * A$. The Figure 1-8 shows the current density and power density ($p_u = \frac{P_u}{S}$ with P_u as the useful power produced) profiles in function of the voltage

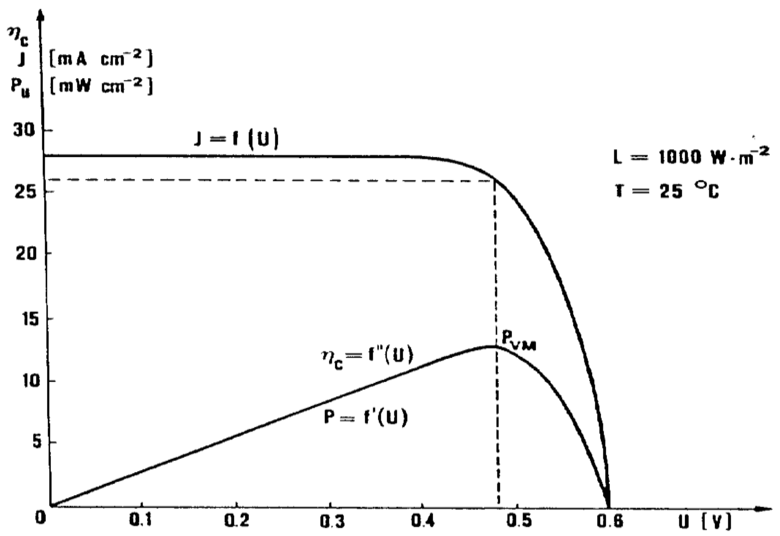

Figure 1-8 Current density J and power density p_u dependence on voltage [44]

It can be viewed that the conversion efficiency's curve has the same behavior as the useful power.

1.4.6 Series and parallel connections

Series and parallel connections of solar cells are done by the necessity of reaching higher levels of voltage and current, as the loads to be supplied require higher levels of power that a single cell wouldn't be able to give. However, connecting cells in series may give loss problems due to the "mismatching" effect to be mentioned subsequently. [42]

1.4.6.1 Series connection

When N_S identical cells are connected in series, forming a string, the characteristic curve I(U) is the sum, for the same current, of the voltage of all the cells in the string. As a result, the open circuit voltage of the string is

$$U_{OC,series} = \sum_{i}^{N_S} U_{OC,i}$$

(3)

However, if there's a cell different from the others (because of constructive problems or shading) the mismatching effect occurs. As a result of this, the current generated by the string is limited by the current of the "weak cell"

$$I_{SC,series} = min(I_{SC,i})$$

(4)

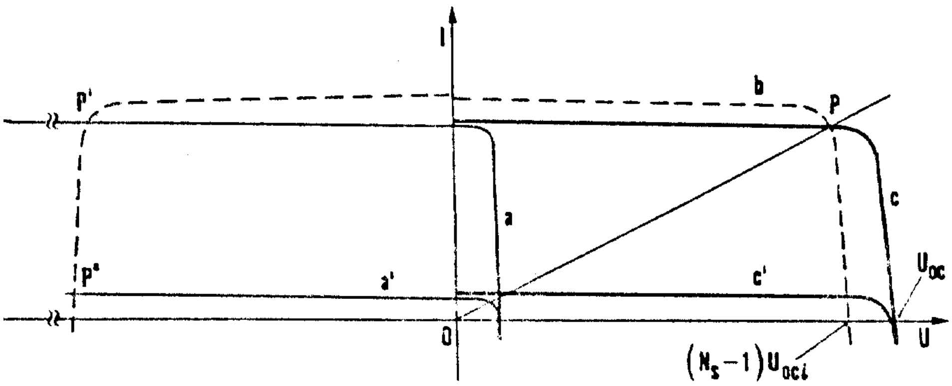

Figure 1-9 Mismatching problems on cells connected in series [43]

Consequently, the current deliverable by all the string is reduced and, subsequently, the power deliverable is reduced drastically. Moreover, this effect represents a risk to the cell as, if the external load requires a current higher than the short-circuit current of the weak cell, the cell is going to operate as a load, absorb more power and could cause a failure. This problem ca be solved by putting a diode in parallel, a bypass diode, that will prevent the load operation of the shaded cell. [45]

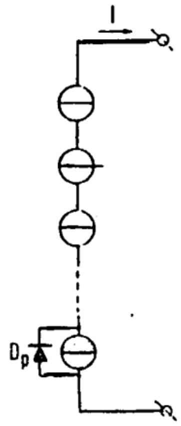

Figure 1-10 Bypass Diode [45]

1.4.6.2 Parallel connection

On the other side, when N_p identical cells are connected in parallel the characteristic curve I(U) is the sum, for the same voltage, of the current of all the cells involved in the connection. As a result, the short-circuit current is

$$I_{SC,parallel} = \sum_{i}^{N_p} I_{SC,i}$$

(5)

However, if there's a cell different from the others (because of constructive problems or shading) the mismatching effect occurs. As a result of this, the voltage generated is limited by the voltage of the "weak cell"

$$V_{OC,parallel} = min(V_{OC,i})$$

(6)

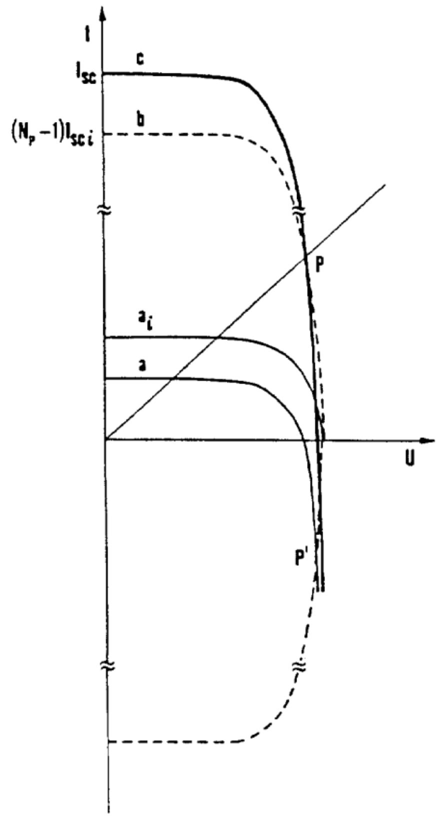

Figure 1-11 Mismatching problems on cells connected in parallel [45]

As a result, the voltage deliverable is reduced and, subsequently, the power deliverable is reduced drastically. Moreover, this effect represents a risk to the cell as, if the external load is an open circuit, the shaded cell must absorb the current generated by the other cells. This can cause over-temperatures and possible failures. However, a diode connected in series to the cell in parallel could avoid the reverse currents. [45]

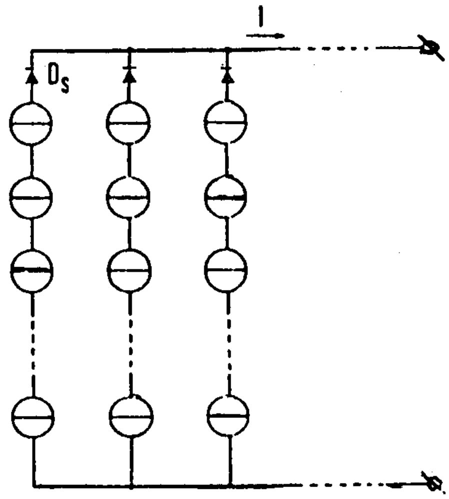

Figure 1-12 Blocking diodes [45]

1.4.7 Photovoltaic modules

The photovoltaic module, also called panel, is composed of a set of solar cells connected in series or in parallel that are also environmentally protected and assembled to operate. Between these protections are two transparent panels to hermetically close the panels, this to prevent humidity penetration. [46] [43]

For a module, protections are used against the mismatch problems addressed previously. Those protection diodes used are, a bypass diode D_P for each string of modules in series, and a protection diode D_S in series with the module or the string of modules in series. This way, the shaded cells are protected, and the module don't see a radical reduction of its injected power by the presence of shading in the module. On the other side, the protection diodes also prevent the problems of mismatch between strings in parallel. [43]

On the other side, photovoltaic generators also are characterized for having an operating point that depends on the load characteristics. For a given value of irradiance and temperature, the maximum performance of the generator is obtained at the maximum power point (MPP). However, changes in the irradiance and temperature conditions change the characteristic curve moving the maximum power point, thus, changing to an operating point that couldn't be the optimal point. Given this, to exploit the generator at its maximum performance a maximum power point tracker (MMPT) can be used. [43]

1.4.8 Standard Test Conditions and Nominal Operating Cell Temperature

To refer the modules characteristics to a standardized system, the IEC/EN60904 standard defines the Standard Test Condition (STC). Those conditions are

- Irradiance $G = 1000\ [W/m^2]$
- Air mass $AM = 1{,}5$
- Cell temperature $T_C = 25\ [°C]$

Furthermore, it's defined the nominal operating cell temperature (NOCT) as temperature of equilibrium of the cell in a module, placed in the sun, within the following normalized environmental conditions defined by the CEI EN 60904-3

- Irradiance $G = 1000\ [W/m^2]$
- Wind speed $u_w = 1\ [m/s]$
- Ambient temperature $T_a = 20\ [°C]$

It's a parameter given by the constructor. By knowing this value, it's possible to calculate the temperature of the cell T_C for any value of irradiance and ambient temperature. [47]

2 Energy communities

2.1 Definition of energy communities

One of the main aspects of the energetic transition highlighted on the European Green Deal is the participation of the citizen on the transition towards the renewable energy sources. This main characteristic is possible thanks to the develop of new generation technologies, like rooftop photovoltaics or distributed storage systems, that allow the user to produce his own energy, store it, manage it, and eventually sell it to the grid. This characteristic transforms the user from a passive consumer into a ”prosumer”, which can be defined as “an energy user who generates renewable energy in its domestic environment and either stores the surplus energy for future use or vends to the interested energy buyers” [23].

Moreover, during the last years, due to the energetic transition, the rise of new different ways of production and the decentralization of it, the EUs has developed a set of new directives with the aim to define and give legal support to these new entities. These directives, the 2018/2001/UE (Renewable Energy Directive II, REDII) and 2019/944/UE (Internal Energy Market Directive, IEM) define new ways of collective participation on energetic production, the so called “energy communities”.

2.1.1 2018/2001/UE directive

The Renewable Energy Directive II (REDII) has the objective to “strengthen the role of renewables self-consumers and renewable energy communities” [25]. This is made by defining the Renewable Energy Community (REC).

The renewable energy community, defined on the 2nd article of the REDII, is set as a legal entity with the following characteristics:

- It is open and voluntary to participation, autonomus and it is effectively controlled by shareholders or members localted in the proximity of the renewable energy projects, owned and developed by the same legal entity.

- The share holders or members can be natural persons, medium-sized enterprises (SMEs) or local authorities, including municipalities.
- Its primary objective is to provide environmental, economic or social community benefits for its shareholders or members or for the local areas where it operates, rather than financial profits [48].

Additionally, on the article 22 it requires the member states to "ensure that final customers, in particular household customers, are entitled to participate in a renewable energy community while maintaining their rights or obligations as final customers". It also requires the member states to ensure that RECs are entitled to

- Produce, consume, store and sell renewable energy
- Share, within the REC, renewable energy that is produced by its owned production units
- Access all suitable energy markets both directly or through aggregation in a non-discriminatory manner.

Finally, it also requests that member states will evaluate the current barriers for the development of RECs and will provide a framework to promote their development.

2.1.2 2019/944/UE directive

The directive on common rules for the internal electricity market includes new rules to encourage active consumer participation in all markets, "either by generation, consuming, sharing or selling electricity, or by providing flexibility services through demand-response and storage".

The directive defines "active costumers" as a final customer who consumes, or stores electricity generated within certain boundaries or who sells self-generated electricity or participates in flexibility or energy efficiency schemes.

On article 15, the directive gives more information regarding active customers. It requests the member states to ensure that they are entitled to operate directly or through aggregation, to sell self-generated electricity and to participate in flexibility and energy efficiency schemes [49].

Furthermore, it also defines the Citizen Energy Community (CEC) as a legal entity that

- Is based on voluntary and open participation and is effectively controlled by mebers or shareholders that can be natural persons, local authorities, including municipalities, or small entreprises.
- Has as primary purpose to generate environmental, economic or social community benefits to its members or the local areas rather than generate financial profits.
- May engage in generation.

On article 16, the directive requests member states to enable regulatory frameworks for CECs ensuring that participation is open and voluntary, members are entitled to leave the community and they don't lose their rights and obligations as household customers or active customers. Finally, is relevant to note that requests the cooperation of the distribution system operators to facilitate electricity transfers within CECs.

2.2 CEC and REC definition comparison

As seen on the definitions, both have a lot of common aspects, but also important differences that need to be highlighted. The most important aspects to address are

- Both definitions require that the community is entitled as a legal entity but deepening in defining what type of entity should be.
- Requires that both of the organizations are voluntary and open to participation
- Regarding whom may be part of the community, the REC definition allows natural persons, medium-sized enterprises and local authorities to be part as long as their main activity is not related to energy. On the other side, CECs definition also allows large scale enterprises to join the community as long as it's not its main economic activity.
- The geographical limits are addressed on the RECs definition by requiring the proximity of the shareholders to the projects without giving an exact definition of "proximity". On the other side, CECs do not give any reference to geographical requirements.
- The main objective of RECs and CECS is to give environmental, social and economical benefits to the community rather than seeking financial profits.

- RECs need to be autonomus while CECs autonomy is not addressed on the definition.
- Both RECs and CECs have to be effectively controlled by its shareholders
- In the definition, it is required that RECs are entitled to produce, consume, store and sell renewable energy while CECs may engage in generation but not restricting it to renewable energies [50] [51].

According to this, RECs are a subset of CECs as shown in Figure 2-1. CECs are made to participate in different activities on the energy sector as well as RECs, but this last is more focused on renewable energy activities. RECs are also more restricted on the eligibility of its members, excluding large scale companies.

Figure 2-1 Relationship between RECs and CECs [51]

2.3 Definition of legal entity and proximity

Some aspects that are not specified in the directives are what type of legal entity the community should be and what intends on “proximity” to the projects. The responsibility to make these definitions is delivered to the member states, adapting their laws to their national context. For this reason, it is important to review what types of legal entities are the different energy communities across Europe and examinate the different definitions of proximity are used in different countries.

2.3.1 Legal entities

Respect the legal characterization of the community, different models have been used for already existing community-ownership business model that are summed up in the following table

Community-ownership model	Description
Co-operatives	Co-operatives are characterized for being a natural legal form for community power projects. They are owned by their members to achieve common economic, social and cultural goals. They also combine flexibility, public participation based on a "one member-one vote" democratic principle to make choices.
Partnerships	Partnerships are characterized for having individual partners as members who own shares in the community-ownership model. The main objective is to generate financial profits for the shareholders. In contrast with co-operatives, partnerships may not have a "one member-one vote" logic to take decisions but it has a more democratic, transparent and informal way to take decisions than traditional companies.
Non-profit organizations	Non-profit organizations rely on the investments made by its members who are responsible of the financing and do not take back profits. The profits made up by the organization are re-invested in the community where it takes place.
Community trusts	Community trusts are a good type of ownership model to assure that the returns are used on community projects to generate social benefits. Also, it allows

	local citizens that are not able to invest directly to participate in the benefits.
Housing associations	Housing associations are private non-profit organizations that offer housing to low-income individuals and families.

Table 2-1 Common legal forms of community-ownership business models [52] [53]

2.3.2 Proximity definition

A crucial aspect for the implementation of RECs in the EUs member states is what is intended in the different countries for proximity as it is necessary to evaluate if a member is qualified to get into a community. Up to the present day, different countries have had different approaches in defining proximity for RECs being three the main approaches.

- First and foremost, a geographical proximity criterion seems logical to establish who is qualified to participate in the community. It is done by defining a certain perimeter for RECs. This criterion has certain drawbacks as "it would not be transparent on what grounds the centre of the perimeter is set, and to what dimensions this perimeter is bound to" [54]. This criterion is used, for example, in Lithuania where 51% of the members need to be residents in the municipality of the production plant or a neighbouring municipality. Also is used in Greece, where equally the 51% of the members are expected to have lcoal ties within the district where it is located the community [50].
- Another criterion, is to define proximity by the use of political districts or postal codes. This has a great advantage to the community as its participants would be "immediately aware of with whom they could form an energy community" [54]. But it has the drawback of restraining smaller districts or villages without technical reasons.
- Finally, grid levels can be used to define proximity between different users. It can be done by restraining the members to the same low voltage level, criterion used, for example, in Slovenia [50]. But it has the drawback of restricting the participation of industrial and commercial customers, wind farms and most hydro power plants. Another criterion, is to use the same medium voltage level. It is used, for example, in

Austria and Italy [50]. The drawback of the grid level approach is that "customers do not yet have the ability to verify to which branch of the low-voltage grid their dwelling is connected to, making it almost impossible to know who they could establish a REC with" [54].

2.4 Benefits and barriers of energy communities

An important thing to examine are the different benefits that energy communities could give to the different actors related to them, and the different barriers they may face during its planification, implementation and operation.

2.4.1 Benefits

As the directives points out, the main objective is to give environmental, economic, or social community benefits rather than getting financial profits. The benefits given to these aspects are

- Environmental benefits: As the size of the community energy plants are more bigger than each one separately, this model "can enable aggregation of demand for energy-related assets and negogiation of better prices (…) thus lowering the upfront investments needed for community members" [52], as the investments necesary to develop a project go down it is more easy to develop more energy communities and if they are RECs it would produce an increment of renewable energies. Another environmental benefit is the "formation of a better understanding of renewable energy technologies" [55] which would give an "energy saving behavior, often combined with a general awareness rising for issues connected with energy consumption, like climate change" [55], a study in the UK has shown that "people involved in CE activites are generally more receptive to ethical and environmental commitment and question their behavior with respect to energy consumption" [55].
- Economic benefits: these benefits on energy communities are shown by two main aspects, a possible drop on the cost of it and the possibility to sell energy or provide services to the grid. The electricity costs from local renewable plants may be cheaper than the electricity offered by the grid [52]. Also, as the"demand charges (also called peak) are an important component of electricity bills (…) on-site battery storage

systes can be used to manage peak loads and reduce demand changes" [52]. On the other side, it has been identified that selling the energy would help "in generating an income for the communities near to the RE generation sites, often in marginalized regions with economic disadvantages" [55]. These benefits are generated by direct financial ganes due to energy sale or by stimulating regional economy creating jobs that are necessary to the implementation and maintenance of the projects [55]. Furthermore, UK research reports has shown important positive effects on energy saving measures, social programs and environmantal issues made possible by funding made by energy communities [55].

- Social benefits: these benefits are shown in many different social aspects. For example, revenues made by selling electricity to the grid can be reinvested in community projects like "sports centers, children's daycare or other services". Also, by educating the members of the community involved in the project it is possible to raise the acceptance of renewable energies. The acceptance of the project can be increased more if the "community can participate in the planning process from the beginning on and there are direct possibilities to buy shares of the RE installations and receive financial benefits as well" [55].

2.4.2 Barriers

The implementation of energy community projects is not exempt of a variety of barriers that slow down or even prevent the projects to develop. First and foremost, energy communities lack of political and institutional support. In the UK "acquiring initial funding is a complex process which requires a lot of effort, research and network, making it difficult to access state support funding" [55]. Moreover, there have been difficulties on entering the market as it "structure and legal framework are laid out for centralistic, big-scale energy production" [55] as there are no great incentives for small scale plants to connect to the grid, costs rise and make it difficult to develop projects. Some solutions are creating policy frameworks for energy communities to stimulate further investment and adapt it to the local and country-specific circumstances [52]. On the other side, for market barriers "appropriate regulatory provisions need to be developed for community-owned projects and other DERs to enable energy supply arrangements such as third-party sale or peer-to-peer energy sharing [52]. Furthermore, financial support is a key aspect on projects, it has been study that there is a lack of long-term financial support and great problems in obtaining initial financing [55]. This problem can be solved if "the community can partner with local business or developers to fill the funding gaps and increase the creditworthiness of the projects" [52] or by enabling low-cost loans and grants given by governments and development banks.

2.5 Energy communities' frameworks across Europe and examples

As a consequence of the recasts of the renewable energy directive (REDII) and the electricity market directive (EMD), where renewable energy communities and citizen energy communities, the different EU's member states must transpose these directives into their national laws by the end of 2020. The directives defined diverse aspects in general terms so the different countries could be able to adapt them according to their national reality. Collective self-consumption schemes already were a reality in different countries as they had frameworks to support them as well as community ownership law regulations. Also, at the moment different member states already managed to transpose, at different levels, the EU's directives. According to a study from the Joint Research Centre the number of initiatives across Europe are shown in the Figure 2-2 [56]

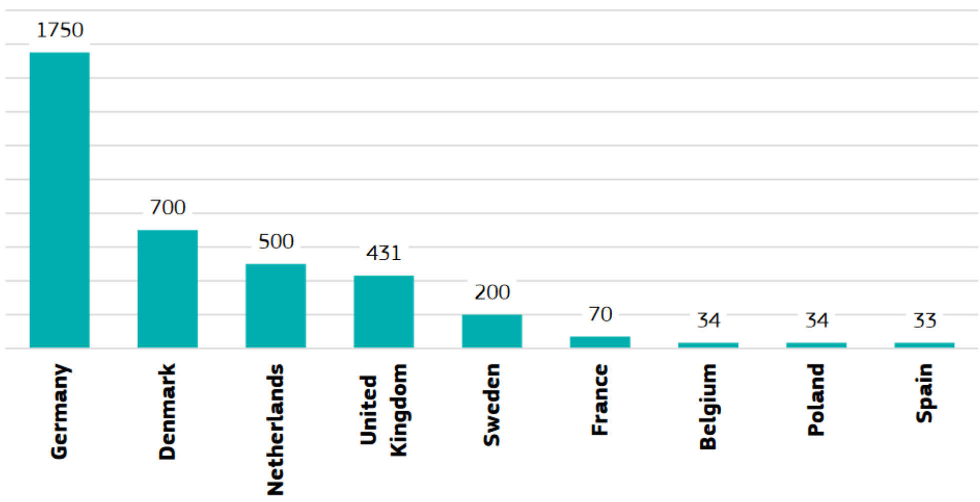

Figure 2-2 Approximate number of community energy initiatives in Europe [56]

2.5.1 Germany

Germany is a country characterized for his long tradition on collective energy actions and for his strong and stable support for renewable energy. Moreover, an energy transition was introduced in 2020 by putting very ambitious targets in the areas of renewable energies, energy efficiencies and greenhouse gas reductions, together with the support of Feed-in Tariffs. All of this to meet an 80% of the energy demand supplied by renewables by 2050 [57]. There are estimates that show that individual citizens and communities own a 34% of the total installed PV capacity [58].

Collective energy actions in Germany can take the following forms [58]:

- Energy cooperatives
- Collective self-consumption
- Citizen energy companies

Energy cooperatives are characterized by a democratic governance, distribution of profits and losses in a way that surpluses are reinvested in the community. There is an estimation of about 800 energy cooperatives in Germany that provide services in the areas of operation, supply, renewable plants ownership and energy efficiency services [58]. The main legislation in Germany for prosumers is the Renewable Energy Sources Act 2017 (EEG) that defines self-supply and citizen energy companies [59].

A citizen energy company (CEC) consists of at least ten natural persons who are members eligible to vote where at least 51% of the votes are held by natural persons with a permanent residency in the administrative district where the project is located [56]. This aspect and the fact that there is a maximum amount of voting rights equivalent to 10% guarantees the autonomy and effective control principles of governance [60]. The CEC is focused on being mainly a wind power electricity producer and also has two privileges: reduction of financial security deposit and a clearing price instead of a bid price [58].

Finally, it is possible to share electricity in the same neighborhood or multi-apartment building due to the Tenant Supply Act (EEG) where it is introduced the concept "Mieterstrommodell" which is a model where the owner of a building may produce photovoltaic electricity on the roof and sell it to the tenants [59].

An important project made in Germany is Bioenergy Jühnde, the first bioenergy village established in 2006 in Jühnde, a small village of 750 inhabitants in the southern part of Lower Saxony, Germany [57]. It consists of a 700kW CHP generator that runs on biogas to produce electricity and a 550kW woodchip boiler used for heating distributed by the local network on winter while in summer it is used to dry woodchips that are going to be used in winter [61].

Figure 2-3 Bioenergy Village Jühnde [62]

The original idea was made of by the University of Göttingen who were looking for rural villages for a competition where the winner would host a new bioenergy plant to demonstrate an alternative to fossil fuels [61]. The main challenge during the implementation was motivating the different actors involved in the area, challenge that was overcome thanks to a successful motivation strategy that was composed of a correct advertising throughout the village, the open participation of villagers and using a competent person in the village disposed to provide information about the project [63].

At the end, the village reached to produce 70% of its heating demand and the double of its electricity demand thanks to this project, as it is owned locally and collectively by the residents that are able to buy shares from it and purchase heat and electricity. At the present, 75% of Jühnde's inhabitants are members of this cooperative [61].

2.5.2 Denmark

Denmark is characterized of its long history of strong policy support for wind energy. This adherence to wind energy has its source in the oil crisis of the 1970s when the country reacted by developing wind power as a way to reach more energy reliability and security. Furthermore, at a cultural level, the idea of being greener and supporting renewable energies its further accepted by the population. Last, but not least, protests against nuclear energy in the 1980s reinforced even more the citizenships support of wind power as a green and clean alternative fuel. Moreover, there is also a widespread use of district heating where municipalities and communities own their heat and power generation plants establishing a much more decentralized energy system in comparison with other countries [57].

To encourage community participation, there is a requirement for wind energy developers to offer 20% of the shares to residents that live near the wind farms, this also includes the right to buy up to 50 shares if they live within 4.5km of a project. Moreover, for 2018 and 2019, the right to local ownership will be extended for large-scale solar PV [56].

Finally, collective self-consumption is allowed on building scale in Denmark. The policies determine that all consumers as well as the generation plant must be behind a common utility meter. Also, a proposal for the amendment of the Danish Electricity Supply Act was published for consultation in 2020. This proposal defines CECs and for aggregators and active consumers their rights and obligations are addressed [50].

A project that symbolizes both the wind power and cooperatives tradition in Denmark is the Middlegrunden Wind Farm Co-operative. This cooperative is located 3km from the Copenhagen harbor and consists of 20 offshore turbines of 2MW each, enough to satisfy the 3% of the city’s electricity needs [57].

Figure 2-4 Middelgrunden Wind Farm [64]

This project started as a private partnership formed in 1997 and had the objective of producing electricity through the establishment and management of 20 wind turbines on Middelgrunden shore. The cooperative was established as a partnership formed by the Working Group for wind turbines at Middelgrunden [65]. The wind farm consists of a 50-50 joint venture between Copenhagen Energy and Middelgrunden co-operative and has the achievement of being the largest community-owned wind project in the world [52]. This was achieved thanks to Denmark's decentralization of energy targets and flexible planning agreements that originated in a strong co-operative energy projects tradition which helps to gain support between the public [57].

2.5.3 Austria

Austria is one of the first countries to introduce a collective self-consumption scheme normative applied to photovoltaic electricity. It was introduced in 2017 as part of an amendment of the electricity act (EIWOG), this allowed multi-apartment building to consume the electricity produced in the same place with photovoltaic panels as a consequence of the electric grid in it made private [66] [67].

Also, in July 2021 there was established the Renewables Expansion Law (WAG) that enabled a general framework for RECs In relation to renewable expansion and its support, while EIWOG included a more detailed framework for RECs and CECs. EAG also establishes that, by the end of 2023, the Federal Minister for Climate Protection, Environment, Energy, Mobility, Innovation and

Technology hast to evaluate the implementation of the law covering RECs, CECs and CSCs evaluation to identify improvements, obstacles and barriers [67].

RECs are primarily focused on electricity production. The law enables them to, not only generate, store, and supply renewable energy but also act as an aggregator. RECs can be organized as associations, cooperatives, partnerships or corporation, association of housing owners or similar legal bodies. Finally, respect to the proximity definition, it must be established within one network limited by the low or medium voltage [50].

On the other side, CECs can be established over the entire territory. Besides electricity generation, storage, sale and aggregation it can provide services in the areas of energy efficiency or EV charging services. As the EMD established, the effective control is limited to natural persons, local authorities, and small companies [50].

An example of a collective self-consume scheme in Austria. At the Lavaterstrasse 5, Wien, building the photovoltaic electricity is produced with PV models installed in the roof and its distribution is controlled according to the instantaneous demand, this dynamic control allows to reach higher proportions of self-consumption. It has been reported savings of about 30% with respect to grid tariffs. These tariffs permitted that 47 of 68 apartments adhered to buy photovoltaic electricity generated by the rooftop modules [66].

2.5.4 Netherlands

The Netherlands is well advanced in terms of collective energy actions as they already had regulations allowing energy cooperatives before the publication of RED II and EMD directives. Even though, concepts as RECs, CSCs and CECs have not been transposed to Dutch regulation [58].

The principal law for prosumers is the Electricity Act 1998 that foresee incentives for prosumers and make possible different forms of self-consumption. A particularity of this regulation is the use of postal-code-area to identify which members can join into the same community and run a REC so they can exchange electricity among themselves [68].

One example in the Netherlands is the Amelander Energie Coöperatie U.A. a cooperative company located in Ameland; a municipality located in an island in the north of the Netherlands. This company was founded “with the aim of supplying Amelander energy users with sustainable electricity and CO2 compensated gas at attractive rates”. It consists of a solar park of 23000 solar panels that make enough power to cover all households in the island. The objective is to become a self-sufficient island and reach an 100% green energy supply [56].

2.5.5 France

The French energy market, after its liberalization pushed by the EU until it was completed in 2007, is characterized for being one of the most centralized in Europe. An important characteristic is its dominance of both nuclear and hydroelectrical energy, generation types characterized for being for large-scale plants [68].

France has the particularity of being the first EU Member State to introduce dedicated incentives to promote participation in renewable projects in 2015. This law allowed joint stock companies and cooperatives to develop renewable energy projects financed in part by local citizens or municipalities [68].Years later, collective self-consumption schemes were introduced in 2017, previously to the publication of the European directives, defining power limits and limiting energy share to the members located in the same low voltage substation. Also imposed the requirement that a single legal entity has to be in charge of the management of production and consumption [66].

Finally, the 8th of November 2019 the French Law of Energy and Climate introduces the concept of Renewable Energy Communities as a transposition of the RED II directive. The definition in the French law is identical to the definition made up in the RED II directive as it allows RECs to “produce, store, sell and share renewable energy” [60].

An important energy supplier in France is Enercoop, a cooperative launched by French ecological and ethical business organizations which has the objective to decentralize the energy production and engage the citizens in the energy transition [69]. It is organized as a cooperative (Société Coopérative d’Intérêt Collectif) that buys directly from producers and sells it to the consumers at a fair price [56]. It follows a multi-stakeholder governance model where any member has one vote. Nowadays, it has around 70000 members [65] and supplies 53% of its energy from wind power, 39% from hydraulic plants, 7% from photovoltaic plants and 1% from biomass [70].

2.5.6 Belgium

In Belgium the situation differs between regions due to its regional government structure, both Wallonia and Flanders manage different frameworks. In Wallonia, in October 2018 it was adopted a framework for collective self-consumption that was followed by a decree defining renewable energy communities [50]. Moreover, in May 2019 a legislative framework promoting CSC and RECs was adopted. RECs were defined with the objective to balance the consumption and production flux on the grid this is made by enabling them to "produce, consume, store and sell renewable electricity for the benefit of participants at the local level using the public network or a private grid" [50].

The framework defines and limits different aspects of RECs. First of all, to share and store the production of the different members the electricity has to be produced exclusively from renewable energies or high-quality consumption. Furthermore, it also gives a definition for "proximity" describing "local perimeter" as "a grid segment whose connection points are located downstream of one or more stations of public electricity transformation of medium or low voltage. Finally, the members of the REC can be any natural person, local authority or small or medium company located in the local perimeter, the participation is free and open and it forces the corporations to not have energy as their principal activity [50]. This definition seems as similar as the one described in RED II with the difference of having a stricter criteria for geographical limitation for the participants, enforcing the totality to be located in the local perimeter [60].

A cooperative located in Belgium is BeauVent, a cooperative funded in 2000 by some households of Westhoek who had the goal to save electricity without sacrificing comfort. The cooperative produces both electricity and heat generation. It acts as a renewable electricity producer and sells it to large consumers. Also collects funds to invest in renewable technologies and informs citizens by raising awareness on energy issues [56] [65].

3 Energy communities in Italy

As well as all the other EU's member states, Italy has to reach the objectives set out in their Integrated National Energy and Climate Plan (PNIEC) towards the decarbonization of the country. Moreover, to reach these goals, an important task to do is the transposition of the REC II and IEM directives into national laws that allow the RECs and CECs to exist, operate and involve the citizens in the energy transition.

3.1 Electrical national system

Up to the present day, the electrical market works on a competitive regime established by Bersani Decree in 1999 due to the enact of the 96/92/CE European directive that started the liberalization of the European electrical market. [71] The liberalization of the Italian Electricity Market is done by declaring on the Bersani Decree that "the activities of production, import, export, purchase and sale of electrical energy are free in compliance with public service obligations contained in the provisions on the present decree" [72]. Whereas the state oversees transmission and dispatch activities attributed in concession to the national transmission grid operator and distribution activities are assigned on a concession regime. [72]

3.1.1 Actors in the electrical system

There are different actors playing important roles for the correct operation and management of the electrical system. The Bersani Decree stipulates the need of having a national transmission grid operator that must do the transmission and dispatch activities. In the case of Italy, Terna is the responsible for the transmission, described as "the management, maintenance and development of the Italian high voltage electricity grid, and for dispatching, which consists of managing the electricity flows on the grid at any time" [73] Its operation consists of a natural monopoly system within a market regulated by the Italian Regulatory Authority for Energy, Networks and Environment (ARERA). [73]

The Italian Regulatory Authority for Energy, Networks and Environment (ARERA) is “an independent administrative authority that operates to ensure the promotion of competition and efficiency in public utility services and protect interests of users and consumers” [74]. The sectors in which it operates are electricity, natural gas, water services, waste cycle and district heating. And operates by balancing different objectives, from economic and financial goals to social and environmental goals. [74]

Another important actor is the GSE (Gestore Servizi Energetici), a company that works in four different areas: renewable energy, energy efficiency, community and institutions and international context. Its work is done by managing different incentive mechanisms, promoting renewable energies, doing different research and studies, and dialoguing with different foreign institutions and operators. [75]

Finally, GME (Gestore Mercati Energetici) is a company wholly owned by the Italian Ministry of Economy and Finance set up by GSE. It operates power, gas, and environmental markets. [76]

3.1.2 Segments of the electrical system

The entire Italian National Electricity System is a very complex scheme that the electricity must go through to arrive to the different users. However, it can be divided in four stages or “phases”.

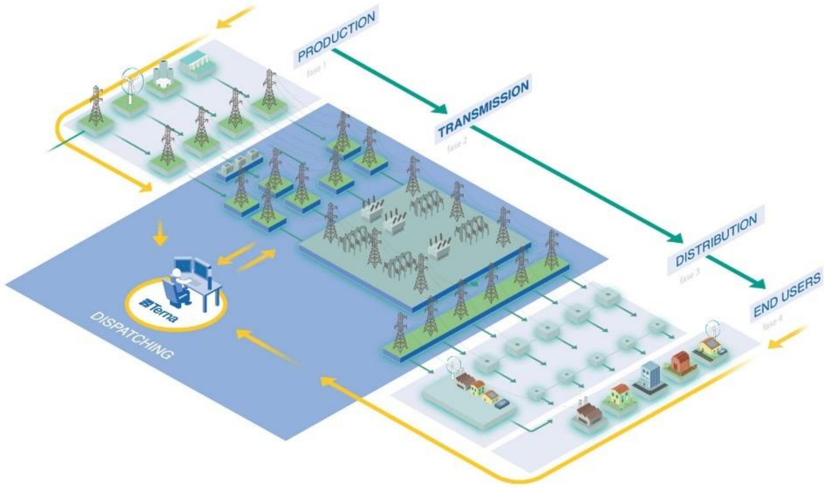

Figure 3-1 Electricity System Scheme provided by Terna [73]

The first phase is the production of the electricity. Electricity is produced in the different power plants transforming different primary sources into electricity. There are different types of power plants according to the renewability of its source, it can be a non-renewable source (natural gas, coal and oil) or renewable source (geothermal, hydroelectric, solar and wind energy). Moreover, the production market is completely liberalized, and the information of the production is sent to the TSO (Terna) for dispatching. [73]

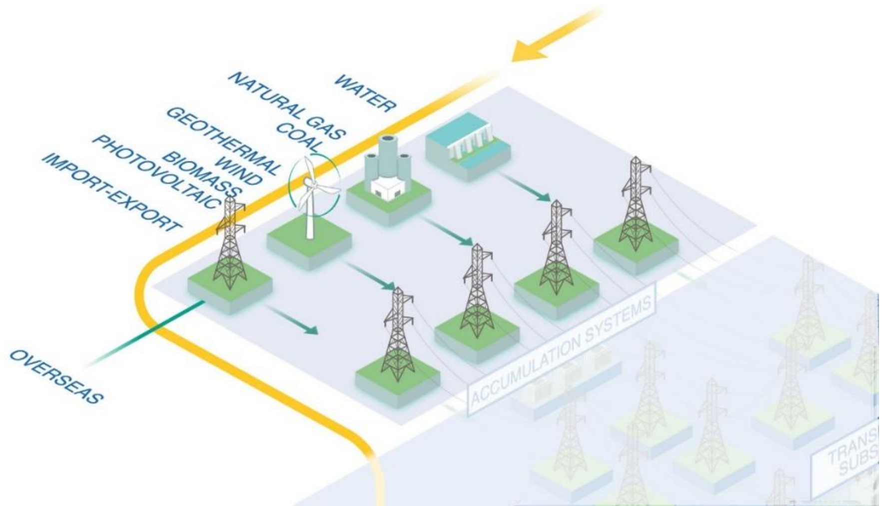

Figure 3-2 Production scheme [73]

The second phase is transmission. Transmission is regulated by Terna who has to regulate the correct flow of the power from the sources to the users and the correct functioning of the network by doing the dispatching services. These services include the monitoring of the power flows, the arrangement for managing the coordinated operation of all elements of the system, the programming of grid unavailability and to do forecasts of the electricity demand and comparing it with the production programs. [73]

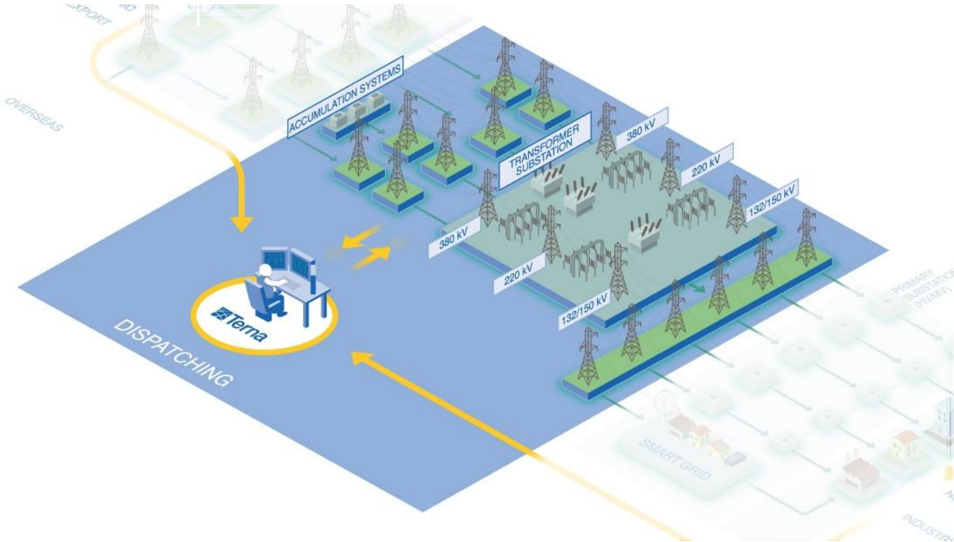

Figure 3-3 Transmission Scheme [73]

The third phase is distribution. Through the use of primary substations (which transforms high voltage into medium voltage), secondary substations (which transforms medium voltage into low voltage), transformers and a grid infrastructure the distribution system operator (DSO) has to provide de high voltage electricity to the end users. [73]

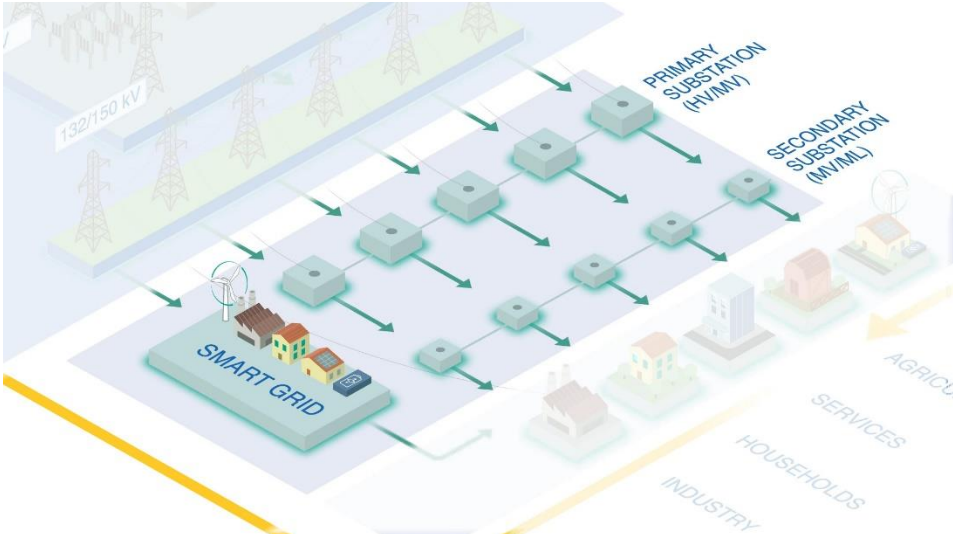

Figure 3-4 Distribution scheme [73]

Finally, the last stage of the system are the end users. They can be from households to agriculture, industrial and tertiary enterprises who receive the electricity produced through the coordination of the system. [73]

Figure 3-5 Utilities scheme [73]

3.2 Regulatory framework for energy communities in Italy

The regulatory frameworks and normative have been changing these last years as there were already a framework for self-consumption and it was needed an implementation of the REC II and IEM European directives.

3.2.1 Milleproroghe Decree

The article 42-bus of the Milleproroghe decree (that the became 8/2020 law the 29th of February 2020) is a framework for collective self-consumption and introduced renewable energetic communities' schemes. The regulations wanted to collect data and information useful for the implementation of the European directives and to reach the objectives of the PNIEC. [77]

To form an energy community, some requirements are needed [78] [79]

- Participation: open and voluntary.
- Members: can be fisical persons, SME or local authorities.
- Objective: the main objective of the energy community is to give enviromental, economic and social benefits for the community itself and the surrounding area rather than a finantial objective.
- System: the system's power has to be lower than 200kW and be powered after the enactment of the decree. Moreover, the energy exchanges must be done via the already existing distribution grid and the users must be connected to the same BT/MT cabin.
- Contract: the relations within the community must be regulated by a private contract. Also, the member are able to leave the community at any moment and conserve their final client's rights to choose their own energy dealer.

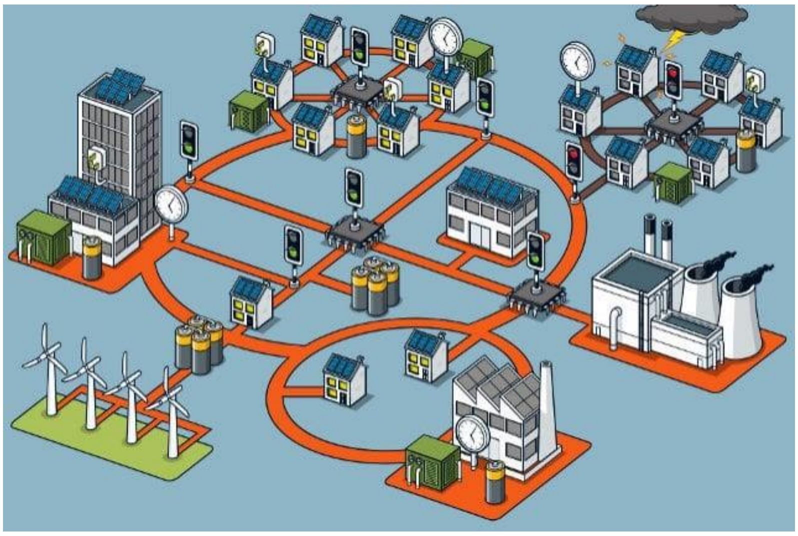

Figure 3-6 Energy community typology example [77]

3.2.2 Final implementation of the European directives

The experimentation phase done thanks to the 8/2020 law between the end of 2019 and the beginning of 2020 that partially implemented the RED II directive was characterized by some requirements [80]

- Renewable energy systems for energy communities or collective self-consumption schemes must have entered in service after 1st march 2020.
- The power of each plant can’t be superior to 200 kW
- Plants and consumers must be connected to the same MT/BT cabin for energy communities and the same building for collective self-consumption schemes.

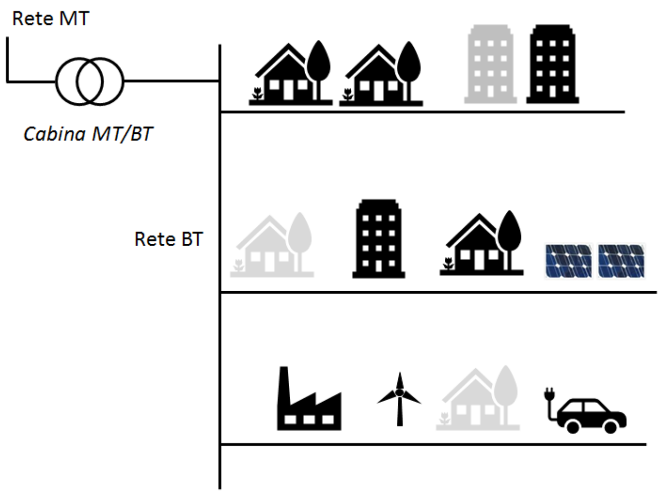

Figure 3-7 Renewable energy community scheme satisfying the 8/2020 law requirements [80]

After the implementation of the law and during the first months of 2021, the first collective self-consumption schemes and energy communities entered service. However, there were seen limitations for the maximum power limits and the MT/BT cabin perimeter. As a result of this, some modifications were done to the total implementation of RED II and IEM directives. Finally, 8th November of 2021 the directives were implemented thanks to the legislative decrees 199, for RED II, and 210, for IEM directive.

The final implementation can be summarized in the following table

Topic	LD 199/2021 (RED II)	LD 210/2021 (IEM)
Control and participation	REC is an autonomous legal entity and the control is done exclusively by natural persons, SME (energy must not be their principal activity) or local authorities, including municipal administrations, research institutes, tertiary sector and environmental protection institutes, situated on the	CEC is a subject of law, with or without legal personality: 1) funded open and voluntary participation 2) controlled by members being natural persons, local

	municipality territory where the plants are located. The participation is open to all the consumers.	authorities included municipal administrators, research institutes, tertiary sector and environmental protection institutions.
Objective	Give environmental, economic, or social benefits at community levels to all their members or the local area is located rather than financial profits	Give to their members or the area where is located environmental, economic, or social benefits rather than financial profits.
Areas of activity	Can produce diverse forms of energy from renewable energies with the objective of being used by their members. Can promote home automation or energy efficiency interventions, electric vehicles charge services, sale company for the members or offer ancillary or flexibility services	Can participate in generation, distribution, provision, consumption, aggregation or storage of energy, efficiency energy services, electric vehicle charge services or energetic services to the members.
Energy sharing	Shared energy is defined as the minimum, for each hour period, between the produced and injected energy from the renewable sources and the electric energy taken from the final clients situated on the same market area.	Energy is shared in the same market area distribution grid. Energy shared is, for each hour period, the minimum between the produced and injected electric energy and the energy taken by final clients.
Incentives	Can access to incentives renewable energy plants with a power non	

	superior to 1 MW that entered into service from the date successive to the one was the decree was implemented. Plants and users must be connected to the same primary cabin.	

Figure 3-8 Summary of the implementation of the RED II and IEM directives [80] [81]

The main changes and additions to the energy communities are the incentive on shared energy for systems with a power inferior to 1MW and the expansion of the perimeter from the MT/BT cabin to the AT/MT cabin, thus, allowing to bigger plants to be able to be part of an energy community. [80]

3.3 Energy communities' examples

3.3.1 Pinerolo

At Pinerolo, Piedmont, the first self-consumption condominium was inaugurated in Italy from the project Energheia, born between Acea Nuove Energie and Tecnozenith with the collaboration of the Energy Center of Politecnico di Torino. It was an already existent building that was energetically requalified and a photovoltaic solar and thermal systems were installed. AS a result, there was verified a reduction of the overall consumption that is covered 90% by self-consumption. This was done also thanks to the installation of storage systems to enhance the energetic autonomy of the building. [82] [83]

Figure 3-9 View of the building [83]

On the details, it is an nZEB building with 20 kW of photovoltaic modules and 13 kWh of storage systems. On the other side, solar thermal panels produce hot water and a heat pump is used for air-conditioning. [83]

3.3.2 Veneto

As a result of the collaboration between *Coldiretti Veneto* and ForGreen society, the first agriculture energy community was born, called *Energia Agricola a km 0*. It is composed by 1268 users composed of business and users that are proprietary of renewable energy plants that can produce energy both for self-consumption or exchange it to a third person. All the energy is managed by ForGreen. The total exchanged energy between producers and consumers goes to 42398 MWh and its estimated 11469 of tons of CO2 emitted have been avoided every year. [84] [85]

3.3.3 Emilia Romagna

At Emilia Romagna, the GECO project, acronym of Green Energy Community, will be the first energy community in the region. It's going to be located at north-east of Bologna including the Bologna Caab agricultural center. It is going to be composed by a residential area of 7500 habitants, the agricultural center, two commercial centers and an industrial area. It will have a 200-kW photovoltaic system, a storage system and an organic waste biogas management plant. [78] [84]

3.3.4 Roseto Valfortore

In Roseto Valforte, Puglia, the project is born as a cooperation between Roseto Valfortore Municipalyte and Friendly Power, a society that promotes, develops, implements, and manages energy communities. The project is intended to increase annually the share of self-production of every citizen until reaching a 100% self-production levels in 3 years since its start. [84] [86]

Figure 3-10 Inverters and smart meters used [84]

One of its main characteristics is the use of more advanced technologies and systems such as smart meters, nano grids and powercloud. Every system will have an intelligent meter that will manage the entering and exiting flows. The nano grid will manage its own production and storage systems but also to interact with other nano grids by exchanging energy, creating a micro grid. [84]

3.3.5 Magliano Alpi

At Magliano Alpi, Cuneo, a municipality of about 2230 habitants, the first Italian renewable energy community was formally established with the name of "Energy City Hall". It was an initiative made by the municipality; it is composed by 2 photovoltaic systems that made 40 kW of production. [82]

Figure 3-11 Magliano Alpi photovoltaic system [87]

The energy community's first users were the municipal hall, library, gymnasium, schools and 4 residents that wanted to adhere to the initial project. It is intended to also be connected two electric vehicle charge points that will be free to use by the residents. Also, during 2021 dozens of new prosumers and users were intended to be connected to the community. [87]

4 PVZEN project

4.1 Overview

The research project PVZEN, that means Photo Voltaic Zero Energy Network, is a multidisciplinary project located and developed in Politecnico di Torino in the context of the design, development, and operation of nearly zero energy buildings (nZEB), self-sufficient systems and renewable energies. The project involves three of the university departments, Energy Department (*Dipartimento di energia DENERG*), Architecture and Design Department (*Dipartimento di Architettura e Design DAD*) and Electronics and Telecommunications Department (*Dipartimento di Elettronica e Telecomunicazioni DET*).

4.1.1 Objective

The project consists of the planning, building and operation of a building that follows the nZEB rules by using high efficiency energetic materials to reduce its energetic needs and reduce the power demand for heating and cooling necessities. Moreover, the choice of the correct materials, location and dimensions are fundamental for achieving a low energetic demand and good exploitation of natural light. In conclusion, the main objective is to achieve a high thermal and electrical efficiency structure.

4.1.2 Description

The building will feature 2 study rooms for the students, a control room, and a technical room where the electrical panel and components will be in. For the heating and cooling requirements heat pumps will be used as a way to electrify them, transforming the heating demand into an electrical demand.

From the electrical point of view, the control and technical rooms will be considered as one user. Furthermore, there will be a total of 3 electrical users in the building, considering every studio room as a single user. Every user will have its own solar panels and storage systems that will help to reach high levels of self-sufficiency for the users and the entire micro-grid. An important characteristic of the micro-grid it's its ability to allow the users to exchange energy between them which allows to get into higher levels of self-sufficiency, this can be done when users in deficit can be powered by users that have extra energy to spare [47].

At the day, the electrical system is implemented in a provisory configuration at the roof of Politecnico's building. It has been done in this way while waiting for the buildings to be built to make its first experimental tests.

4.2 Electrical system and components

As previously stated, there will be a total of three users in the building consisting of both the studio rooms, and a third user consisting in the sum of the technical and control rooms into a single user. Every user is able to work independently from the others, as it has its own photovoltaic generator, storage system and loads.

Storage systems are able to work both as a load as a generator depending on the systems' situation. If the system has more power generated from the panels than the load demand, the storage will act as a load and charge itself. Otherwise, if the system is not able to supply its own load with the power generated by the solar panels, the storage system will supply the missing power by acting as a generator discharging power.

The three users, apart from working independently, they are able to share energy through the internal micro-grid and to exchange energy with the electrical grid as shown in the Figure 4-1

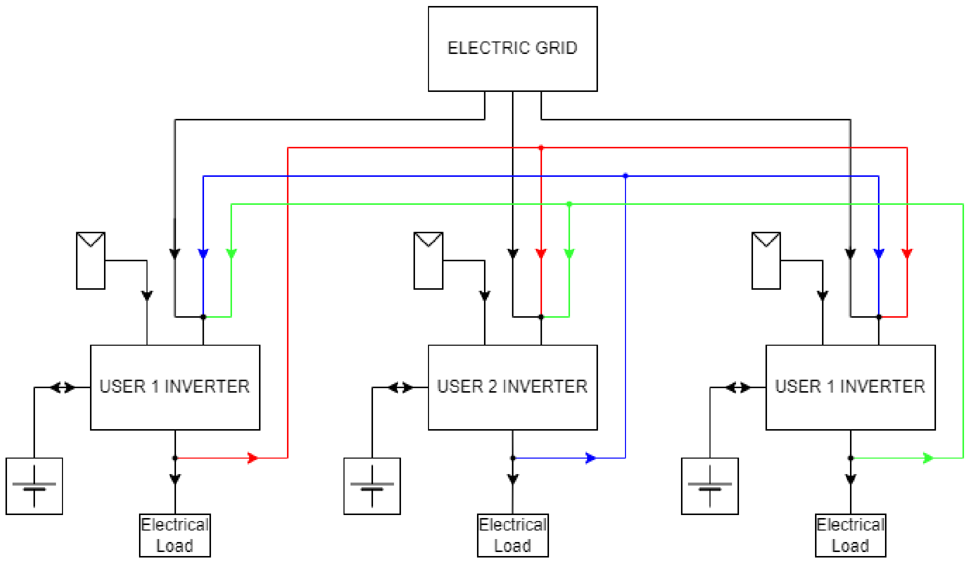

Figure 4-1 Electrical wiring connections of the system

The internal exchange of energy happens when a user isn't capable of supplying its own load with its own generation and storage systems. If this happens, other users can supply this user if they have excess power to share. In other words, if a user is generating more power than the loads' needs, is charging its battery within its power limits or the battery its already charged he can share this energy surplus with other users through the micro-grid or, if the system itself has supplied its needs it can be sold to the grid. Otherwise, if the system itself cannot guarantee to fulfil its own demand neither with its production nor its storage systems, the missing power must be withdrawn from the grid. The summary of the power exchanges can be seen in the following scheme

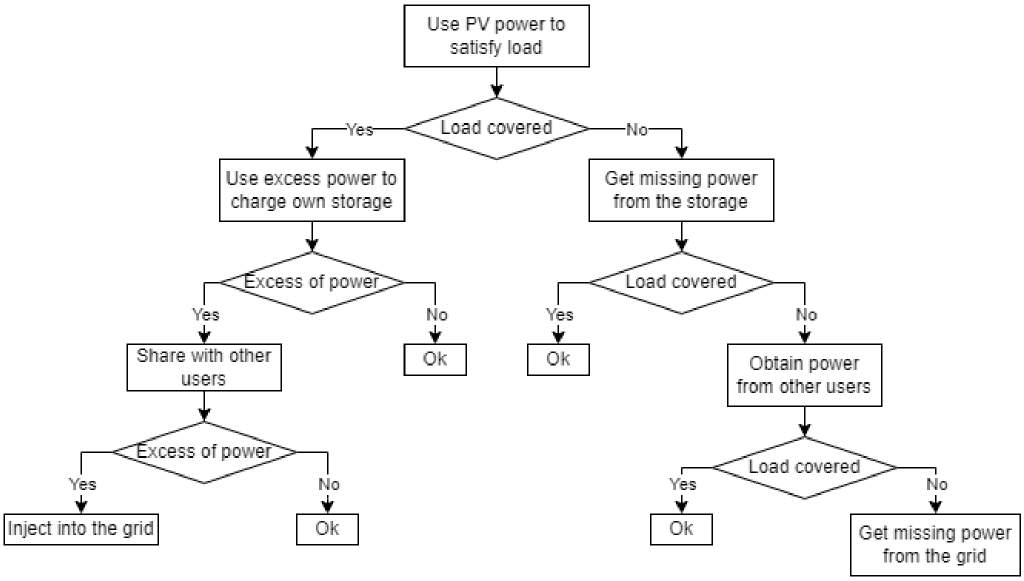

Figure 4-2 Flowchart of the power in the system

To achieve and control these power exchanges, electrical wirings will be used to interconnect the three users. These lines will have its own contactors and switches for its correct operation. These dispositives will be used to allow the different desired system's configurations according to the requirements of the system throughout its operation, and will be commanded through a programmable logic controller (PLC)

The system is composed of different electronical equipment. The most important for every user are the photovoltaic panels, the storage system, and the users' inverters, among others. To the present day, those equipment are installed in the roof above the Electronics and Telecommunications Department (*Dipartimento di Elettronica e Telecomunicazioni DET*) where a special place for the photovoltaic strings can be found and a room where the electrical panels, inverters and the storage system is located.

4.2.1 PV generators

The photovoltaic panels used are the LG NEON R, important characteristics are indicated in the following table

Characteristic	Value	
Number of cells	6 x 10	
Type of cells	N Type	
Dimensions	1700 x 1016 x 40 mm	
Electrical characteristic	Value	Unit
Max Power (Pmax)	370	W
MPP Voltage (Vmpp)	37	V
MPP Current (Impp)	10,01	A
Open circuit Voltage (Voc)	42,8	V
Short circuit Current (Isc)	10,82	A
Module Efficiency	21,4	%

Table 4-1 LG NEON R Characteristics [88]

For the system it had been installed a total of 30 modules divided in 10 strings of 3 modules each one. This way, each string will proportionate a maximum power of 1110 W, an open circuit voltage of 128,4 V and a short circuit current of 10,82 A. The modules had been installed in the south side of the roof to avoid the shading of the structure and perpendicular to the wall to optimize the roof's space. The positioning of the modules is shown in the Figure 4-3

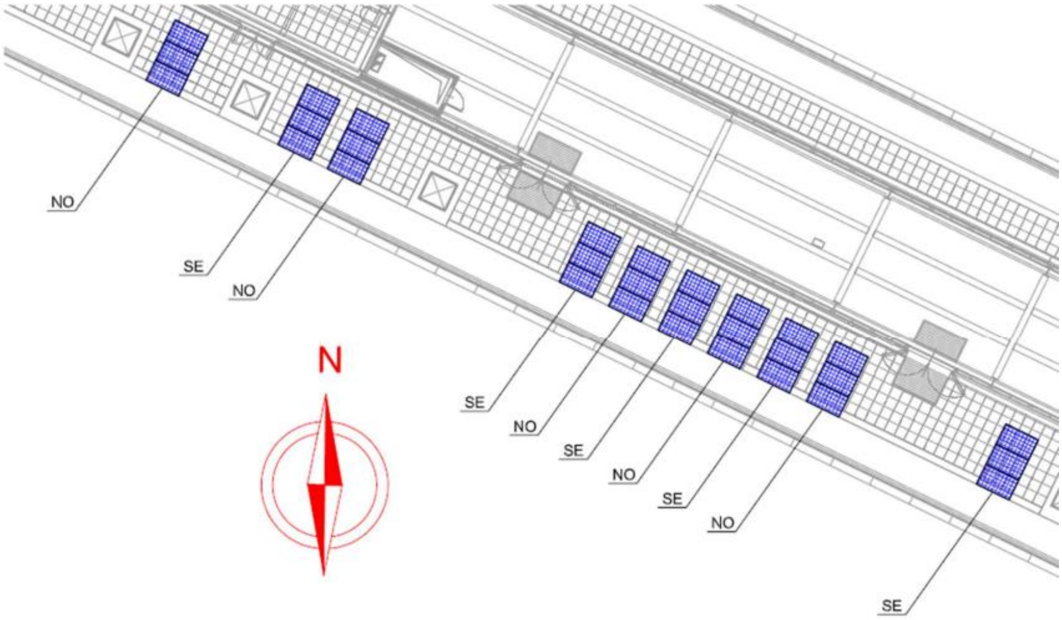

Figure 4-3 Module's position on the roof [47]

As seen in the previous figure and as it is shown in the next picture, the strings are placed with different orientations, 4 strings are oriented in a north-west orientation and 6 are oriented in a south-east orientation. This is done in this way, to make an approximation of the way the modules will be oriented in the PVZEN project where there are modules oriented in the south-east, south-west, north-west and north-east directions. With this configuration, the power profiles of the different users will have different behavior throughout the day as the get different amount of solar irradiance according to the moment of the day.

Figure 4-4 PV panels next to the PVZEN laboratory

Finally, from the picture it can be seen that the modules were placed alternating the modules that face different directions and with a separation between them. The first thing is done to ensure that there will not be shading between modules and the second separation distance is done to allow maintenance and cleaning procedures. [47]

4.2.2 Storage

The storage system used for the system are the Pylontech US2000 lithium batteries. Considered by the manufacturer the “last technological frontier for photovoltaic storage applications” [89]. Its main characteristics are shown in the following table

Characteristic	Value	Unit
Voltage	48	V

Rated current	50	A
Rated power	2400	W
Dimensions (lenght, depth, height)	440 x 89 x 410	(mm x mm x mm)
Weight	24	kg

Table 4-2 Pylontech US2000 main characteristics [89]

Advantages of this batteries addressed by the manufacturer are its life cycle of more than 6000 cycles, equivalent to approximately 11 years of work with an end-life capacity of 80%. Moreover, it’s also characterized of having a depth of discharge of 90%, ideal for applications with strong peaks. Finally, it’s modularity represents a great advantage as its easy to install in a rack, just how it is at the present day.

Figure 4-5 Batteries' rack

Every user will have a total of 2 batteries, giving every user a total of 4,8 kWh of total energy capacity.

4.2.3 Inverters

The inverters used are the "Western Co Leonardo Off-Grid 4kW/5000/48 GE Py". Its main characteristics are shown in the following table

Characteristic	Value	Unit
Inverter		
Output power	5000	VA
Battery voltage	48	V
Output voltage	230	Hz
Output frequency	50	Hz
Efficiency	95	%
Maximum charging power	3500	VA
PV charger		
MPPT inputs	4	
Maximum power per channel	1.15	kW
Module current per channel	13	A

Open circuit module voltage	200	V

Table 4-3 Electrical characteristics of Leonardo Off-Grid 4kW/5000/48 GE Py inverter [90]

The inverter, as the manufacturer says, was intended to be “conceived and specially developed for the production and storage of domestic energy; combined with photovoltaic modules and lithium storage batteries, it provides power to the house until it is fully self-sustaining” [90] It has been made to work in off-grid conditions as it’s able to supply the load by using the generation of the photovoltaic panels, the storage system or an emergency generation from a genset as shown in the following picture.

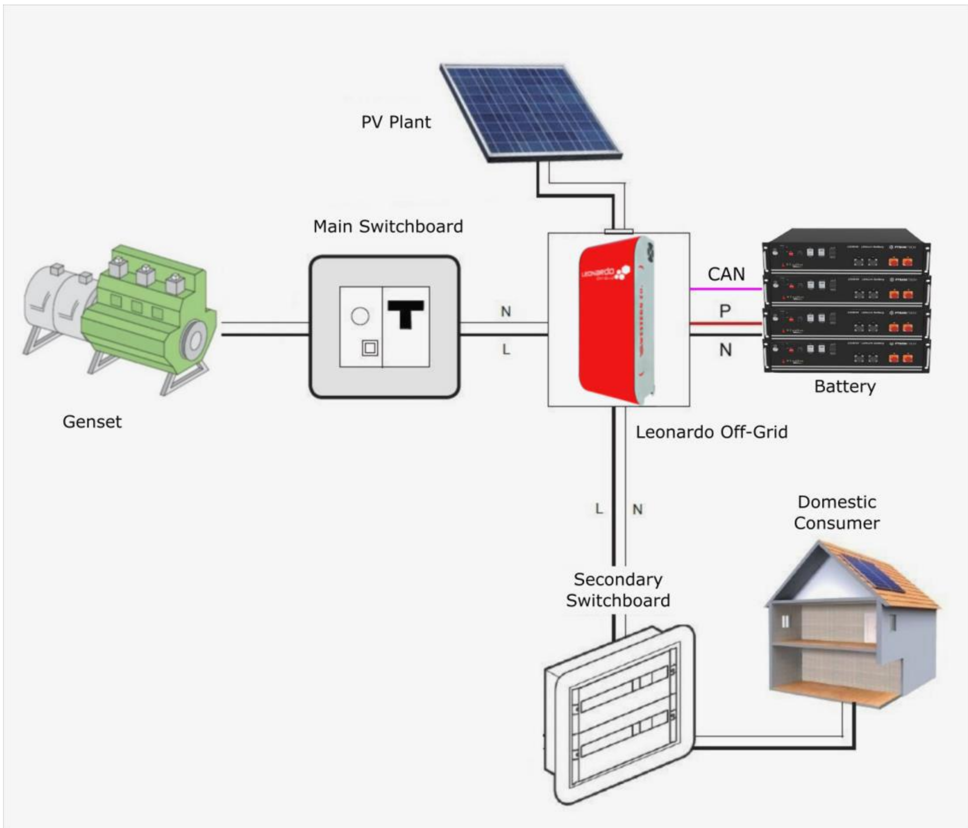

Figure 4-6 Principle diagram [90]

The manufacturer also provides an internal diagram of the inverter that is shown in the Figure 4-7

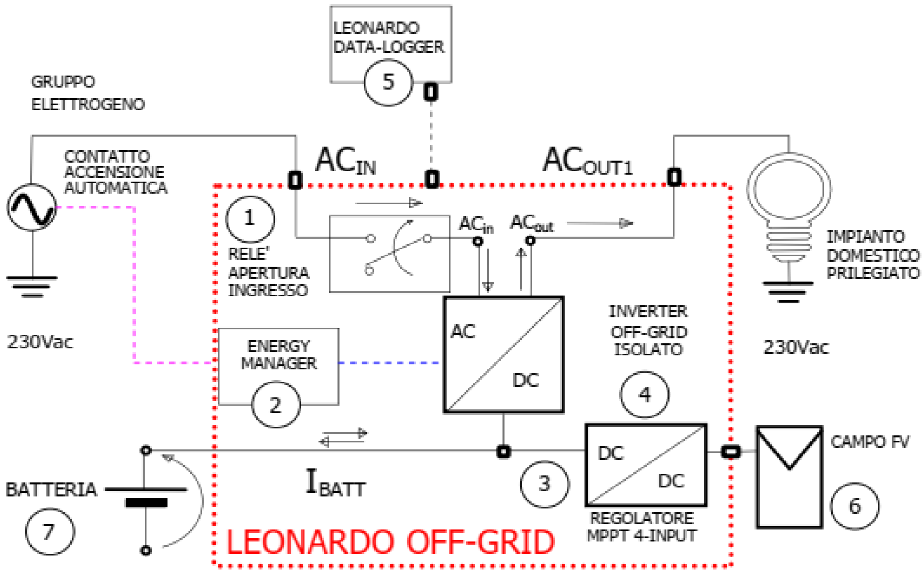

Figure 4-7 Internal diagram of the inverter [90]

Important aspects of this diagram are the AC-IN input connection that allows the genset to provide power, if available. Moreover, the AC-OUT output is used for the connection of the domestic consumptions. Also, there is present an energy manager that provides control and management of the system. Finally, a data-logger provides information about instantaneous power flow as well as saving the historical data of the different energy assets. [90]

An important aspect to highlight is that the inverter sets priorities in which energy source uses to feed the system. Its priority is the energy produced by the photovoltaic modules, if the energy produced is enough to cover the load, the remaining power will be used to charge the batteries. Secondly, if the photovoltaic production is not enough, then the storage systems are used by discharging the power stored. Finally, if neither the photovoltaic generation and the power injected by the batteries is enough to cover the load, the genset connected at the AC-IN is used to fed the missing power, being the last priority for the inverter of feeding choice.

In the studied PVZEN system, there will not be an actual genset, but there will be a connection to the electrical grid by using commutators that will allow the user to maintain this connection or to exclude the system from the grid. [47] In the actual application, the following connections will be used for the inverter:

- MPPT input: the inverter has 4 MPPT inputs used for the connection with the photovoltaic strings.
- DC bus: that is going to be used to connect the storage systems so they can exchange energy with the system depending on the situation of it. It allows the batteries to charge themselves or to discharge them to cover up the demand.
- AC-OUT: bus that will be used to feed the loads
- AC-IN: will be used only in case the photovoltaic production or the storage systems are not able to cover up the loads' demand.

The AC-IN input has an important role into the micro-grid operation of the system. If the AC-OUT of another inverter is connected to the AC-IN input of the inverter, it is going to create a master-slave relationship between them, where the AC-OUT terminal, acting as a master, will feed the AC-IN of the slave inverter, allowing an exchange of energy between users. This configuration is essential, as it allows the three users to exchange energy between them creating a micro-grid. The actual placement of the inverters is shown in the Figure 4-8

Figure 4-8 Installed inverters

It is noticeable that the inverters are placed at different heights, this is not a random choice, but it has been done to facilitate the ventilation of the inverters. If they were placed at the same height, one inverter would interfere with the ventilation of the inverter next to it. Otherwise, if a space is left between inverters, it provides a better ventilation of each of the inverters.

4.2.4 Other components

In the inside of the laboratory, aside from the inverters and the battery racks, there are the other components that make the system operation possible. Between them, as shown in Figure 4-9, there are the AC and DC panels which contain the protection and control dispositives of the system. Moreover, the panels also contain the required dispositives to monitor the different powers that are flowing through the system. These can be the power produced by the photovoltaic stings, the exchanged power of the batteries or the electrical grid, or the power that feeds the load.

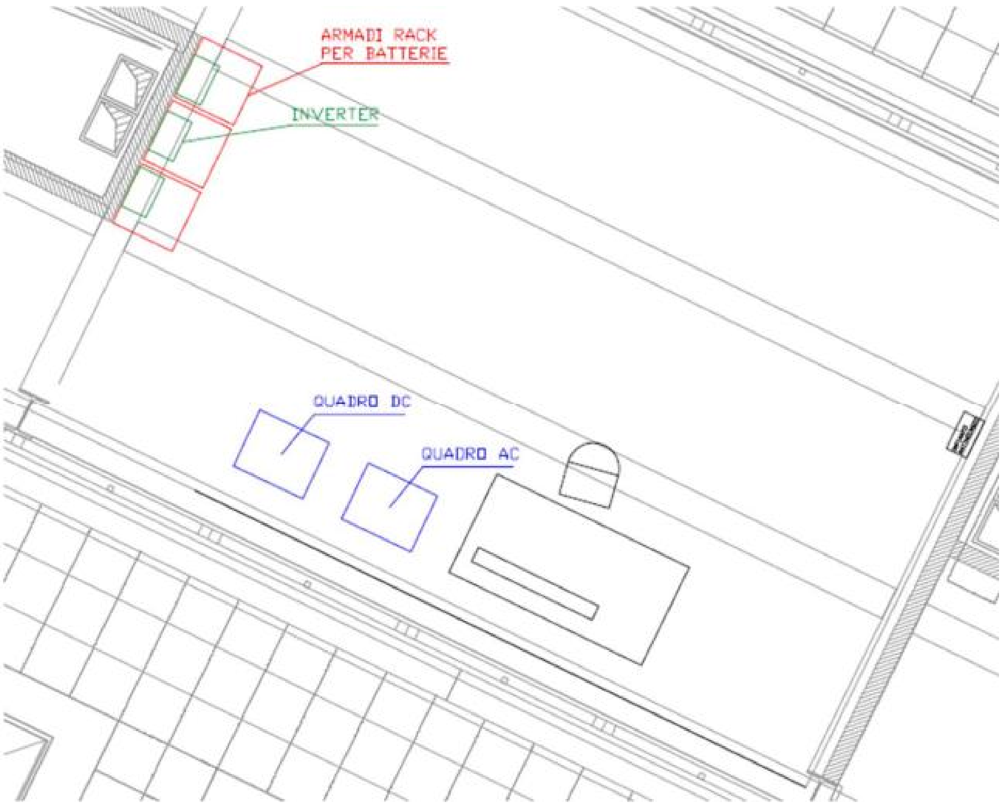

Figure 4-9 PVZEN laboratory internal room component's distribution [47]

Apart from the dispositives already mentioned there is a computer besides the AC and DC panels that will be used to host the software system that will allow the system itself to communicate. This software, that has its approach in this thesis, will allow the computer to take measurements from the inverters, elaborate a control logic and simulations and will communicate its decisions to the system. A fundamental dispositive to control the energy flows in the system, is going to be a programmable logic controller (PLC) that will communicate with the software and will control the switches that interconnect the inverters and the electrical grid to achieve the energy flows desired by the software's logic control. The software's communications can be achieved thanks to a local router used to connect the dispositives to internet, in that way, through a local area network, the different dispositives can communicate between them.

4.3 Loads

As the building is composed by two study rooms and a technical an control rooms, and they are going to be used by, practically, only students. It can be viewed that, in general terms, its energy consumption is going to be normally during scholastic hours, in other words, the load is characterized for being predominantly diurnal, similar to a tertiary sector building.

Furthermore, the load can be characterized according to its function in the building. There is the load that has a conditioning objective, in other words, the load that is in charge to the heating and cooling functions, this task is done by the heating pumps. Moreover, the load also has a functional component that represents the illumination and the different electronic dispositives used by the users of the building.

Moreover, the load also depends on whether its being analized the control and technical room or the studio rooms. Nevertheless, there are common components between the three users, as there are also specifical components for each user.

Common loads are

- The conditioning system: is composed by a ventilation system shared by all the users of the building and the heat pumps. The conditioning system is used for both heating, during winter, and cooling, during summer. Each heat pump has a rated power of 2 kW and a SCOP of 3,5.

- Illumination: it consists of spotlights for the technical room and ceiling lamps for other ambients. It's a LED based illumination. There will be three spotlights of 9W, twenty ceiling lamps of 23 W in the studio rooms and 3 ceiling lamps of 23 W in the control room.

Specifical loads are

- Two projectors of 190 W for the studio rooms
- Specific illumination: For the studio rooms and the control room its expected to use LED's spotlights. It's expected a total of 20 of 9W for the studio rooms and three of 9" for control room.
- Electrical sockets for all the deck stations located in the studio rooms and three sockets for the control room.

It is expected that the maximum peak of load will be approximately around the 6kW. [91]

4.4 Configurations

Although the three users can work independently between them as they have their own respective photovoltaic generation, storage systems and connection to their own load. The system has the capability to interconnect the three users, using the inverters' functionality to exchange energy in a master-slave logic.

The interconnection depends on the state of the switches located in the panels.

- Independent users: if the switches are open, there interconnection between users doesn't exist and each one of the users will work as a single system.
- Interconnection: if the switches are closed, the inverters will be able to exchange energy between them, allowing the power flow between users and generating a micro-grid system

4.4.1 Independent users

If the switches that interconnect users are open, there will not be any possibility of energy exchange between users. This way, the users will operate independently. Therefore, there can be two options according to the energy balance for the user. The first option consists of having more photovoltaic production with respect to the load, in this case the surplus can be used to charge its own battery or inject it into the grid with the respective profit of selling it. The second option is being in a condition where the produced power is not able to cover up the load, in this case the storage system can be used to feed the demand but, if it is not enough, the user is going to be obliged to disconnect some loads, or to get the missing power from the grid, with the respective cost of buying it.

A scheme of this situation is shown in the Figure 4-10

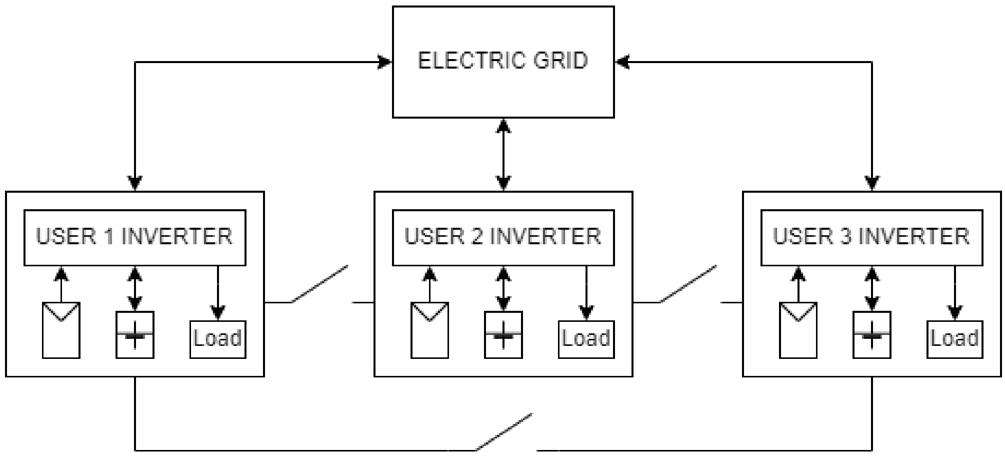

Figure 4-10 Independent users configuration

4.4.2 Interconnection between users

The other configuration available for the system is obtained by enabling the interconnection between users. This configuration allows to reach higher levels of self-sufficiency, as it allows users that have excess of power to supply users that have production deficit increasing the proportion of the load covered by local produced energy, thus increasing the self-sufficiency of the whole system. This system works as a micro-grid, as there are different users sharing a common network.

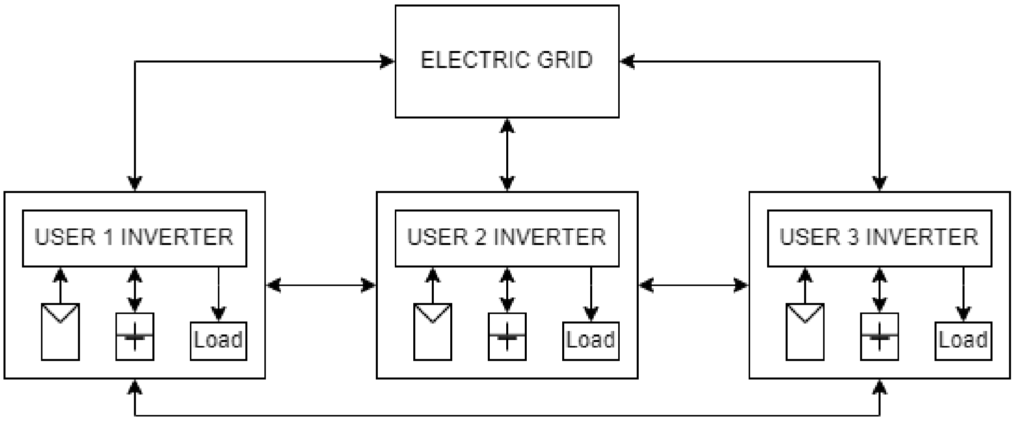

Figure 4-11 Interconnection configuration

5 Control software for PVZEN

To establish an interconnection between the three users in PVZEN it is necessary to monitor, control and take decisions on the different energy assets in the system. To do this, measurements must be taken. With the measurements being read, it is necessary to impose a control logic determine how the energy has to be shared between users. Finally, the decisions taken have to be communicated to the system that has to reconfigure its connections to fulfil the decision made by the control logic.

5.1 Objective

The objective is to develop a software capable of reading data from measurements made by the equipment in PVZEN, plot the data and use it to take decisions on how the energy will flow through the system, once the decision is made it has to be able to communicate the system how to adapt itself to uphold the control logic's goals.

5.2 Implementation

The control software's objective is done by developing a software through MATLAB's App Designer, an app that makes easy to create professional apps through a simple drag and drop system that allows to design graphical user interfaces (GUIs) in a very easy and intuitive way.

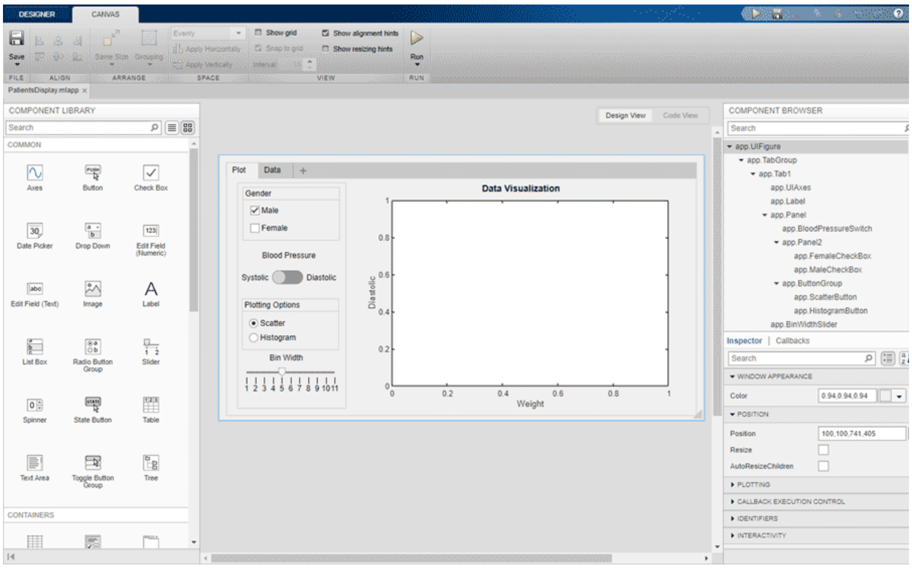

Figure 5-1 Design View in App Designer [92]

Moreover, MATLAB’s App Designer also allows the user to incorporate MATLAB’s scripts and functions into the app’s behavior, this is a key factor considering that communication and data elaboration functions made by the user can be developed and tested apart before integrating them into the app.

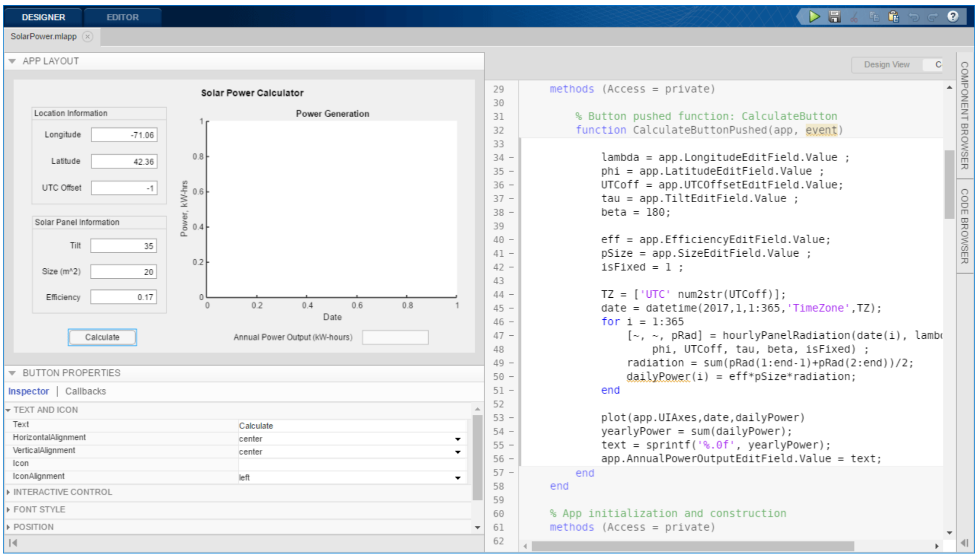

Figure 5-2 Code View in App Designer [92]

5.3 MATLAB Software's Structure

The proposed scheme for the software can be viewed in Figure 5-3

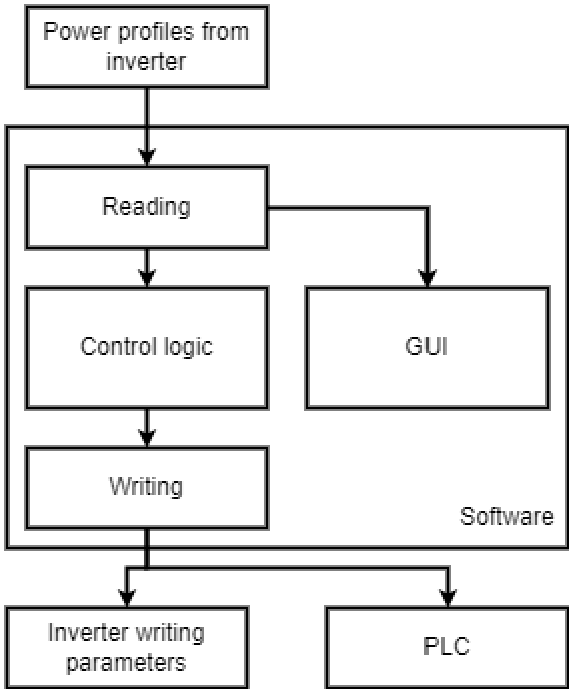

Figure 5-3 PVZEN software's scheme

The software reads the measurements from the inverters, this is done by using Modbus protocol to communicate the system's computer with the inverter. Then, the measurements are plotted into the graphical user's interface and also, they are used by the control logic to determine the system's configuration for the timestep. Finally, the result of the control logic is sent by writing into the inverter via Modbus and communicated to the PLC that will physically implement the system's configuration decided by the control logic.

5.3.1 Reading

The first phase of the software consists of reading the data from the inverter via Leonardo ProX TCP/IP Modbus Communication Protocol. This protocol allows the software to read the different measurements the inverter does. From all the different measurements, the relevant for the software's operation are shown in the following table with their respective description, variable on software and measurement unit.

Measurement description	Variable	Unit
Battery state of charge	soc	%
Power exchanged by the battery	P_batt	W
Power produced by PV field	p_PV	W
Power input on ACin	PacGrid	W
Power output on ACout	p_carico	W
Charge or feed-in Power Setpoint	Pac_set	W
Maximum percentage of the inverter power allowed in discharge	Lim_perc_Disc	%
Maximum percentage of the inverter power allowed in charging	Lim_perc_Charg	%

Table 5-1 Measurements from the inverter [93]

These measurements are made and read for the three inverters. Through this process it is possible to obtain the state of charge of the batteries, the charge/discharge power of the battery, the power produced by the photovoltaic unit, the power exchanged with the grid and the power consumed respectively, among other variables such as the last three ones (PacGrid_Set, Lim_perc_Disc and Lim_perc_Charg) that are set by the user and allows power limitations for the inverter at any instant.

5.3.2 Control logic

For this phase, no matter if it's the actual PVZEN system or a simulation of its behavior, the scheme remains the same and the same code is used for both. The control logic phase consists of two main steps: the single-user power balance and the interconnection among users.

5.3.2.1 Single-user power balance

The single-user power balance step has two objectives. The first one is to determine which users are in power deficit and which ones are in power surplus. This is done by calculating, for each inverter, the difference between photovoltaic generation and load power.

$$P_{PV} - P_{load} = \begin{cases} \leq 0 \rightarrow deficit \\ > 0 \rightarrow surplus \end{cases} \tag{7}$$

The second objective comes up after determining the inverter's situation and it consists of calculating the battery's charge/discharge power with the remaining/lacking power from the PV-load balance. This battery power is calculated considering the battery's electrical limits; thus, the charge and discharge power limits and the battery's energy limits. The single-user overall process is shown in the following scheme.

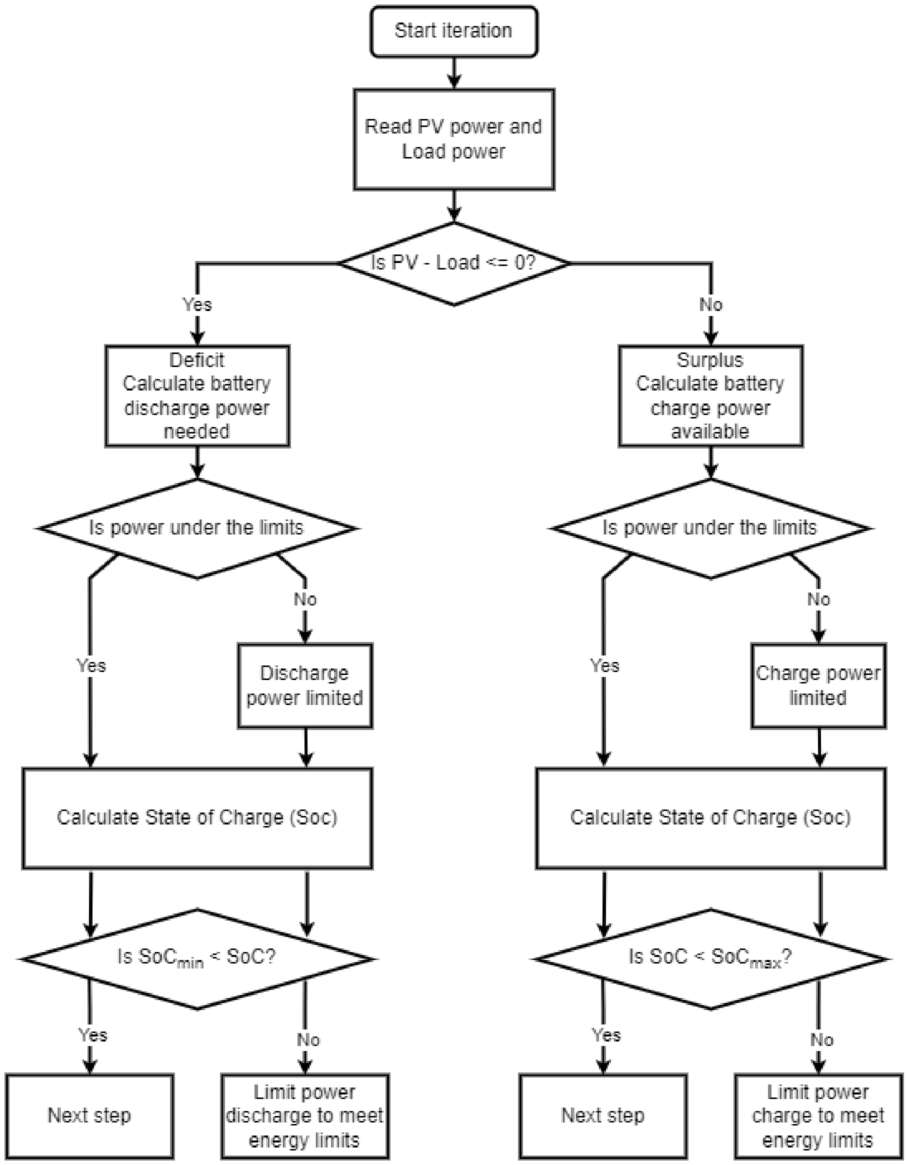

Figure 5-4 Single-user power balance scheme

Once the battery's charge/discharge power has been calculated in the actual timestep, the energy of the respective battery is updated, considering the power calculated as constant during the duration of the current timestep. In case of battery discharge, the updated state of charge is calculated with the following formula

$$E_{bat}^{k+1} = E_{bat}^{k} - \frac{P_{disch}^{k} * \Delta t}{3.6 * 10^{6}}$$

(8)

As seen by the formula, the new battery energy in discharge, considering only a single-user situation, is equals to the previous energy minus the energy discharged by withdrawing $P_{discharge}$ (considered constant) in a Δt time (which corresponds to the duration of the timestep, equivalent to the time between measurements). The dividing factor in the second element allows a conversion from Watts-seconds $[W * s]$ to a more standard kilowatt-hour $[kWh]$ energy measurement unit.

On the other hand, in case of a battery charge, the following formula is used to calculate the updated battery energy.

$$E_{bat}^{k+1} = E_{bat}^{k} + \frac{P_{ch}^{k} * \Delta t}{3.6 * 10^{6} * \eta_{bat}}$$

(9)

By the formula it can be seen that follows the same principle as the discharge formula. The final battery energy is calculated adding to the previous energy the amount of energy obtained by injecting P_{charge} (considered constant) in a Δt time. Also, the constant factor dividing allows to turn the component into a kilowatt-hour component. In addition to that, a new component η_{batt} corresponds to the battery energy charge efficiency, a factor that considers that not all the energy injected into the battery participates into its charging.

5.3.2.2 Interconnection among users

Once the single-user power balance is done for the three users, the control logic, based on the three inverters situation (surplus or deficit), determines the configuration in which the system should operate to distribute the surpluses between the users in deficit. Furthermore, given the configuration, it also determines the power that is transferred between the users and the final energy stored in the users' batteries.

The first two configurations to analyze are the one in which all three users are in surplus and the one in which all the three users are in deficit. The software, for these two configurations, don't make any other calculations since there is no need for exchange of power between the users and consequently no update is needed for the energy stored in the users' batteries. In the first case, if all the users are in surplus there is no need of exchange between users and the remaining power can be injected to the grid. On the other hand, if the three users are in deficit, it means that not even the PV generation with the user's battery were able to cover the load, thus the missing power has to be withdrawn from the grid or other sources.

Another configuration to consider is the one when there is only one user with power surplus and there are two in deficit. In this situation, the excess of power is shared with the users in deficit. The user in deficit will prioritize covering its demand with the power received. In addition to this, if there is even more power remaining after supplying its own missing demand, the remaining power is used to charge its batteries, consequently, power and energy limits control have to be imposed. The respective scheme for this configuration is shown in the Figure 5-5.

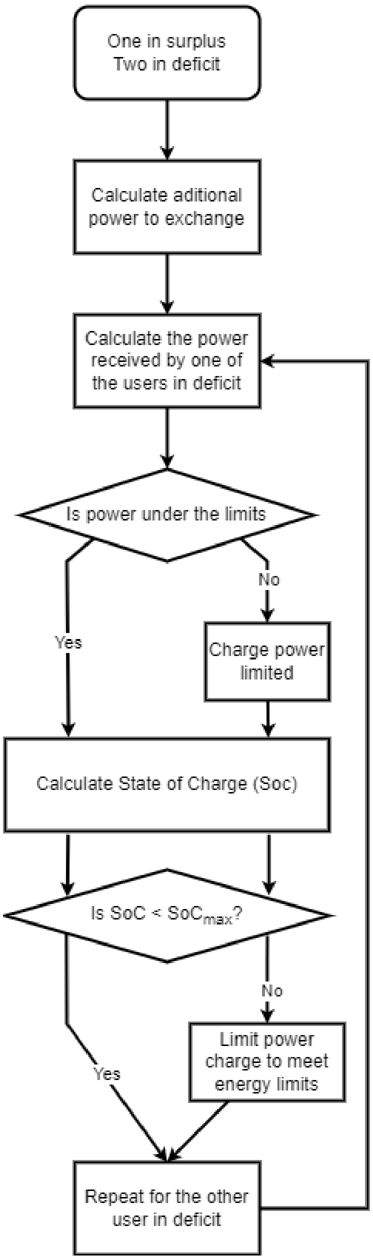

Figure 5-5 Scheme for a configuration of one user in surplus and two in deficit

After the calculus of the power available to charge both the users in deficit batteries considering their power and energy limits, the updated battery's energy of the users is calculated using the charging formula already seen. It is necessary to consider also that the surplus power has to be divided among the users. This criterion is chosen by the software's user, but for simulation purposes the surplus is divided in half between the users.

Finally, the last configuration to be considered is the one in which there are two users in surplus and one in deficit. In this situation, it is assumed that the user in deficit will receive the sum of the excess of power of the another two users. This excess power will be prioritized by the user to cover up its missing demand. However, if there is a remaining power, it will be used to charge its own battery. This configuration is shown in the Figure 5-6

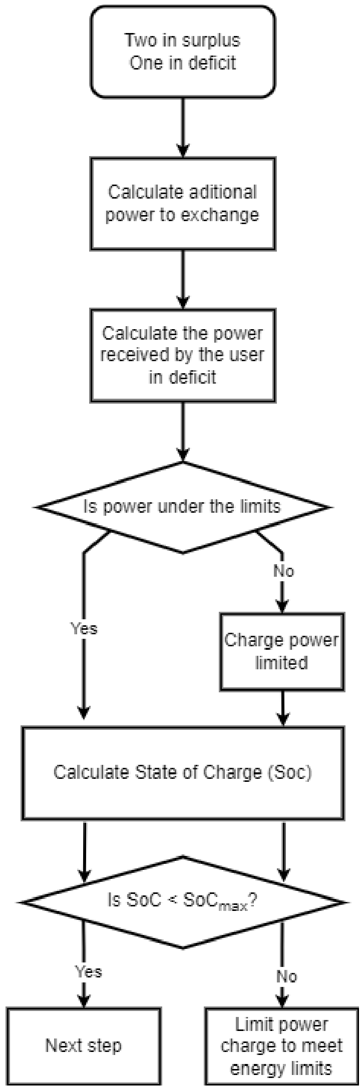

Figure 5-6 Scheme for a configuration of two users in surplus and one in deficit

At the end, after the available charging power is calculated, the updated battery energy is calculated using the charging formula already seen.

Finally, after the single-user power balance and the interconnection and energy share between users is done and the battery's energy of all users are updated. These values are stored for the simulation, as they represent the final energy in the current timestep, and it will be used in the next iteration with the new readings.

5.3.3 Writing

After the control logic decides the system's configuration during the timestep, this decision has to be communicated to the physical system. First of all, there are certain parameters that can be chosen by the user with respect to the inverter and are shown in the following table with their respective description, variable name and measurement unit.

Description	Variable name	Unit
Change or feed-in Power Set point Setting	PacGrid_Set	W
Maximum percentage of the inverter power allowed in discharge	Lim_perc_Disc	%
Maximum percentage of the inverter power allowed in charging	Lim_perc_Charg	%
Battery discharge OFF threshold	Soglia_Off_Disc	%
Battery discharge ON threshold	Soglia_ON_Disch	%

Battery charge OFF threshold	Soglia_OFF_Charg	%
Battery charge ON threshold	Soglia_ON_Charg	%

Table 5-2 Inverter parameters that can be determined by the user [93]

These parameters are communicated via Modbus communication protocol and are chosen for the respective inverter of the different users. On the other hand, the system's electrical configuration is communicated to the PLC that will physically interconnect the users according to the decisions made by the control logic in the software.

5.4 Graphical User Interface

The graphical user interface is shown in the following picture

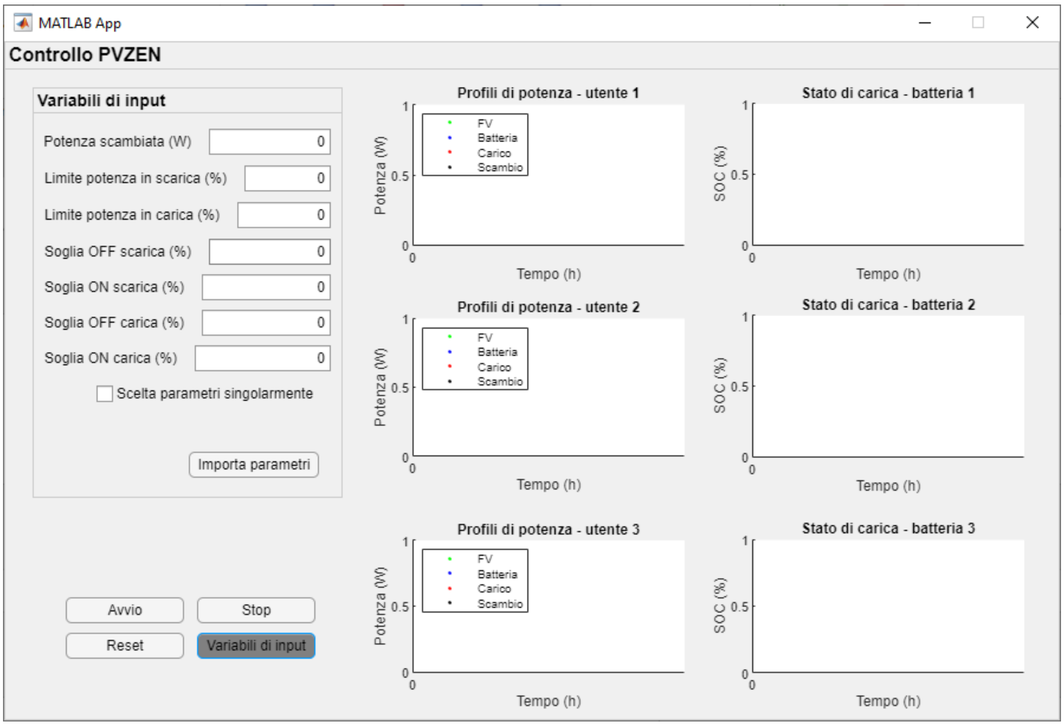

Figure 5-7 Graphical user interface before being started

At the left of the window, it can be found the section of input variables (*Variabili di input*) where the user is able to determine the parameters that will be written into the inverters that was explained previously. This input parameters can be defined in the same window or through a .txt file. Also, it is also available the option to establish the same parameters for all three inverters or, by selecting the *scelta parametri singolarmente* option, establish the parameters separately for each inverter.

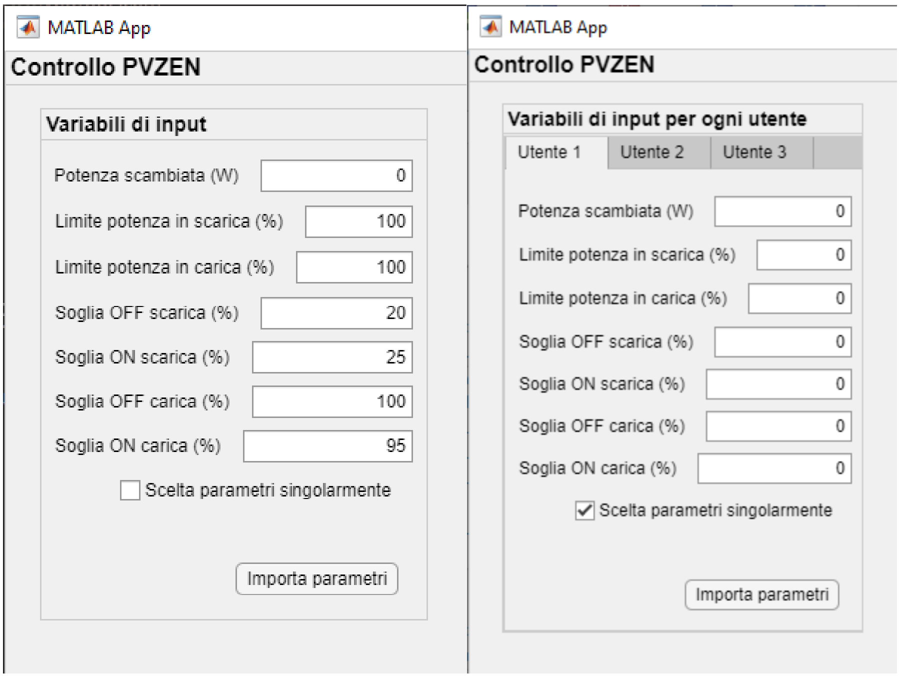

Figure 5-8 Input variables options

Furthermore, below the input variables, it can be found four different buttons for the software control. The buttons offer the user to control the operation of the software and other functionalities. The first button, *Avvio*, allows the user to start the measurements from the software and running the internal program consisting of the continuous reading, control logic and writing iterations. The second button, at the left of the start button, *Stop*, allows the user to stop the program, freezes the graphical data and detains the internal iterations. The third button, at the bottom left, is the *Reset* button that allows the user to stop the program and reset all the graphical and stored data. Finally, the *Variabili di input* button allows the user to hide or show the input variables panel which could be useful to hide the panel when it's not used during the run of the program.

Figure 5-9 Control buttons

Finally, at the right of the window, the measured data is displayed in different plots. There are altogether 6 plots which correspond to 3 pairs of plots corresponding to every single user. Every pair consists of two plots. First of all, the plot in the left shows the different power profiles of the user with the respective legend. The data plotted corresponds to the photovoltaic generation (green), the power exchanged by the battery (red), the load power (blue) and the power exchanged with the other users (black) respectively. Secondly, the plot in the right corresponds to the state of charge of the battery in every timestep according to what the control logic estimated based on the readings.

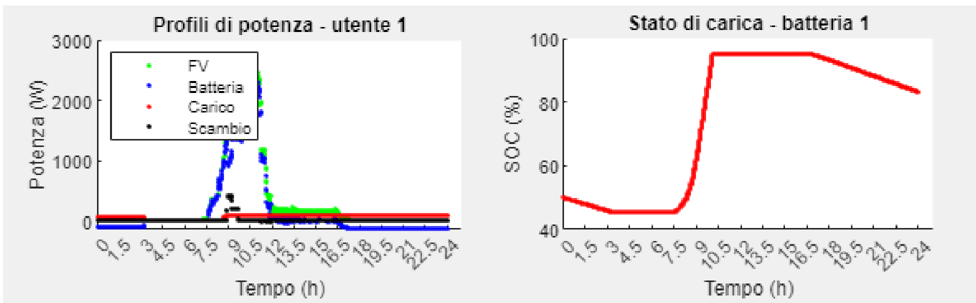

Figure 5-10 Example of plots for user 1

5.5 Additional functionalities

Additional features included in the software are two: the ability to import the input parameters through a .txt file and the capability of saving all the measurements throughout the day in a .mat file. The import of the input variables needs a .txt with a specific structure that has to be respected for its correct operation. An example is shown in the Figure 5-11

Potenza_scambiata_1	0	[W]
Limite_potenza_scarica_1	100	[%]
Limite_potenza_carica_1	100	[%]
Soglia_OFF_scarica_1	20	[%]
Soglia_ON_scarica_1	25	[%]
Soglia_OFF_carica_1	100	[%]
Soglia_ON_carica_1	95	[%]
Potenza_scambiata_2	0	[W]
Limite_potenza_scarica_2	100	[%]
Limite_potenza_carica_2	100	[%]
Soglia_OFF_scarica_2	20	[%]
Soglia_ON_scarica_2	25	[%]
Soglia_OFF_carica_2	100	[%]
Soglia_ON_carica_2	95	[%]
Potenza_scambiata_3	0	[W]
Limite_potenza_scarica_3	100	[%]
Limite_potenza_carica_3	100	[%]
Soglia_OFF_scarica_3	20	[%]
Soglia_ON_scarica_3	25	[%]
Soglia_OFF_carica_3	100	[%]
Soglia_ON_carica_3	95	[%]

Figure 5-11 Import file structure

The file consists of three columns, the first corresponds to the parameter, the second is available to the user to make changes and the last one is the corresponding measurement unit of the row. The file also contains the different parameters for the three inverters in case the individual parameters option is chosen. Otherwise, the system will impose the first users' parameters for the three users.

On the other hand, at the end of the iterations, in other words, at the final of the day, the software executes a saving procedure to save the most important profiles obtained during the day. Those profiles are saved in a .mat file containing the profiles shown in the following picture.

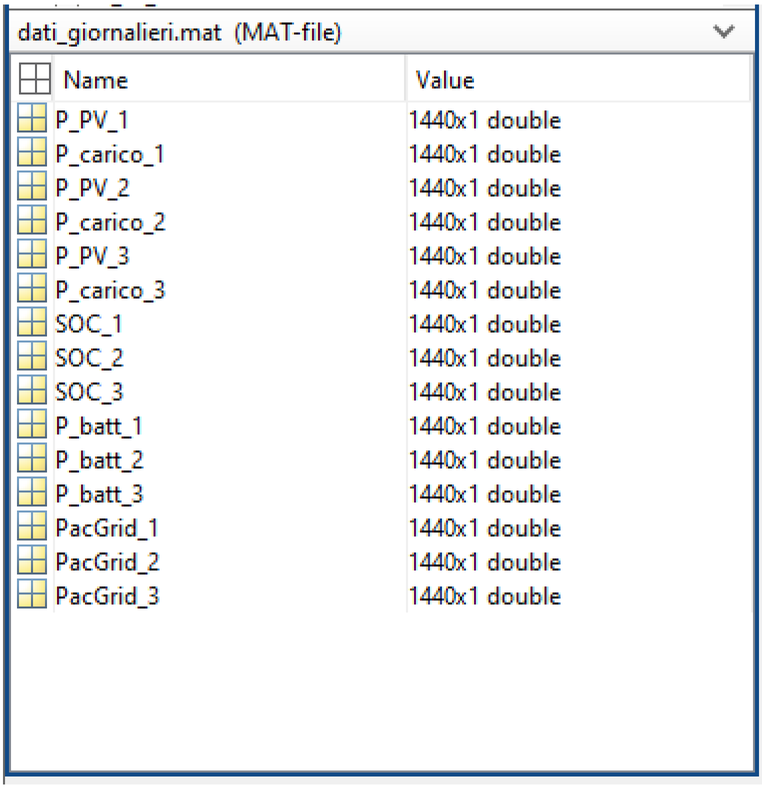

Figure 5-12 Final saving file

As seen by the picture, the data stored and saved for the day corresponds to the photovoltaic generation, load power, battery power exchange, grid power exchange and state of charge of the batteries' profiles. These profiles are saved in arrays with $N_{measurements}x1$ dimensions, where $N_{measurements}$ correspond to the number of measurements taken during the day and depends on the timestep chosen for the software. In the case of the Figure 5-12 it is used a 1 minute timestep, which gives a total of 1440 values saved for a 24 hour day.

6 Simulation of power profiles

6.1 Case study

The software developed in this thesis is tested by using it to simulate and analyze the user's behavior for three different types of days. It has been chosen three specifical days, 21^{st}, 22^{nd} and 24^{th} of December of 2021. These days were chosen for their weather characteristics as there is a sunny, a partially cloudy and a mostly cloudy day. This will allow to visualize and analyze how the system behaves when there is full photovoltaic production with a clear sky, when there is presence of irregular cloudiness and how it behaves when there is a lower production if the sky is mostly cloudy.

Moreover, for these three specifical days, the self-consumption and self-sufficiency is calculated considering the three users separately and for the whole system. Therefore, these parameters are also calculated considering the impact of the storage systems and considering the case where the batteries impact is omitted. This way it can be addressed the impact of the cloudiness on the photovoltaic generation and, as a consequence, its impact on the system's self-consumption and self-sufficiency.

6.1.1 Methodology

To analyze the power profiles for the three users, and the whole system, during these days. Measurements from the inverter were stored to simulate the state of charge of the batteries during these days, with the objective to analyze and test the proper functioning of the developed software. The useful profiles stored were photovoltaic generation power, load, and battery power exchange for the three users separately.

After the measurements were stored in Excel spreadsheets, a simulation software was developed to import the spreadsheets information to be iteratively read the profiles' values simulating a real-time reading. The software developed takes the spreadsheet information and elaborates the control logic consequently updating the state of charge of the three users' batteries. This simulation software has the following scheme:

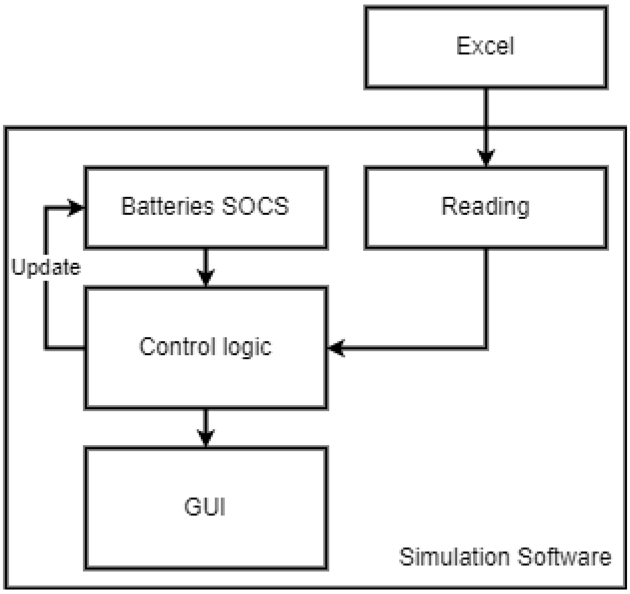

Figure 6-1 Simulation software scheme

As shown in the scheme, first of all the photovoltaic, battery and load measured profiles are imported from the Excel file and temporally save in a .mat for a faster simulation time. Therefore, for every iteration the reading process is simulated by reading every row of the .mat file as it is a real-time reading.

Given the power information, it is given to the control logic so it can elaborate the single-user power balance, the decision of which configuration the system has to follow and the final interconnection with the respective power exchange. Finally, the state of charge of every battery is updated and the next iteration is carried out.

Alongside with the power balance on the system, the software updates the graphical user interface plots, updating the different power profiles according to the information read and the batteries' state of charge according to the calculus made by the control logic. As the simulation follows a real-time-like reading of the information, the graphical data is plotted following a real-time plot of the information.

6.1.2 Days to be analyzed

The days to be analyzed were from the 20 to 26 of December of 2021. Specifically, the days taken for the simulations were the 21, 22 and 24 of December. These days were chosen as they show us three different days with respect to the cloudiness present during the day. As shown in the following pictures taken from the Time and Date website [94] it can be viewed the weather reports in Turin.

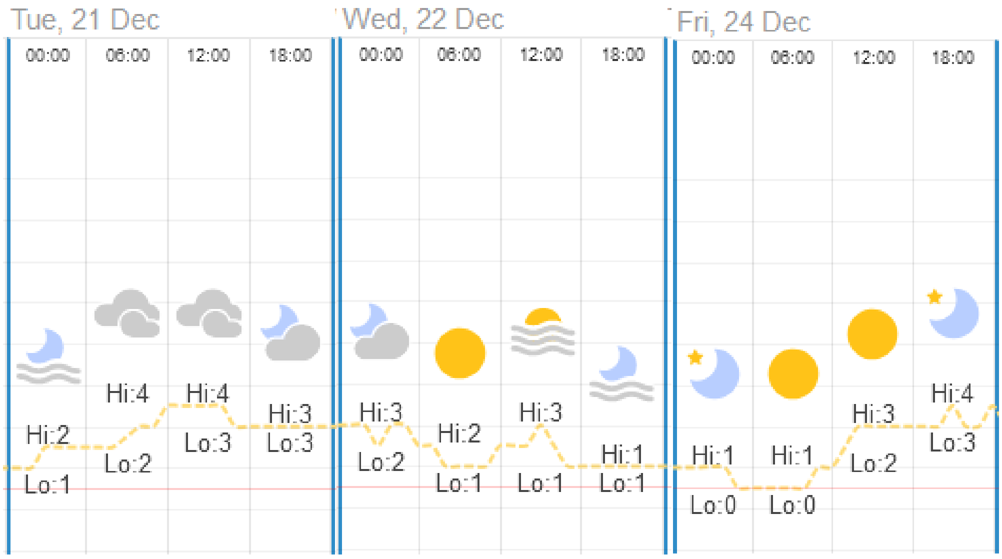

Figure 6-2 Weather reports for the days 21, 22 and 24 of December 2021 [94]

As it can be viewed, the weather reports shows that the day 21st of December it's clearly a cloudy day, while days 22nd and 24th seems to be a more sunny days. Nevertheless, this information, even if it gives us a general understanding of the weather these days, needs to be complemented with a more precise measurement of the sky's conditions. For this purpose, a more detailed information about the cloudiness over the skies of Turin is shown in the following pictures taken based on the historical data stored by the site Weather Spark [95]

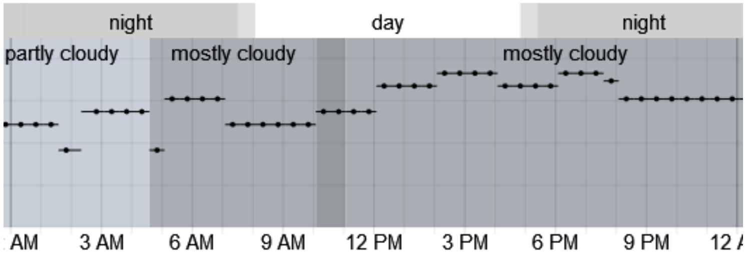

Figure 6-3 Cloud cover in Turin on the day 21/12/2021 [95]

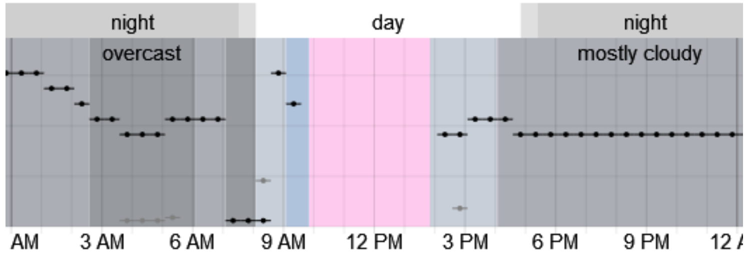

Figure 6-4 Cloud cover in Turin on the day 22/12/2021 [95]

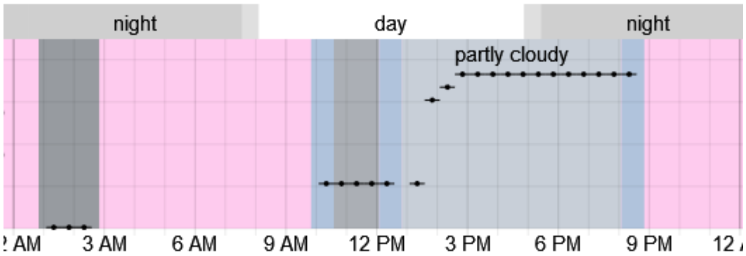

Figure 6-5 Cloud cover in Turin on the day 24/12/2021 [95]

As seen by the information shown previously, it can be viewed that the 21st of December was clearly a mostly cloudy day, with a constant cloudiness throughout the day. On the other side, days 22nd and 24th have differences that let us conclude that the day 22nd was, in proportion, sunnier through the light hours than the day 24nd, that has a mixed position between the 21st and 22nd. Given the information, for simulation purposes, the day 21st is considered as a cloudy base day, the 22nd a sunny base day and the 24th as a partly cloudy day between the other two days.

With the information viewed previously, and the days been chosen and categorized. The measurements taken by the PVZEN laboratory these days are used to simulate the system's behavior and elaborate the respective analysis and conclusions.

6.2 Results

After the days to be simulated and analyzed had been chosen, the measurements taken by the inverters are extracted into an Excel spreadsheet file. Therefore, the measurements are used to simulate the state of charge of the batteries' behavior throughout these days by using the developed software described in this thesis. The results are shown in the following sub-chapters showing the overview of the graphical user interface after the day is completely simulated. Additionally to this, the calculus of the self-consumption and self-sufficiency is done for every day taking into account the situation without considering the storage impact and another situation considering its impact.

6.2.1 Cloudy day

In the following figure it's shown the final result of the simulation of the day 21st of December, considered for this simulation the "cloudy day".

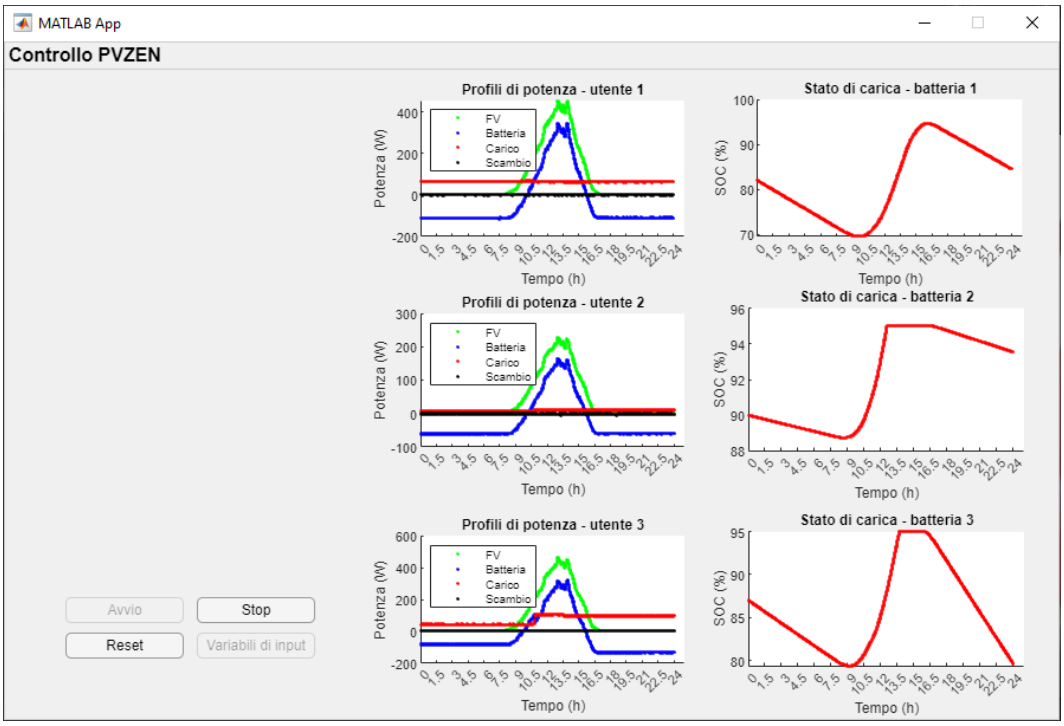

Figure 6-6 General overview of the simulation of 21/12/2021

As it was viewed in the cloud cover reports shown previously, this day was characterized of being, during the daylight hours, a constant mostly cloudy day. The effect of this cloudiness can be equally viewed in the photovoltaic production in the three users. The photovoltaic production follows an almost-normally trend throughout the day without having big spikes during its operation, that could have been caused by a cloud covering the modules for a time, so it can be concluded that the sky didn't had big changes on its cloudiness. Regarding specifically the photovoltaic production, it follows a typical photovoltaic generation throughout the day but with a general diminution of the production. This can be viewed, for example, on the user 1 that produced a peak of approximately 420-430 W as shown in detail on Figure 6-7

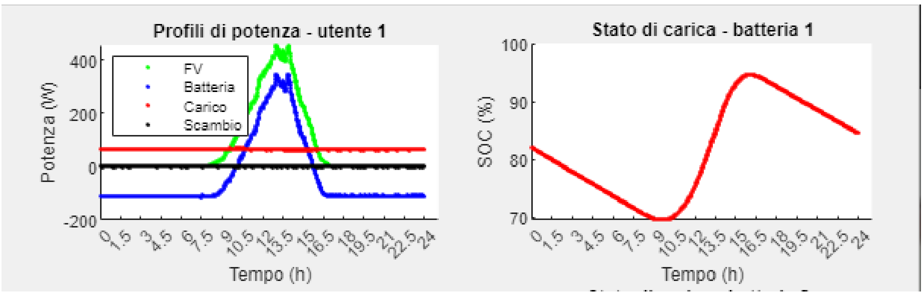

Figure 6-7 User 1 results for the cloudy day

The production for the user 1 is expected to be almost 1500 W that defer a lot from the almost 430 W produced for this day. Also, by seeing the state of charge profile, it can be viewed the impact of both the load and production on its behavior. The day was characterized of having a constant load throughout the day. Firstly, before the photovoltaic modules begin to generate electricity, the power demand is covered by the battery as seen in the figure with the steady decline on the battery's state of charge. Therefore, once the panels begin to produce, the load begins to be covered by the generation and, once it surpasses the load's requirements, it begins to charge the batteries, as shown by the rapid rise of the battery's state of charge. Finally, as the sun sets, the battery returns to cover the load and discharges its energy stored.

The other important user to be analyzed is the user 3, whose results are shown in Figure 6-8

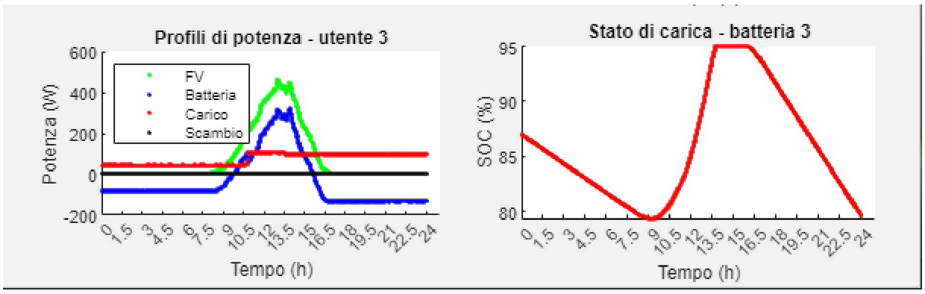

Figure 6-8 User 3 results for the cloudy day

The user 3, as well as users 1 and 2, is characterized for having a lower production than the one expected for a full production day. Nevertheless, a difference with the other users is its increment on the load at approximately the 11 am. This change on the load can be more clearly seen on the slope of the batteries discharging when it's used to cover the load. The slope on the energy changes between the morning and the evening-night and it decrements more in the evening as it has more demand of power from the load, so it has to discharge energy in a major rate.

6.2.2 Sunny day

The results for the day 22nd of December, considered the "sunny day", are shown in the following figure

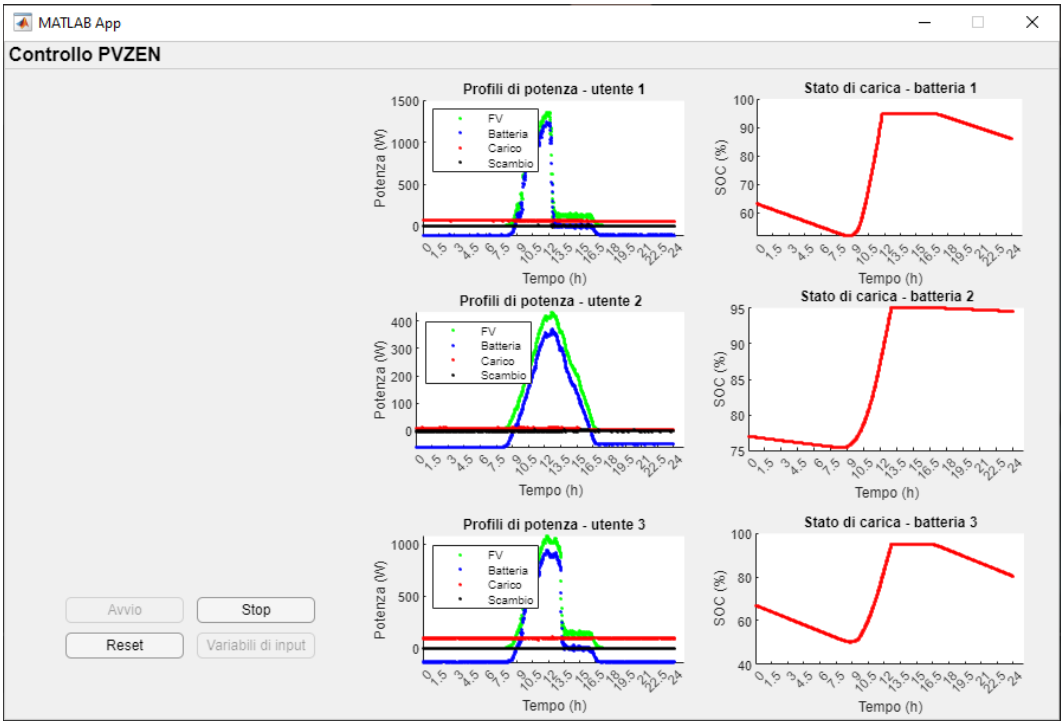

Figure 6-9 General overview of the simulation of 22/12/2021

The first noticeable aspect to address with respect to the previous case is the amount of photovoltaic production of all the three users. This is expectable as it was reported as a mostly sunny day according to the data from Time and Date [94] shown previously on Figure 6-4. The clearer sky benefited the production giving a peak of almost 1400W, 430W and 1100W for each of the three users respectively, a highly increment than the user's production on the cloudy day.

Moreover, there are other aspects to be addressed with respect to this case. A phenomenon to be analyzed is the one that can be seen on the production of both the user 1 and user 3 that can be seen in the following figure.

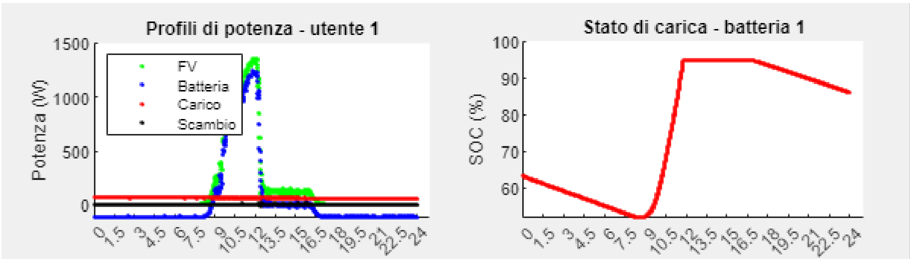

Figure 6-10 User 1 results for the sunny day

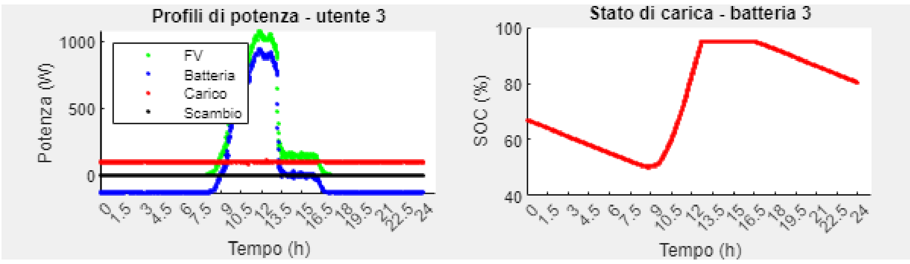

Figure 6-11 User 3 results for the sunny day

As it can be seen, at around the 13 the photovoltaic production experiences a drastic diminution in both user 1 and user 2, it is a radical diminution that goes from the peak production power to a constant amount that remains at the same value until the sun sets and the production goes to zero. This phenomenon is not weather related neither the normal expected production but, as seen on the state of charge profiles, it can be seen that it happens alongside with the saturation of the state of charge on the maximum value possible. Therefore, this event, accompanied by a low load consumption, happens when the load is fully covered, and the battery is fully charged. Given these requirements the inverters don't have a place to transfer this power, so it changes the internal power operating point, limiting the amount of photovoltaic generation produced.

6.2.3 Partly cloudy day

The last day to be simulated and analyzed is the 24th of December, the considered "partly cloudy day". The results of the simulation are shown on Figure 6-12

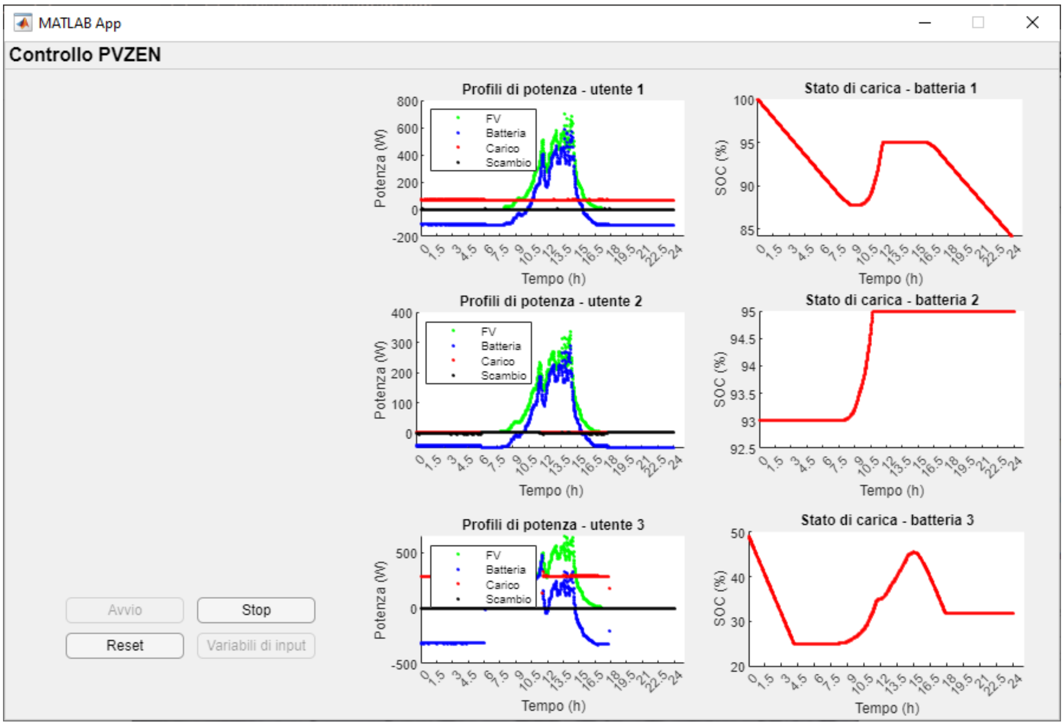

Figure 6-12 General overview of the simulation of 24/12/2021

Based on the general overview of the simulation, it can be seen that the three users experience the effects of an irregular cloudiness. First of all, the three users experience a diminution of the general photovoltaic generation as they produce less than the expected for a sunny day, this is totally expected as it can be deduced by the partial cloudiness seen on Figure 6-5. However, the three users achieve a higher generation than a mostly cloudy weather.

Furthermore, a more precise analysis of this situation can be done, as there are specific aspects to be analyzed for each user separately that will be addressed subsequently.

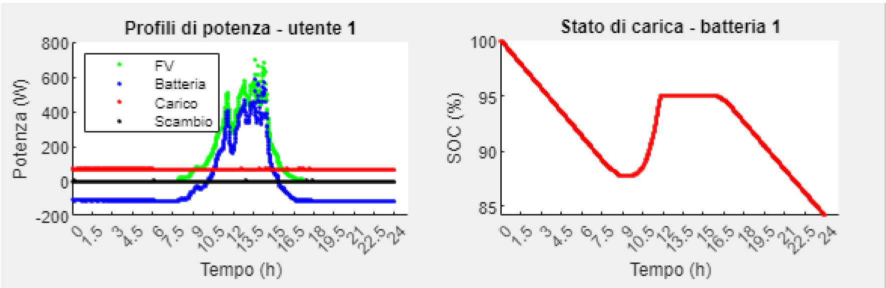

Figure 6-13 Power profiles and state of charge for user 1 for the partly cloudy day

The user 1 is characterized for having an almost constant load during the day. Firstly, it is covered by the battery that discharges its energy to meet the load power requirements. Once the photovoltaic generation begins to produce power, the generation begins to cover the load and to charge the batteries. However, in contrast to the sunny and cloudy days, the generation has production spikes through the day. This phenomenon could be a consequence of the passage of clouds as, how it was seen on the Figure 6-5 the day was partially cloudy with some variations through the day. Nevertheless, this phenomenon, even if it affects the generation, doesn't affect the state of charge of the battery in this specific case, as it begins the day fully charged.

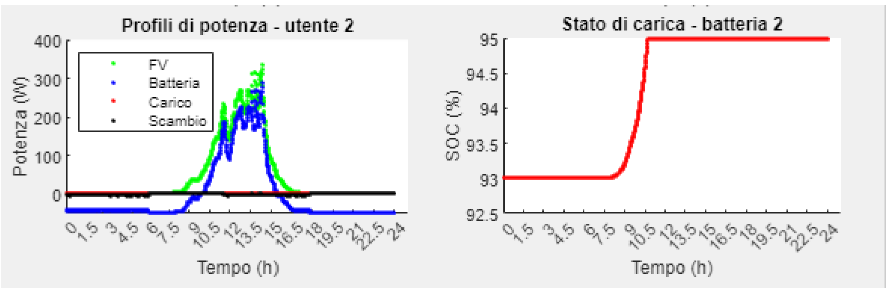

Figure 6-14 Power profiles and state of charge for user 2 for the partly cloudy day

The user 2, in contrast to the user 1, doesn't have the constant load consumption throughout the day. As a consequence, and as how its seen in Figure 6-14, the battery doesn't discharge but only gets charged when the photovoltaic generation begins to produce power. The photovoltaic generation, as the user 1, doesn't produce as much as a sunny day and presents the same power spikes as user 1. This way, it can be also addressed that there was an irregular cloudiness that produced changes in the modules produced power.

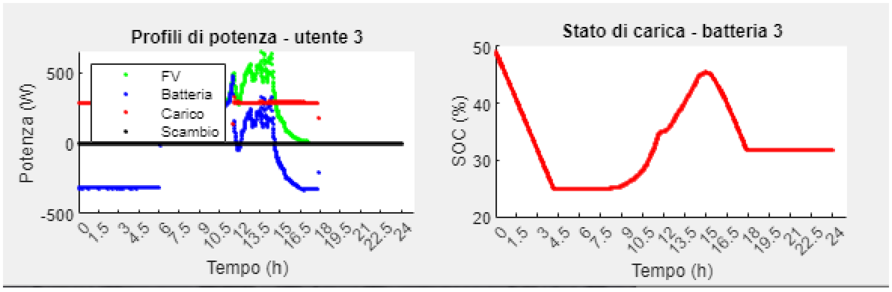

Figure 6-15 Power profiles and state of charge for user 3 for the partly cloudy day

Finally, the user 3 presents some differences with respect to the other 2 users. First of all, during almost all day there is a considerably load consumption. First is covered by the battery until it reaches the minimum state of charge of the battery. Moreover, the photovoltaic modules begin to produce power, the load is covered, and the battery begins to charge. As equal to the other two users, the photovoltaic generation presents power spikes produced by the non-constant cloudiness situation. This aspect, in addition to the important load consumption, provokes that the battery doesn't charges a lot as it barely reaches the 45%, less than the initial 50% of battery capacity at the beginning of the day. Finally, at around the 18 the load falls to zero, there is no more photovoltaic generation, and the battery doesn't discharge power, maintaining the final state of charge until the end of the day.

6.2.4 Self-sufficiency of the system

Given the power profiles of the three users on the three users, the self-sufficiency of the system can be calculated considering the situation where there is no storage, in other words, the self-sufficiency considering only the photovoltaic generation. The self-sufficiency was calculated with the formula

$$SS = \frac{\sum_i^N P_{PVtoload}^i \Delta t}{\sum_i^N P_{Load}^i \Delta t} 100 \quad [\%]$$

Where the self-sufficiency percentage is calculated dividing the photovoltaic production energy used to cover the load ($P_{PVtoload}^i \Delta t$) with the total load energy ($P_{Load}^i \Delta t$). This is done for every timestep, as the timestep is equal for both vectors it is only a ratio between the sum of the photovoltaic generation power used to cover the load ($P_{PVtoload}^i$) and the load power (P_{Load}^i). Moreover, the generated power used to supply the load is obtained by

$$P_{PVtoload}^{i} = min(P_{PV}^{i}, P_{load}^{i})$$

Therefore, the results for the system's self-sufficiency for the three days is shown in the following table

Day	Self-sufficiency [%]
Sunny day	34,43
Cloudy day	34,66
Partly cloudy day	33,84

Table 6-1 Self-sufficiency percentages without considering batteries impact

As shown by the results, there are not big variations on the system's self-sufficiency between the different days. This is because there is not a big load consumption and, even if the production is decreased by cloudiness, it doesn't affect the normal supply from the photovoltaic generation.

On the other side, by using the results obtained by the simulations and plots shown on the graphical user interface. It can be seen that the load is always covered by either the photovoltaic generation, during the daylight hours, or the battery storage, as seen on the battery's discharge during the hours of darkness. Subsequently, it can be concluded that, for all the three days, the system gets almost a 100% self-sufficiency thanks to the presence of the battery storage that accomplishes its objective of charging itself during daylight and discharging itself the rest of the day to supply the load.

7 Conclusions

Throughout the development of this thesis, different aspects have been addressed regarding the different regulatory frameworks developed internationally and the diverse energy drivers elaborated towards a carbon zero energy transition. Different aspects have been described about the new energy community actors and the impact on the new way to think the energy production and consumption.

On this context, PVZEN project is presented as an innovative multidisciplinary project consisting of the design, development, and operation of a nZEB building. The objective is to simulate and test an energy community consisting in three users, each one with their own photovoltaic generation, electrochemical storage systems and electric load consumption. On this thesis, a control software was developed to monitor and manage the energy exchanges on the PVZEN project to improve its energy efficiency. This software has three main phases: a reading phase where the different power profiles are read from the inverters, a control logic that elaborates these data with the objective of establishing which configuration the micro-grid must operate considering if the users are in a deficit or surplus situation. Finally, a writing phase is done by communicating this decision to the system by writing this information into the inverters and the PLC that will physically interconnect the users according to the software's decision. Moreover, a graphical user interface was developed with the objective of visualizing the power profiles of the three users and their respective battery's state of charge. Therefore, a graphical tool was implemented so the user can visualize the system's behavior.

Moreover, the control software was tested by simulating the battery's state of charge in three different days with different weather conditions. The 21st December, characterized of being a mostly cloudy day, the 22nd December, a mostly sunny day and the 24th December, a partly cloudy day. From these simulations, the power profiles had been graphically plotted into the software's GUI which permitted to see the effects of a high, mid, and low photovoltaic generation on the system's behavior. The most notorious effect of cloudiness on the system was on the generation profiles, as expected, the impact is direct as the presence of cloudiness reduces the power production. In addition to this, the storage system impact on self-sufficiency was graphically evident, as the battery's covered the load consumption during the dark hours by discharging its energy stored while during daylight the photovoltaic system was capable of supplying directly the load. In conclusion, the batteries permitted the whole system to achieve 100% of self-sufficiency levels.

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