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Simulation of a self-consumption project of an apartment building and a school

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Chapter 1

Introduction

In a period in which new technologies are required to slow down the environmental degradation that is proceeding, renewable sources combined with efficient storage systems can represent a solution.
The integration of diversified renewable resources is fundamental in order to fulfil the increasing demand for energy and to reach the limit imposed by the European Roadmap to 2050, in which by the mid-century it is expected a reduction of green house gases (GHG) emission of at least 85 % below 1990 levels [1].
Since renewable sources are now spreading, it is adequate to consider the penetration of the renewable energies inside our production energy system. It can be expressed as a percentage of electricity generated by a clean resource with respect to the overall electricity consumed.
In 2019 the Italian electricity consumption amounts to 311.9 TWh of which 6 031.0 GWh ($\approx$ 1.9 %) from geothermal, 47 499.0 GWh ($\approx$ 15.2 %) from hydro, 23 689.0 GWh ($\approx$ 7.6 %) from solar and 20 245.0 GWh ($\approx$ 6.5 %) from wind [2].

Along with the integration of renewable systems, the core would be if the pre-existing grid is able to sustain their unpredictable behaviour. This is particularly true for the PV panels that have been implemented in the residential realities; they provide energy as long as there is sun available but once the sun sets it is requested to the public grid to ramp in order to satisfy the energy demand.
An interesting study was held by the California Independent System Operator

(CAISO) in 2013 representing a 24 hours snapshot of the energy supplied during springtime [3]. As PV panels got more popular the ramp of energy demanded by the grid increased after the sunset. This phenomena, called the “Duck curve” because of the resemblance of the curves in the chart to a duck, has two main effects: the first one is the need for a flexible grid able to maintain stability as a rough change of the power profile arrives, and the second one is the risk of wasting clean energy when there is an over generation from the PV panels that would be in these cases curtailed [4]. This leads to the necessity of having a good storage system in order to use all the energy from the photovoltaic system.
Based on this, the multi energy districts can be the future in the renewable field in order to promote the integration and penetration of clean sources in the overall energy production. In particular, the concept of energy community, which will be elaborated in this thesis, refers to the complex of utilities proposed to fulfil the energy requirement by promoting a more awareness towards the resources available. Nowadays, Italy claims twelve energy communities including private citizens and businesses, introducing the concept of prosumption together with the need of a storage system. The aim at the current state of the art cannot be to fulfil the whole national need; the aim should be to facilitate the penetration of renewables and a more aware use of the energy that we consume.

The thesis focuses on the concept of a renewable energy community in a residential area in which new technologies for the production and storage must cooperate with the responsible use of those resources. In order to take full advantage of this new reality, some aspects of the realization are taken for granted and are listed in the study case section. The area chosen is hypothetical because of some initial assumptions but the aim is to provide a feasible project, therefore the group of buildings is situated in Verona. For a social concern the study case includes a public space; in the future the expectations are that either in private and public spaces solutions as the energy community may be adopted. After a personal experience inside a Civic Movement in Verona the main idea is that, also along with private investment, sites as schools and public offices should be renovated as a demonstration of a practical action towards the climate emergency with a social and economic rewards. Moreover, from a practical and technical point of view intervening on spaces that are mostly used at daytime can contribute to store more energy needed in private building.

For what concerns the test case, it has been chosen a group of buildings located one next to the other in the same street, connected to the same MV/LV substation to comply with the territoriality constraints [5] . It includes one private building for private citizens and one public structure, in particular a school. This configuration must be compatible with the limits imposed by the law referring to the maximum power for sizing the plant, which is 200 kW, and it has to be adequate with reference to the storage system to be designed. As mentioned before, the possibility to include structures with different needs in terms of energy should allow to have more energy stored.
Since this thesis will not deal with the design of the power plant, a set of PV panels has been chosen based on the following aspects. Firstly, as the project is located in a residential area in the city centre, PV panels represent the most feasible solution for a local energy source, and secondly the introduction of public structures inside the energy community allows to have a bigger surface available for mounting panels knowing that the stored energy will be principally used by the private building.
In the configuration just described some assumptions are made. In particular, the whole project finds its meaning if the building itself has been energetically upgraded.
The concept of the energy community must be associated with the development of good materials for the construction, able to minimize the thermal dispersion, and a smart system that allows to control the amount of energy produced and consumed in order to maximize its efficiency. By using the PV panels, the way people treat energy changes completely; usually home appliances tend to be used in the night time in order to spend less, while now the most reasonable thing to do is to use these appliances during the day because it is when most energy is available.
Several systems are now available to have the traceability of the energy consumption and to keep under control the availability of the energy and the temperature in the spaces, so that the most efficient solution can be applied. Without these means the energy community cannot be at its maximum efficiency.
On these bases, a comparison between the demand and offer profile is made in

order to have the information regarding the energy flow of the overall system and the exceeding energy stored in the storage system. For this, many solutions have been evaluated. This is the technical and most significant part of the thesis, in which the aim is to focus on the storage system in its whole life.
The whole discussion is centred on the concept of sustainability, which can be a sensitive issue for batteries. Sustainability has several perspectives, it is very important to deal with the environmental aspect as in materials used and their recovery, and with the social aspects concerning the extractions of these same materials. There is a dedicated chapter regarding the whole life cycle of the storage system with a particular focusing on environmental and social aspects.

As mentioned, the thesis was chosen based on a personal interest in this developing field that can represent a turning point in the future once it will be more widely implemented. In order to have a relevant impact on the environment, new technologies and a higher awareness of the consumption must co-operate. The energy community in this meaning is the perfect example, since consumers are called to have their part in how they handle the energy available.
The aim is to have a wider knowledge on this topic in order to understand the impact that this new configuration might have, remaining faithful to the environmental and social sustainability.

In Chapter 2 is discussed the context in which the renewable energy community (REC) develops, in terms of legal background and existing example of these realities. Later, the thesis follows with a qualitative analysis regarding the consumption and production of the study case. In order to simulate the real approach towards these kind of projects, the first thing is to prove its feasibility.
A relevant focus of the thesis is the introduction and the selection of the storage system. In Chapter 4 the technology chosen for the system is justified by giving a framework on the current solutions available.
Following, the most technical part of the study is discussed in Chapter 5, in which the simulation, using the software Matlab/Simulink, is implemented to represent the system and its operation.
The aim is to prove the feasibility of the project, being aware of the limits regarding

the study case. In fact, it is important to take into consideration that the buildings must be upgraded in terms of construction and electrical technology of latest generation to obtain a better outcome. Means as thermal coats, high efficient appliances and smart meters can only lead to an improvement, enhancing the work.

Chapter 2

Renewable Energy Community

Renewable energy communities (RECs) can represent a turning point in the process of decarbonisation of the power sector. Within the struggle against climate change, there are some fundamental concepts that must be implemented such as reductions of waste, penetration of renewable energy sources and shared initiatives that consider the problem from an environmental, social and economic point of view. In this meaning the RECs constitute a collective action towards the climate problem. The environmental advantage resides in the usage of clean energy and therefore a reduction of greenhouse gases in one of the realities, such as buildings, that represent a non-negligible part of the overall emissions in Europe. In particular, buildings are responsible for 40 % of energy consumption in Europe and 36 % of CO_2 emissions [6].
For what concerns the social aspect, it can be found in a local, people directly interested, and global dimension. From a closer perspective, parties who get involved in the RECs will have the availability of a network capable of providing the energy they require without be affected by the usual unbalance that the national grid has to deal with. The grid must be able to continuously handle changes in demand, leading to unbalance and interruption of the service in some cases. Therefore, off-grid systems that are self-sufficient by using a power plant and a back-up storage system are assured from eventual failures of the grid. Moreover, the cost of energy

itself in case of self-production is lower and along with the progress investment costs are falling and more incentives are being allocated [7]. So, many parties can find their interest for an economical reason in a long-term framework.
By looking at the problem from a wider perspective, the implementation of this reality, linked to the penetration of renewable energy sources (RES), can be revolutionary for the whole society. A relevant transition towards RES, as the one needed, can be seen as an opportunity for new jobs in many sectors and a whole new economy related to it. The energy community is not only focused on power plants and storage system, but it is also related to the overall efficiency of the buildings in terms of construction and home automation. It is immediate to understand the great potential of this multidisciplinary innovation.
In the next sections, the surroundings in which the RECs develop is explained, legally and technically wise. In 2019 Europe has defined the limits within which the REC has to be designed and it is important, based on them, to underline the advantages in order to understand the optimal solution and configuration for implementing the REC.

2.1 Legal background

In February 2015, the energy union strategy COM/2015/080 was agreed including several packages of measures to give EU consumers a secure, sustainable and affordable energy.
Later on, the Paris Agreement was designed and entered into force on the 4th November 2016 setting global goals to avoid dangerous climate change. Inside the agreement it is specified the important role of non-party stakeholders to take part into this fight against climate change.
In order to achieve the goals required by the Paris Agreement, in May 2018 the European Union drafted the policy framework “Clean Energy for all European packages” (CEP) that was later finalized in May 2019, by overhauling the previous initiatives and by giving all the European countries two years to transpose the policy into national laws [8]. It is composed of 8 laws aimed at creating a long-term strategy to deliver the European goal of carbon neutrality by the year 2050. Inside these arrangements, first guidelines towards a greener residential sector are

given. In particular, in May 2018 the Energy Performance of Buildings Directive (EU/2018/844) was published outlining specific measurements for the construction sector.
Later on, in December 2018 the Renewable Energy Directive (EU 2018/2001 REDII) entered into force as one of the packages on which the CEP focuses. All measurements were chosen with the binding target of 32 % of RES by the year 2030. This achievement is possible only by enabling citizens to play an active role through energy communities and self-consumption of renewable energy [8].
Citing the Directive EU/2018/2001 Art. 21 [9]:
«

1. Member State shall ensure that consumers are entitled to become renewables self-consumers, subject to this Article.
2. [...] Renewables self-consumers are entitled:
   (a) To generate renewable energy, including for their own consumption, store and sell their excess production [...]
   (b) [...]
   (c) To maintain their rights and obligations as final customers

»

Moreover, in Directive EU/2018/2001 Art. 22 [10]:
«

1. Member States shall 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, and without being subject to unjustified or discriminatory conditions [...]
2. [...]
3. Member States shall carry out an assessment of the existing barriers and potential of development of renewable energy communities in their territories
4. Member states shall provide an enabling framework to promote and facilitate the development of renewable energy communities [...]

(a) Unjustified regulatory and administrative barrier to renewable energy communities are removed

(b) [. . .]

(c) The relevant distribution system operator cooperates with renewable energy communities to facilitate energy transfer within renewable energy communities

(d) [. . .]

(e) Renewable energy communities are not subject to discriminatory treatment with regard to their activities, rights and obligations as final customers, producers, suppliers, distribution system operator, or as other market participants

(f) The participation in the renewable energy communities is accessible to all customers [. . .]

»

After introducing the concept of renewable energy community, a more specific guideline has been released in June 2019 inside the Common rules for the internal market (EU 2019/944 EMDII). As reported "This Directive aims to recognize certain categories of citizen energy initiatives at the Union level as 'citizen energy communities', in order to provide them with an enabling framework, fair treatment, a level playing field and a well-defined catalogue of rights and obligations".
In particular the Directive EU 2019/944 underlines [11]:
«[...]
(44) Membership of citizen energy communities should be open to all categories of entities. However, the decision-making powers within a citizen energy community should be limited to those members or shareholders that are not engaged in large-scale commercial activity and for which the energy sector does not constitute a primary area of economic activity. [. . .] (46) Citizen energy communities constitute a new type of entity due to their membership structure, governance requirements and purpose. They should be allowed to operate on the market on a level playing field without distorting competition, and the rights and obligations applicable to the other electricity undertakings on the market should be applied to citizen energy

communities in a non-discriminatory and proportionate manner. Those rights and obligations should apply in accordance with the roles that they undertake, such as the roles of final customers, producers, suppliers or distribution system operators. [...]
For the purposes of this Directive, the following definitions apply: [...]
(11) ‘citizen energy community’ means a legal entity that:

1. is based on voluntary and open participation and is effectively controlled by members or shareholders that are natural persons, local authorities, including municipalities, or small enterprises;

2. has for its primary purpose to provide environmental, economic or social community benefits to its members or shareholders or to the local areas where it operates rather than to generate financial profits; and

3. may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services or charging services for electric vehicles or provide other energy services to its members or shareholders;

»

Therefore, this new directive provides two scenarios for the energy community, the renewable energy community and the citizen energy community. What distinguishes these two types are the limitation that the REC is within defined. In fact, the REC must fulfill the proximity requirement, a stricter membership since no large company is included and the renewable constraint for which only renewable energy is accepted as a source [12].
The CEP required that each country converts the directive into national law; therefore, in Italy ARERA through the resolution 318/2020/R/eel approved the regulation incomes related to the shared electricity by a group of consumers of renewable sources, either as self-consumers or together inside an energy community. In the annex A of the resolution the following definition for energy community is stated: energy community as a legal entity based on the open and voluntary participation, autonomy and controlled by physical members for whom the energy community does not represent the main business. It is also specified how the main

aim of this project is to give environmental, economical and social benefits to whom is involved and to the territory in which it is situated.

With the resolution 318/2020/R/eel ARERA is entitled to regulate the modalities through which the self consumers share the electricity. It defines the requirements to access to the service and the contractual procedures between the subject and the GSE (Gestore Servizi Energetici) [13]. GSE is identified as in charge of handling the mechanism of incentives through the ordinance 16 September 2020, issued by the MiSE (Ministero dello sviluppo economico) to define the incentive rate in order to promote the penetration of RES and self consumption [14].

2.2 Energy trilemma

Focusing on a more technical perspective, it is relevant to set some requirements that this new reality must fulfil and to understand that behind their creation there is a whole new concept of the grid itself.
An important innovation of the energy communities resides in the possibility of creating a secure and reliable digitalized power system that will enable uninterrupted power supply.
Therefore, the World Energy Council prepared the World Energy Trilemma Index [15]. Three dimensions were presented, all three of them must be considered and balanced either in normal operation and in emergency operations.

- Energy security: it represents the nation's capacity to fulfill the current and future demand through a reliable and resilient infrastructure.
- Energy equity: it represents the nation ability to make the service reliable, affordable and accessible.
- Environmental sustainability: it represents the nation's transition towards technologies harmless for the environments and policies to reduce climate change impact.

Italy nowadays shows itself as one of the strongest Trilemma performers with the scores shown in the Fig. 2.1.

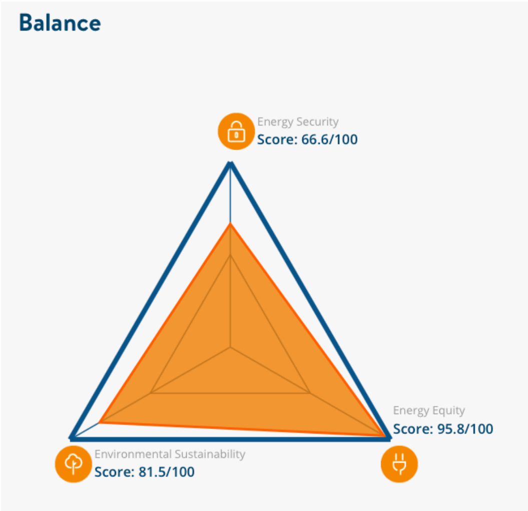

Figure 2.1: Italy Energy Trilemma (World Energy Council [16])

Among the years Italy has improved its scores, in particular in the security dimension as shown in Fig. 2.2.

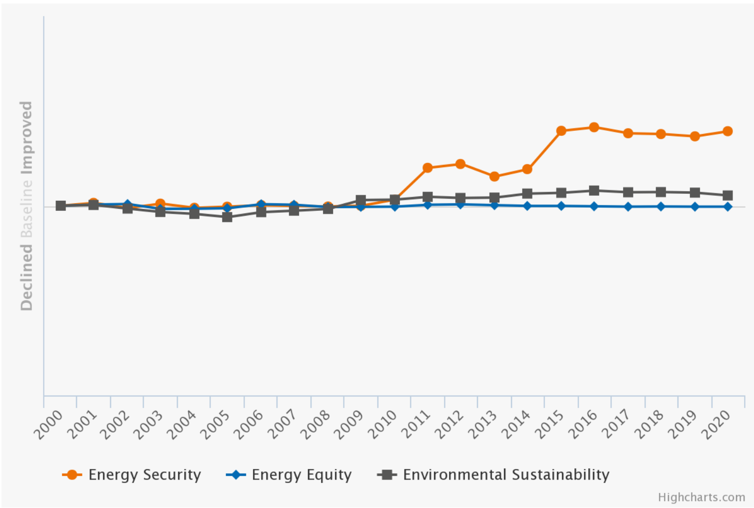

Figure 2.2: Italy Energy Trilemma 2000-2020 (World Energy Council [16])

2.3 Smart grid and Micro-grids

Based on what the energy trilemma has suggested, it is immediate to highlight the importance of security when dealing with the energy system. In particular, the word adequacy is a relevant indicator since it is related to either a normal operation and an emergency operation that presents itself when a contingency occurs.
As the Italian Transmission System Operator Terna defines it, “adequacy refers to the system’s capacity to satisfy electrical energy requirements while complying with requirements on safety and quality of service” [17]. The adequacy of a system can be measured, and it is affected by different factors that present a specific level of uncertainty, as for example the demand or the availability of any kind of energy generation.
Due to this uncertainty and along with the reliability of the system, the grid can be subject to interruptions or blackouts that determine a low-quality of the service and costs. In order to face these weaknesses, a demand-response pattern is defined and requires special types of users to participate when needed to prevent and solve contingencies.
As mentioned, the behavior of the grid is strictly related to its reliability and resilience, and these two parameters express the capacity of the infrastructure to adapt itself to the continuous changes of the technologies. One important novelty in the energy infrastructure is the distributed generation that converts the usual vertical system, made by certain nodes of production on which the electrical grid bases itself, into a system that includes many and spread nodes of production.
Distributed resources are a current reality that operators are facing to maintain and improve the grid. Many technical problems derive from this new decentralized conception of the energy generation and this leads to the raising question of whether, and therefore how, to adapt the grid. Generally, Distributed Energy Resources (DERs) can increase the short circuit currents based on the fact that new generators are connected to the grid without being controlled by the operator; as a consequence protection must be adapted and the whole meshed configuration of the network might not be adequate anymore. Moreover, when focusing on distributed renewable energies such as photovoltaic, there is the technical problem related to the regulation of voltage directly linked to the regulation of the reactive power.

These examples aim to observe how with the new technologies a new evolution of the grid is indispensable.

What can be a revolutionary path, that nowadays is being taken, is the one towards a smart electricity grid, where smart indicates the integration of ICT and automation to allow the bi-directional communication between the utility and its customer. The International Energy Agency stated that “a smart grid is an energy network that uses digital and other advanced technologies to monitor and manage the transport of energy from all generation sources to meet the varying energy demands of end-users” [18]
By adding communication lines and sensors, not only the DSO will be able to maximize the system reliability minimizing the costs, but also the consumer will have access to the information through smart meters regarding their energy status, according to what the Clean Energy Package in 2019 had already stated. The concept of smart finds its meaning not only on the grid, but also on the houses through a digitalized development of all the appliances that will work according to the availability of energy, therefore in a smarter way.
In particular, the algorithm starts with a forecast of the next day in terms of consumption and production, then the profiles are adjusted on the current day and the parameters controlled on a real-time basis. This can be further optimized in particular when controlling a storage system. It is, indeed, proven that in the absence of an optimization algorithm once an hypothetical solar plant stops supplying, the storage system steps in discharging itself. An optimized control is able eventually to take into consideration incentives for shared energy and the cost difference between sold or purchased energy. In this last case, the storage system supplies only in case of surplus in the user demand.
The smart grid represents the solution to allow the renewable energies, as well as the storage systems, penetration in the overall energy system enabling uninterrupted power supplies.

The grid of the future can be seen as in Figure 2.3 provided by the European Distributor System Operator.

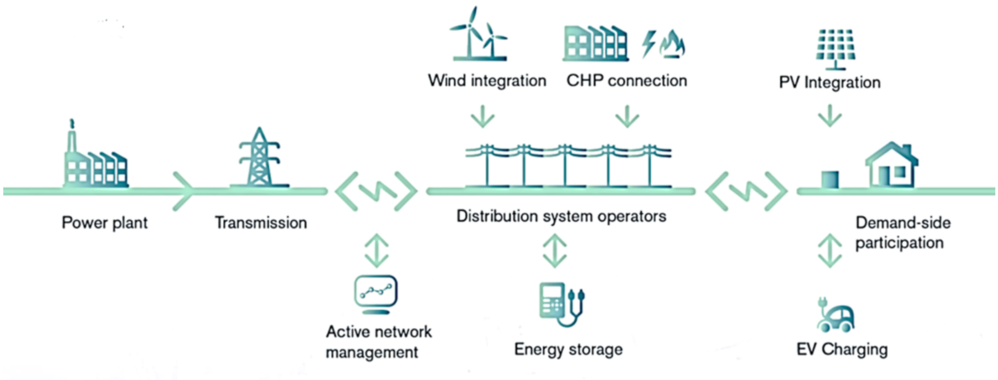

Figure 2.3: E.DSO Smart Grid [19]

Together with the digitalization, the penetration of renewable energies will be possible through the implementation of the micro-grids, which are defined as small distribution systems consisting of generation and load. Micro-grids can be either autonomous or non-autonomous from the grid.
Micro-grids are local, self-sufficient and intelligent and its main aspect is that it will keep the power flowing even when the central grid fails. These features combined with the ones of an energy communities define the community micro-grids. The scheme of a micro-grid is presented in figure 2.4.

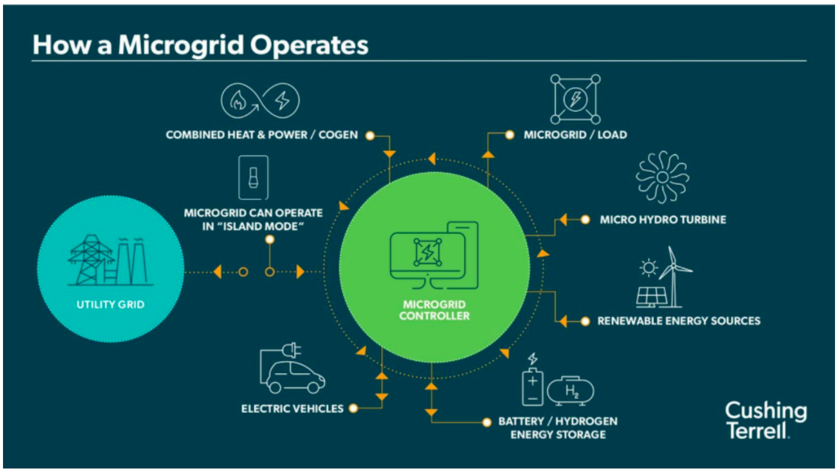

Figure 2.4: Micro-grid [20]

2.4 Current realities in Italy

The figure of the prosumer, as the owners of a power plant for producing the energy in order to consume it, is starting to be part of the current scenario for achieving the ecological transition.
The legal framework in which the energy community is described marks a turning point because the participation is on a voluntary basis, rather than lucrative. The aim is to have an environmental impact along with an economical advantage, fighting the energy poverty and making the service more affordable and accessible. RSE ARERA, the energy system research sector of the Italian Authority of the regulation for the energy network and the environment, conducted a study to map all the prosumption realities present in Italy and 12 of them were counted [21].

- FUNES: situated in Alto Adige, it is a valley supplied 100 % by renewable energy sources. It counts three hydroelectric power plants (San Pietro 775 kW, Meles 2689 kW, Santa Maddalena 225 kW), one photovoltaic plant (170 kW) and two biomass district heating (1100 kW, 700 kW).
- EWERK PRAD: it consists of 17 renewable power plants owned by a cooperative close to Bolzano (4000 kW from hydroelectric, 103 kW from photovoltaic, 1600 kW from biomass). The cooperative today counts 1350 members.
- COOPERATIVA ELETTRICA GIGNOD: situated in Valle d'Aosta with a hydroelectric power plant (6763 MW).
- COOPERATIVA ELETTRICA ALTO BUT: situated in Friuli with five hydroelectric power plants (10.8 MW).
- SEM-SOCIETÀ ELETTRICA DI MORBEGNO: situated in Lombardia, with eight hydroelectric power plants (11 MW) it supplies 13000 consumers.
- COOPERATIVA DI MELPIGNANO: it counts 33 roof integrated photovoltaic systems (179.67 kW) in Lecce.
- COOPERATIVA FTI: it supplies 1300 consumers in the surroundings of Bolzano with a biomass power plant (1500 kW).

- WEFORGREN: it consists of three photovoltaic power plants (3000 kW) in Lecce and Verona, supplying 1471 consumers.
- COOPERATIVA ENERGIA POSITIVA: situated outside Torino, it consists of three photovoltaic plants (250 kW) supplying 100 families.
- COOPERATIVA ÈNOSTRA: it owns six photovoltaic plants, five in the territory of Cunero (400 kW) and one in Sorbolo (99 kW).
- COMUNITÀ PINEROLESE: the community includes in Piemonte 15 photovoltaic power plants, hydroelectric power plants (450 kW) and the production of biogas.
- ASSOCIAZIONE COMUNITÀ ENERGETICA: it consists of an integrated photovoltaic power plant (20 kW) on the roof of a school, close to Bologna.

All the listed realities are an example of how the concept of the energy communities goes beyond the environmental aspect of taking action for the climate change. In fact, it promotes an affordable, accessible and clean electricity, an economic growth in which the parties are responsible and aware of the consumption and of the resources.

Chapter 3

Energy profiles

In the following chapter a qualitative analysis of the energy profiles is treated in order to understand the energy requested by the considered buildings.
All data are reality based, as they are obtained from real databases for what concerns the production and real bills for the private building. Starting from monthly quantities, these were manipulated to obtain a daily profile for production and consumption, to be then overlaid.
The monthly information can return a first impression to understand whether the chosen power plant is sufficient to satisfy the demand, along with the changing seasons that determine a different amount in production and different needs in consumption. It is important to underline that the consumption are the ones of real buildings that can be labelled as medium energy efficiency classes, as a consequence it will be interesting to compare different scenarios of the overall system once renovated. In this meaning, the project is left open to improvements in efficiency. Besides the modification related to the building efficiency, the whole concept of smart house focuses on the introduction of communication lines, so that consumption are strictly bonded to the availability of the energy.

3.1 Private building characteristics

The assumed private building is situated right next to the school, it has four floors, each one with an apartment of 100 m^2.
Considering each apartment, the elevator and the stairs, an available roof surface of 120 m^2 can be considered, assuming a flat roof.
Table 3.1 shows the monthly consumption of one apartment of 100 m^2 lived by 4 people, equipped with air conditioning (used in June, July, August) and heating (used from half October to half March).

Month	**Consumption [kWh]**
January	352.18
February	366.25
March	341.87
April	265.04
May	247.66
June	314.40
3 July	326.40
August	298.40
September	275.70
October	292.40
November	286.70
December	313.40

Table 3.1: Monthly consumption of an apartment of 100 m^2 walkable

The consumption are referred to the year 2019 for electricity, and for gas.
Considering the four apartments and the consumption related to the elevator and the interior lights (additional 10000 kWh/year), the overall monthly consumption are shown in Table 3.2.

Month	Consumption [kWh]
January	2242.05
February	2298.33
March	2200.81
April	1893.49
May	1823.97
June	2090.93
July	2138.93
August	2026.93
September	1936.13
October	2002.93
November	1980.13
December	2086.93

Table 3.2: Monthly consumption of the private building

3.2 School characteristics

The school considered is a middle school in Verona, of which the yearly consumption is known. The total amount of electricity is 60000 kWh and it was divided into the 11 months of activity of the building. The air conditioning is not considered since the school is not provided with one.
For what concerns the heating the amount of energy consumed is 541 kWh and it was divided into the winter months, based on the days of activity (days of holidays excluded). Table 3.3 lists each month with its relative overall consumption.

Month	Consumption [kWh]
January	5217.4
February	5307.6
March	7133.6
April	5478.3
May	7043.5
June	4956.5
July	2608.7
September	6782.6
October	6634.4
November	5307.6
December	3980.7

Table 3.3: Monthly consumption of the school

August wasn't considered since the school is closed for holidays and there is no relevant activities running, and so that, the power consumption is almost null.
Knowing the school in study, the main factors that influence the consumption are the presence of a school gym, the canteen in which the pre-prepared meals are kept warm, the classrooms and one computer laboratory.

3.3 Consumption profile

The two buildings were studied separately because they present different needs in terms of energy, besides having different appliances to supply.
The daily profiles are now presented below, describing the choices made for defining them, then an overall profile demand is built in order to compare it with the produced energy.

3.3.1 Consumption of the private building

Many factors can influence the consumption of the house; besides the location itself, the efficiency of the appliances, the number of people living in it and the type of construction can all have a relevant impact on the final bills in terms of energy used and therefore costs.

All the profiles shown are referred to one apartment, the total request of energy is treated in Section 3.3.3.
The monthly consumption is divided by the number of days of the considered month to obtain the daily energy information.
In order to build a daily profile, the research project MICENE of the Energy department of Politecnico of Milano was used [22]. The study aimed at creating load curves of the appliances present in a domestic environment, knowing that the household appliance requires peaks power as well as stand-by power.
In particular:

- Fridge-freezer: its curve is distributed among the day since it is always working with an average power of 20.3 W. In average 200 kWh/year are spent by a high energy class fridge.
- Washing machine: its curve presents two principal peaks, one around 10.00 am and the other one around 3.00 pm. The average power among the day is 28.5 W and in average the appliance consumes 224 kWh/year.
- Dish washer: its curve presents three principal peaks, one around 10.00 am, one around 3-4 pm and one around 10-11 pm. The average power among the day is 46.4 W and in average the appliance consumer 369 kWh/year.
- TV set: the average value of energy consumed is 355 kWh/year, with an average daily power of 14 W.
- Technology (as personal computer): the average value of energy consumed is 132 kWh/year with an average daily power of 14 W.
- Lights: the average value of energy consumed is 375kWh/year with an average daily power of 43 W. The curve presents its peak at around 9 pm.

These indications were very useful to determine the behavior of each appliance among the day and to create the typical residential profile. The expected trend presents its peaks of request in the early morning, at lunchtime and at dinnertime (particularly true when the heating is on) and the same behavior was recreated.
The program used to plot the graph is Excel, on it a table of 96 instants has been built simulating the usual energy profile which integrates the power required every

15 minutes in 24 hours.
The every-day appliances listed have been considered having the same pattern all year; what changes among the months, and therefore the consumption, is how much heating and air conditioning is used in order to reach the real value indicated on the bill.
In the following each month will be presented with an exemplary daily load profile of one apartment of 100 m^2. For each month starting from the real data of monthly consumption of electricity, the daily consumption has been derived:

$$E_{daily} = \frac{E_{month}}{n_{days}} \quad [\frac{\text{kWh}}{\text{day}}] \tag{3.1}$$

The daily consumption of electricity is related to the appliances previously listed, creating a first approximation of the daily trend. To this the consumption of gas per day has been added considering it distributed during the day. The aim is to assume every appliance to be electric (cooking hubs, oven, boiler) to see if the photovoltaic system is able to fulfill the whole demand of energy.
All the graphs show a Power-time relation in which the colored areas represent the integration of the energy every 15 minutes. The average power is derived by dividing the daily energy by 24.

$$P = \frac{E_{daily}}{24} \quad [\text{kW}] \tag{3.2}$$

For each month two graphs are reported as shown from Figure 3.1 to Figure 3.24:

- The daily household demand for one apartment as an integration of the power every 15 minutes.
- The daily household demand for the building as a load profile, knowing that the area below is the energy requested.

- January: the electricity consumption of one apartment amounts to 3.7 kWh/-day and the gas to 7.6 kWh/day.

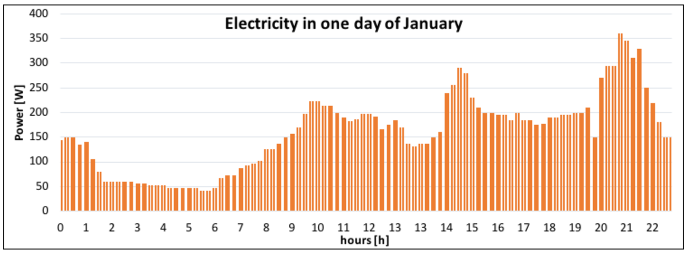

Figure 3.1: Electricity demand in one day of January

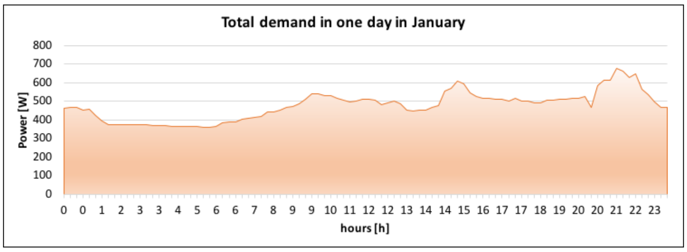

Figure 3.2: Total demand in one day of January

- February: it has a similar trend as January; 3.5 kWh/day of electricity consumed and 9.5 kWh/day of gas consumed.

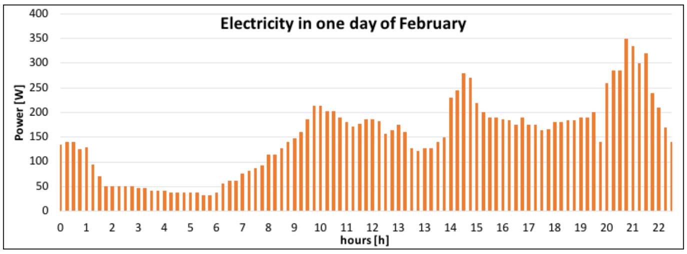

Figure 3.3: Electricity demand in one day of February

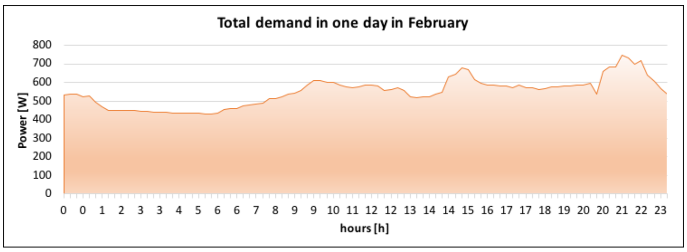

Figure 3.4: Total demand in one day of February

- March: 3.1 kWh/day of electricity and 7.9 kWh/day of gas.

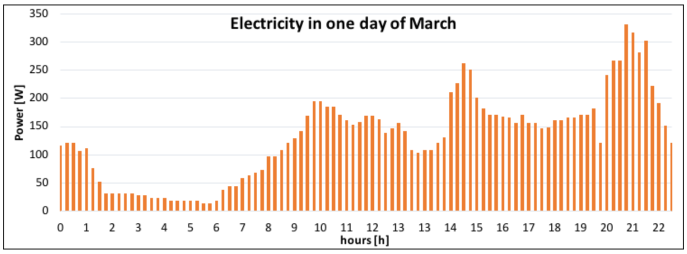

Figure 3.5: Electricity demand in one day of March

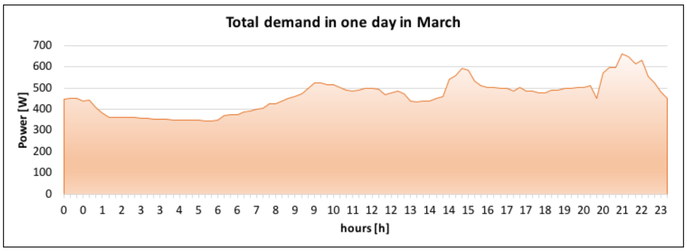

Figure 3.6: Total demand in one day of March

- April: there is no heating nor air conditioning working, therefore the consumption of gas is related to the kitchen and the hot water, 3.1 kWh/day of electricity and 5.7 kWh/day of gas.

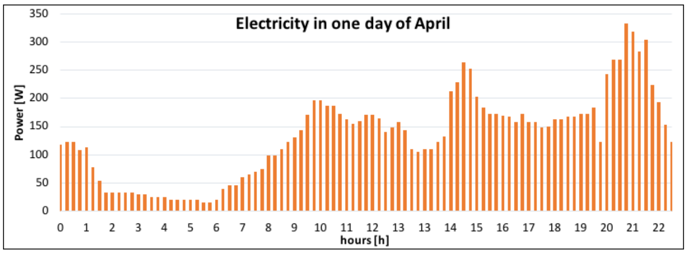

Figure 3.7: Electricity demand in one day of April

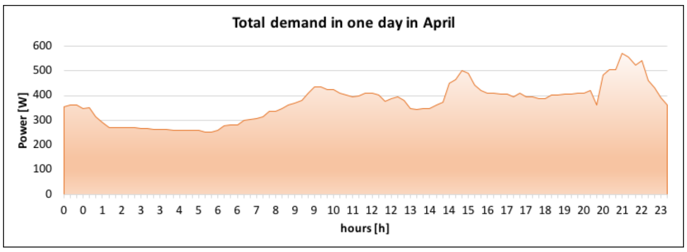

Figure 3.8: Total demand in one day of April

- May: 3.2 kWh/day of electricity and 4.99 kWh/day of gas.

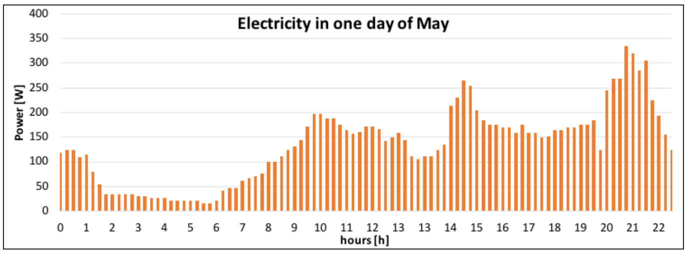

Figure 3.9: Electricity demand in one day of May

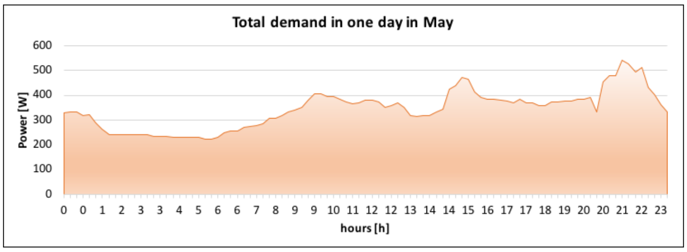

Figure 3.10: Total demand in one day of May

- June: as a summer month the air conditioning start to be used and it can be noticed by the increase of the consumption of electricity, 4.1 kWh/day of electricity and 6.4 kWh/day of gas.

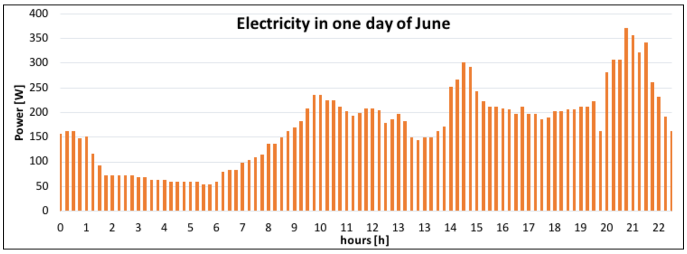

Figure 3.11: Electricity demand in one day of June

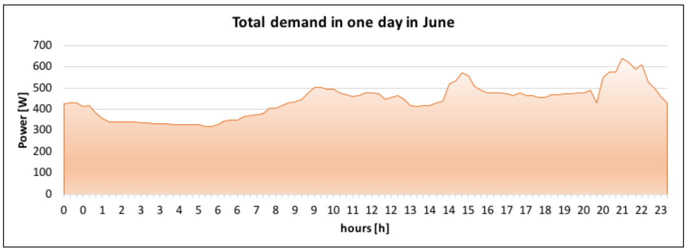

Figure 3.12: Total demand in one day of June

- July: 4.3 kWh/day of electricity and 6.2 kWh/day of gas.

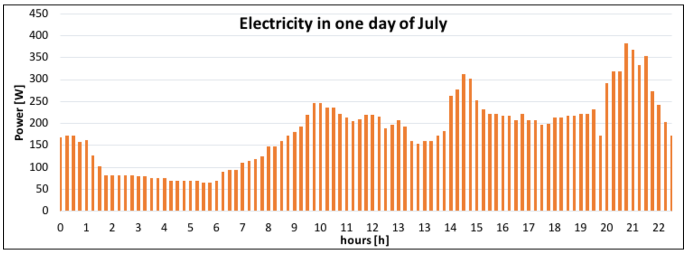

Figure 3.13: Electricity demand in one day of July

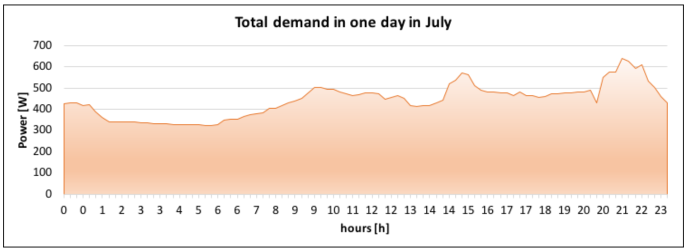

Figure 3.14: Total demand in one day of July

- August: 3.42 kWh/day of electricity and 6.2 kWh/day of gas.

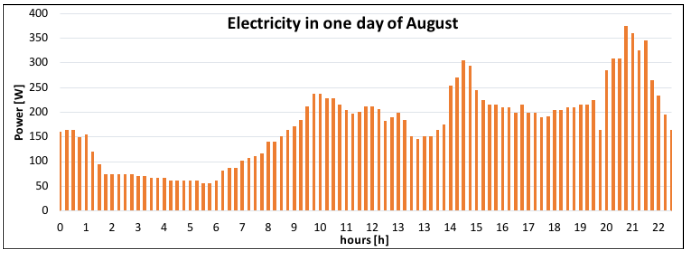

Figure 3.15: Electricity demand in one day of August

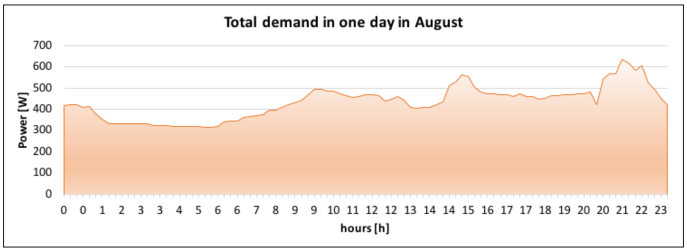

Figure 3.16: Total demand in one day of August

- September: the air conditioning is not used anymore therefore the consumption of electricity decrease to 3.1 kWh/day of electricity while the gas remains at 6.0 kWh/day.

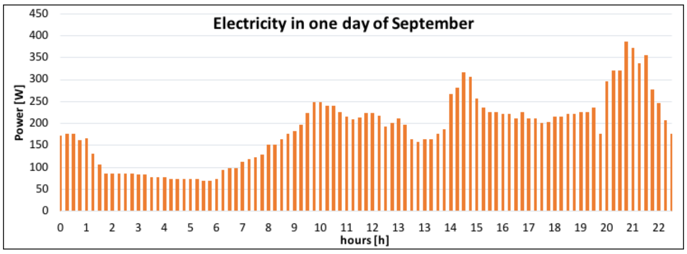

Figure 3.17: Electricity demand in one day of September

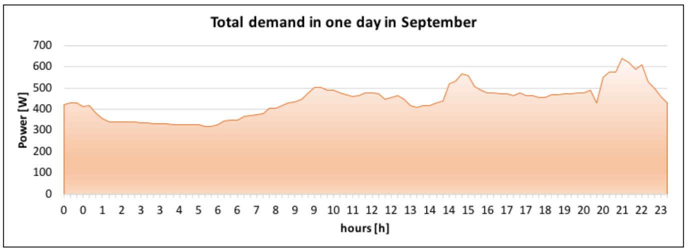

Figure 3.18: Total demand in one day of September

- October: 3.2 kWh/day of electricity and 6.2 kWh/day.

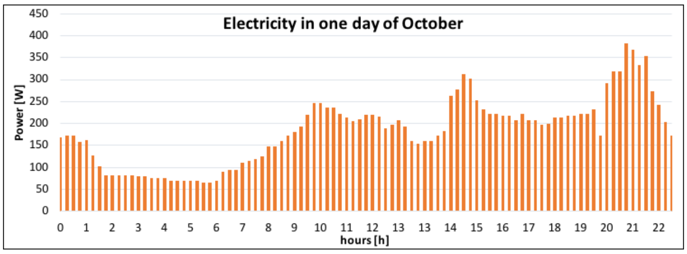

Figure 3.19: Electricity demand in one day of October

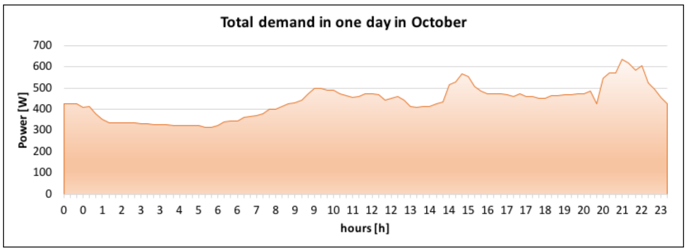

Figure 3.20: Total demand in one day of October

- November: 3.5 kWh/day of electricity and 6.2 kWh/day.

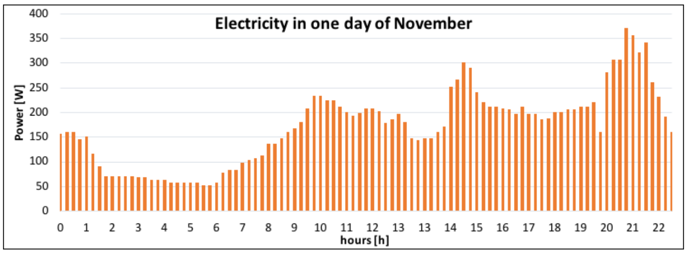

Figure 3.21: Electricity demand in one day of November

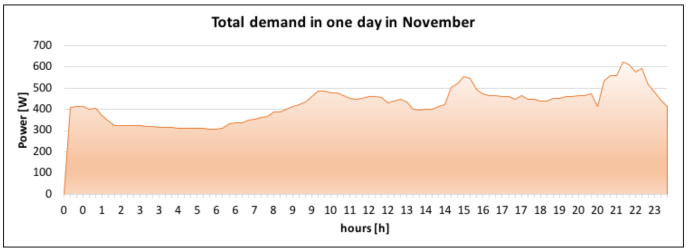

Figure 3.22: Total demand in one day of November

- December: 3.9 kWh/day of electricity and 6.2 kWh/day.

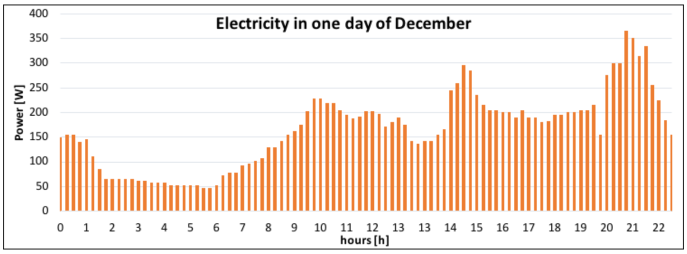

Figure 3.23: Electricity demand in one day of December

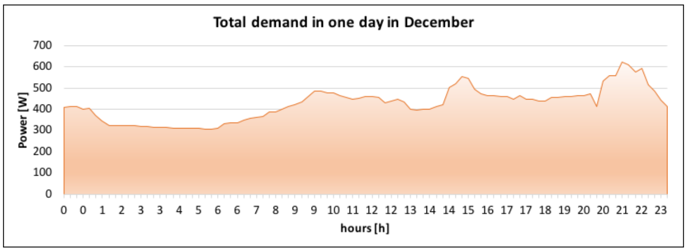

Figure 3.24: Total demand in one day of December

3.3.2 Consumption of the school

The school considered is a middle school and its annual consumption are known: 60000 kWh/year of electricity and 541 kWh/year of gas.
Using a research conducted in New York in 2016 regarding a solar project for infrastructures [23], a daily profile of load was provided and used to create the percentages of energy used in one day. The expected trend is different from the one previously seen about the private building, since the demand is mostly during the morning and early afternoon, when the activities occur.
The percentages among the day were then multiplied to the power requested in one exemplary day for each month.
Gas consumption aside, the consumption of a school tends to be similar every day because of the appliances used. Therefore, starting from a global data of electricity over one year, this was divided into 230 days of activity (school days and days for other activities) obtaining a daily value of energy requested.

$$E_{daily} = \frac{60000}{230} \quad [\frac{\text{kWh}}{\text{day}}] \tag{3.3}$$

For each month the daily consumption has been then multiplied for the activity days of that same month. Moreover, with the same procedure the gas consumption have been added considering 120 winter days.

$$E_{daily,gas} = \frac{541}{120} \quad [\frac{\text{kWh}}{\text{day}}] \tag{3.4}$$

As before, the graphs from Figure 3.25 to Figure 3.35 show the relation Power-time, obtained by dividing the energy for the 24 hours a day.

- January: besides the first week of Christmas holiday, the month presents a high consumption due to the presence of the heating. 5217.39 kWh/month of electricity and 90.17 kWh/month of gas

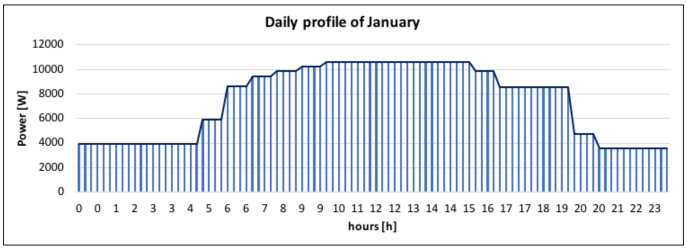

Figure 3.25: Daily profile of January

- February: 5217.39 kWh/month of electricity and 90.17 kWh/month of gas

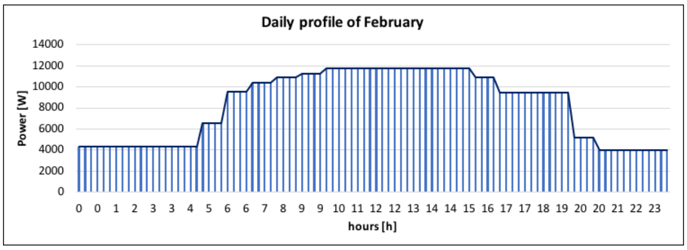

Figure 3.26: Daily profile of February

- March: 7043.48 kWh/month of electricity and 90.17 kWh/month of gas

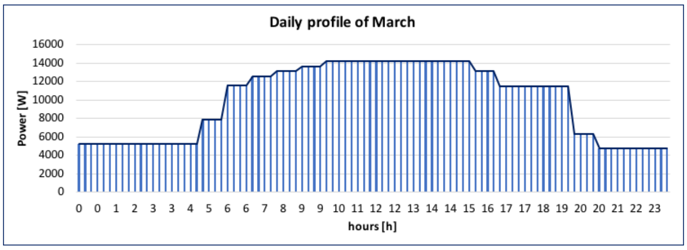

Figure 3.27: Daily profile of March

- April: the heating is not used anymore, therefore only the electricity is considered, 5478.26 kWh/month

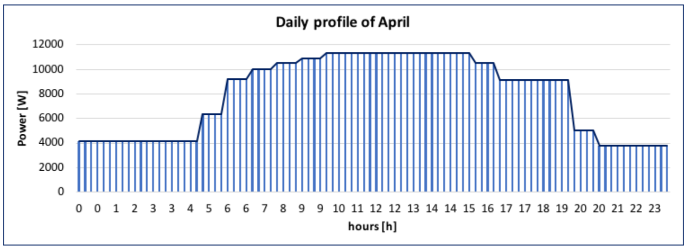

Figure 3.28: Daily profile of April

- May: 7043.48 kWh/month of electricity

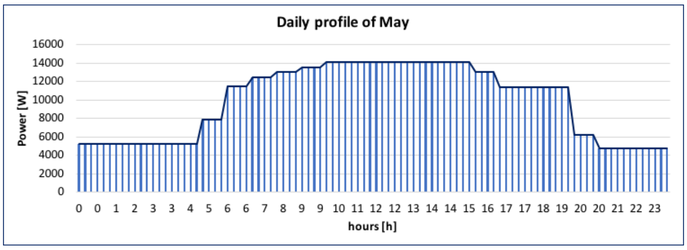

Figure 3.29: Daily profile of May

- June:4956.52 kWh/month of electricity

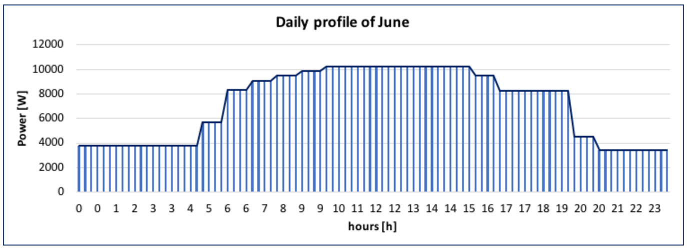

Figure 3.30: Daily profile of June

- July: 2608.70 kWh/month of electricity

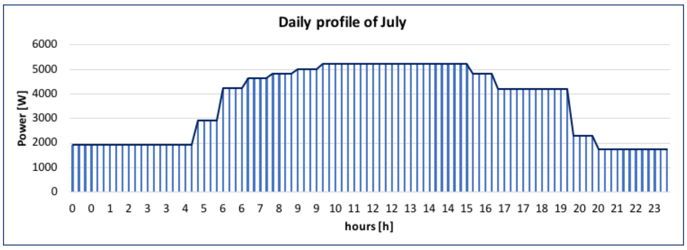

Figure 3.31: Daily profile of July

- August: the consumption is null because the school is closed
- September: 6782.61 kWh/month of electricity

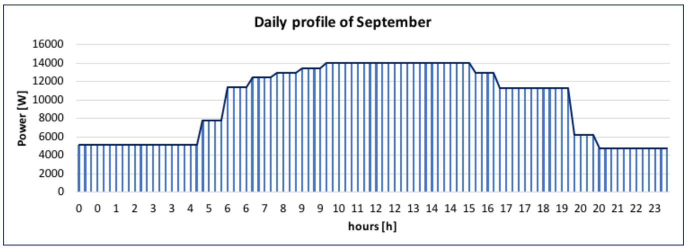

Figure 3.32: Daily profile of September

- October: 6521.74 kWh/month of electricity and 112.71 kWh/month of gas

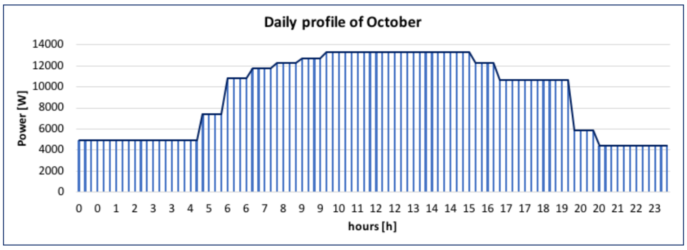

Figure 3.33: Daily profile of October

- November: 5217.39 kWh/month of the electricity and 90.17 kWh/month of gas

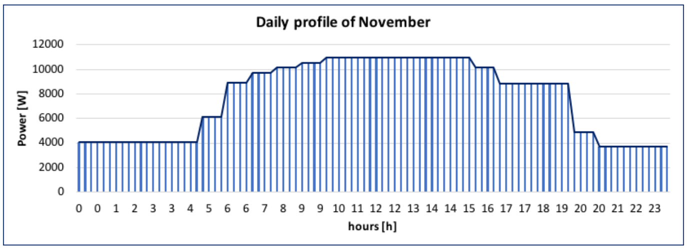

Figure 3.34: Daily profile of November

- December: 3913.04 kWh/month of electricity and 67.62 kWh/month of gas

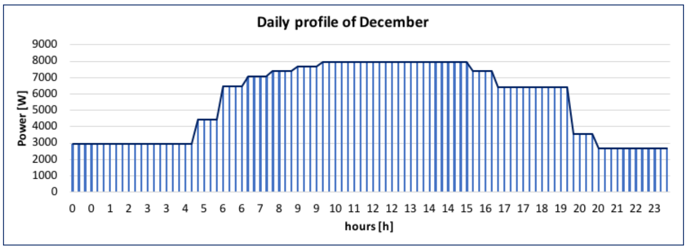

Figure 3.35: Daily profile of December

3.3.3 Overall consumption

After having defined the choices made to create the daily profiles, in the following section the overall demand of energy that will have to supplied by the photovoltaic system is shown.
For what concerns the private building, the load curve of only one apartment was described. Assuming that the building is composed of four identical apartments of 100 m^2 and assuming the presence of the elevator (10000 kWh/year), the resulting request is over the year is represented in Figure 3.36.

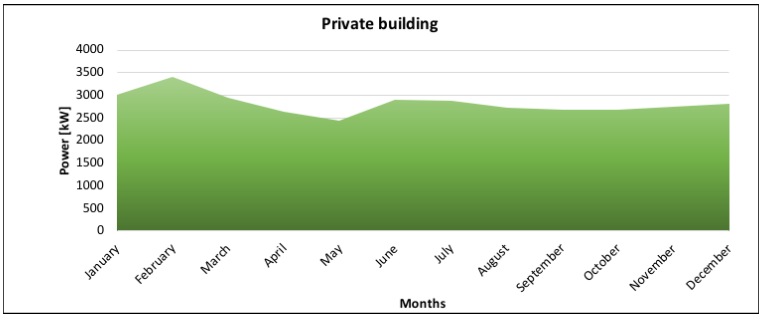

Figure 3.36: Yearly private building consumption

Adding this curve to the yearly demand of the school, the yearly overall consumption is represented in Fig. 3.37.

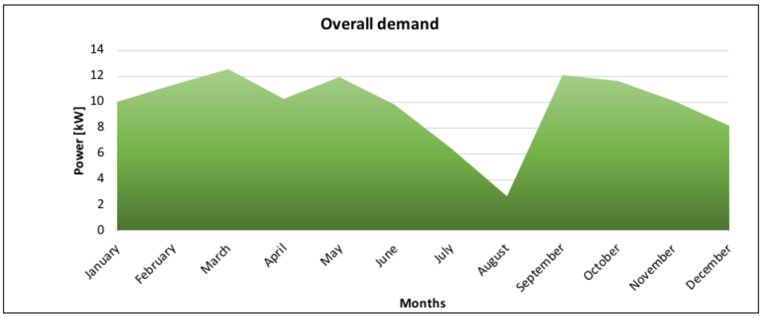

Figure 3.37: Yearly overall consumption

3.4 Production profile

The production of energy obtained by a photovoltaic system depends on the technology itself and on its location.
The solar plant will not be discussed in detail in this thesis, but the production profiles were needed to analyze the feasibility of the whole project. These information were found on the European Community Website in the section Photovoltaic Geographical Information System [24], which allows to estimate the production based on a set of choices that describe the size of the plant and where it has to be installed.
The starting point was choosing the technology of the panels, in particular the monocrystalline ones have been selected. They usually present a peak power of

230-245 Wp and an efficiency of 20%. The plant is roof integrated, so it has no tracking system, and assuming flat roofs both for the private building and the school, the whole roof can be exploited to reach a power plant of 70 kWp. The indicated power is a peak value, it still has to be deprived of the losses due to the plant itself and the losses due to the inverter, which are by default fixed at 14%, both these terms are taken into consideration by the simulator.
The site presents a latitude of 45.450 and longitude of 10.997 and based on this, the angle of orientation and inclination were optimized by the simulator itself. The angle of inclination is the angle of the panels with the reference to the horizontal plane; in Italy the expected angle is between 30 and 40 degrees and the simulator chose as optimal 38 degrees. The orientation angle is the angle of the panel with the reference to the south; the simulator chose as optimal 3 degrees.
The platform works serving itself of a database of solar radiation from 2016 called PVGIS-SARAH.
The overall production in one year amounts to 89027.02 kWh and it is divided among the months as the Figure 3.38 shows.

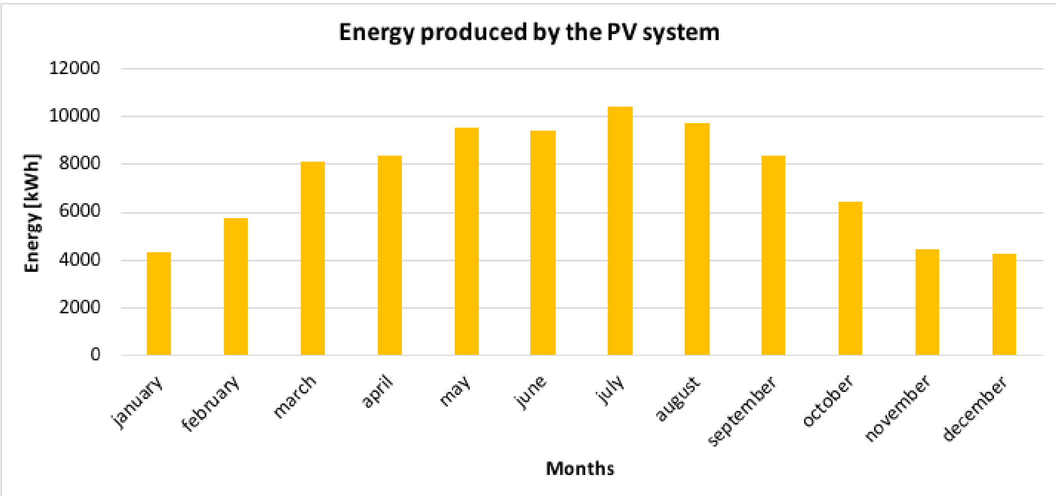

Figure 3.38: Yearly production of the PV system [24]

Month	Production [kWh]
January	4335.68
February	5730.25
March	8094.15
April	8357.69
May	9518.86
June	9404.17
July	10407.96
August	9718.57
September	8339.07
October	6446.01
November	4426.13
December	4248.48

Table 3.4: Monthly production of the PV system

3.4.1 Daily production

For what concerns the daily production, these profiles are not needed because in the simulation made through Simulink the input to the solar power system is the irradiance. All the irradiances are known through the European website that provides the irradiance curve of each month based on the intensity of the sun and the number of hours of light available.

3.5 Merging of production and consumption

In Figure 3.39 the overall consumption and production is merged in order to highlight the self-consumption, the storage of energy and the grid compensation when needed.

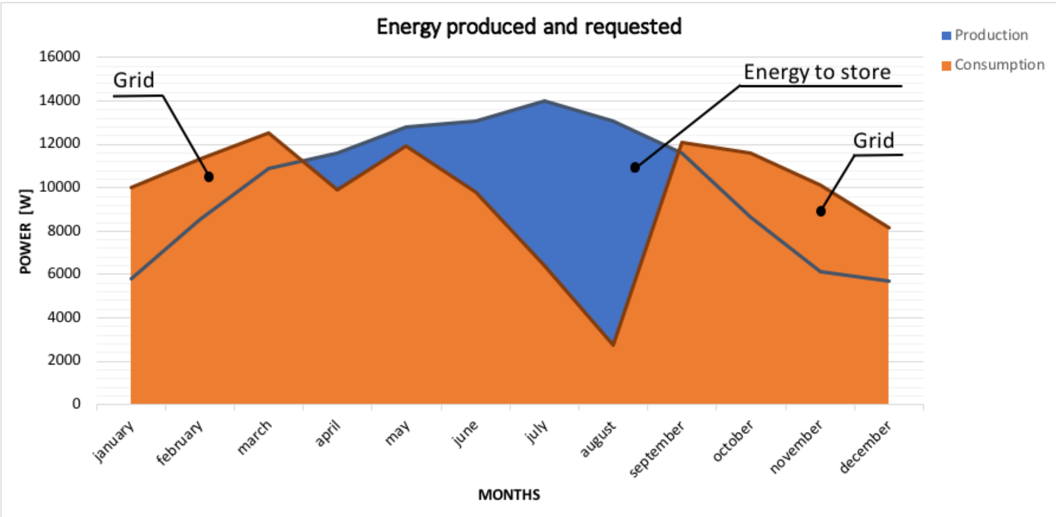

Figure 3.39: Overlaid of production and consumption

Chapter 4

Storage system

4.1 Storage systems

In order to favor a deep penetration of renewable energy sources, an efficient and sustainable storage system is mandatory.
The main concern regarding RES, such as solar and wind energy, is indeed their unavailability and non-controllability. The introduction of storage systems will help to control the resource and to reduce the waste of clean energy produced.
Over the years, lithium-ion batteries have been under spotlights, showing the best performances in terms of energy density. Nevertheless, these technologies are introduced pursuing sustainability, therefore it is important to dig and to understand how sustainable they really are. Sustainability has plural meanings, commonly nowadays it is linked to the environmental one, but the concept has to be taken into consideration in a wider perspective.
Firstly, as happened with the fossil fuel, we have to think in a future scenario in which the demand for the storage systems will increase drastically: from 185 GWh in 2020 to over 2000 GWh by 2030, predominantly because of the electrification of transports [25].
In order to rank its sustainability, the product must be studied in its totality, therefore from the extraction of the material, through the manufacturing processes and untill its disposal.
The main materials used in Lithium-ion batteries are lithium, cobalt and nickel, as

a substitute for cobalt. Lithium itself is not a scarce resource, its main controversy is related to the extraction process that requires a large amount of both water and energy. Cobalt raises concerns related to the working conditions such as violation of human rights and under-aged labor in the mines, which are for two thirds located in the Democratic Republic of Congo. Cobalt is necessary to accomplish the performance of nowadays lithium-ion based batteries, it is expensive and scarce. Cobalt if not handled properly can also be toxic. Further studies have demonstrated that nickel can be an alternative to cobalt, even though it could also face shortages in the long term [26].
Based on these considerations, it is clear how the future in storage system must not rely completely on metals, which are usually scarce, expensive and could lead to relevant environmental and social problems because of their mining.
Once the battery is used, its disposal is crucial in order not to harm the environment. The battery itself is flammable and must be treated responsibly at the end of its life because its degradation can lead to leaks of electrolyte. Even though technologies about recycling are moving forward, the economic driver suggests that in cases in which for example cobalt, which is precious and expensive, is not present mining can be less expensive than recycling[27].
The controversies mentioned above do not fulfill the principal aim of the thesis, which is the pursue of a project of self-consumption whose guide line is sustainability. Besides being the most efficient and performing battery on the market, other kinds of technologies are being developed for grid applications. In fact, the future demand in the storing energy industry can be satisfied only by introducing different possible technologies to adopt. In particular, the field of redox flow batteries appears to be very interesting.

4.2 Redox flow batteries

Flow batteries are a promising solution in grid-scale renewable energy storage. The energy conversion is based on the electrochemical reaction called redox, therefore through the oxidation and reduction that occur at the two electrodes, a flow of electrons is generated.
In the field of flow batteries, the attention is focused on the vanadium redox flow

battery. This technology solves the problem of irreversible cross contamination, since both halves of the cell are vanadium based. Usually the cross contamination of the two species, besides determining losses, is also irreversible. In this case, some contamination is present but it only leads to higher losses during the reaction and no permanent losses in terms of energy capacity [28].

4.2.1 Vanadium Redox Flow Battery

The technology was invented by Maria Skyllas-Kazacos at the University of New South Wales in the 1980s.
The overall system is composed of a cell containing the two electrolytes separated by a proton exchange membrane. Both halves of the cell are connected to an external tank in which the electrolyte is stored. The feature of having an external tank with the electrolyte, to be pumped inside the cell stack, is what defines the technology half way between being an electrochemical battery and a fuel cell.
The structure of the battery can be seen in Fig. 4.1.

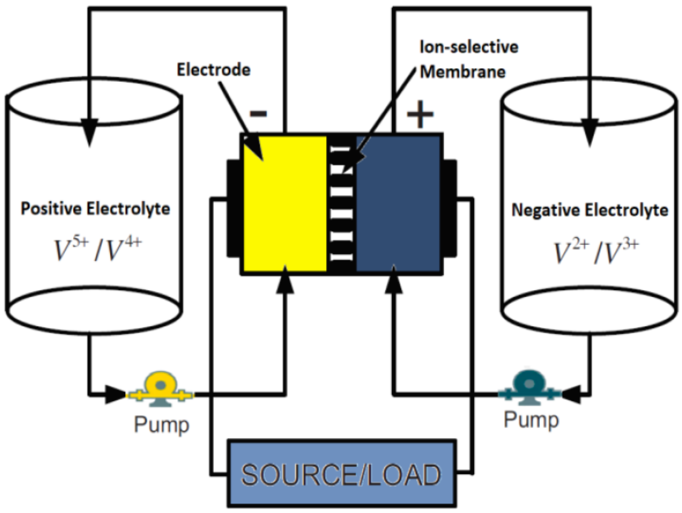

Figure 4.1: Vanadium redox flow battery [29]

The redox occurs involving the four possible vanadium oxidation state.
During the discharge in the anode, negative side, the oxidation reaction takes place, therefore the vanadium passes from its oxidation state 2+ to the oxidation state

3+. By losing one electron, the specie oxidizes itself.
The anodic reaction is shown in equation (4.1).

$$V_{aq}^{2+} \leftrightarrow V_{aq}^{3+} + e^{-} \tag{4.1}$$

On the positive side, cathode, the reduction takes place and the specie gains one electron going to its oxidation state 4+.
The cathodic reaction is indicated in equation (4.2).

$$VO_{2,aq}^{2+} + 2H^{+} + e^{-} \leftrightarrow VO_{aq}^{2+} + H_2O \tag{4.2}$$

In the meantime the flow of electrons is balanced by the diffusion of hydrogen protons by the proton exchange membrane that divides the two halves of the cell.
The overall reaction is:

$$V_{aq}^{2+} + VO_{2,aq}^{+} + 2H^{+} \leftrightarrow V_{aq}^{3+} + VO_{aq}^{2+} + H_2O \tag{4.3}$$

The Vanadium redox flow battery (VRFB) cells present a cell voltage of 1.26 V, an energy density of 27.87 $\frac{\mathrm{Wh}}{\mathrm{L}}$ [30] and an overall energy efficiency of about 85-90% [31].
An interesting characteristic that makes this technology suitable for grid-scale applications, is that, beside its role as storage system, it can participate in grid services. Firstly, the battery is able to decouple peak power and energy capacity since they are linked to two different features of the structure: the peak power is consequent of the voltage stack and the energy capacity depends on the size of the tank. Because of this and based on the battery's fast response, it is able to sustain the grid when surge power is requested.
In order to properly evaluate this technology and understand its penetration in the market, it can be useful to compare it with the technology nowadays most used, the lithium-ion battery.
Both secondary batteries present very different features that can make one more suitable for certain applications than the other.
Considering, for example, the Powerwall made by Tesla for domestic storage system, it is composed of plural cylindric lithium ion batteries (LIBs). When referring to

grid-scale systems applications able to sustain a renewable power plant, thousands of cylindric cells would be needed, and it is immediate to understand how limiting this can be. Even though these cells present the highest energy density, their capacity is still bounded to the amount of material within size. Related to this, VRFBs have the advantage to consist of a cell stack connected to external tanks of electrolyte, therefore, in order to adapt the system to a bigger application, bigger tanks are needed.
This aspect has a favorable outcome also in terms of costs. Lithium nowadays is competitive on the market, its cost indeed has fallen by 97% since 1991 [32]. Nevertheless, a request for doubling the energy storage capacity leads to doubling the price of the storage system itself. In case of VRFBs, even though prices are still higher, there is the possibility to just easily scale the tanks for higher request of energy storage. Therefore, VRFB has a high initial price but it decreases with the increase of the energy capacity.
For what concerns technical specifications such as lifetime, LIBs degradation over time determines a loss in capacity and a finite lifetime. In fact, even presenting a higher energy efficiency they are sensitive to high temperature that can damage them permanently. As already mentioned, by using the same species for both electrolytes in VRFBs, we are able to prevent permanent contamination and the lifetime expected is very high (20 years). Moreover, differently from the LIBs, the flow batteries can be left charged and discharged for long periods without being affected.
In a safety perspective LIBs are known for having risks of flammability and explosion, phenomena that cannot happen with VRFB because the electrolyte is an aqueous based, non-flammable solution with a high heat capacity. This feature is fundamental from the environmental point of view, as recycling and disposal is a crucial point for LIBs [33].

In the following paragraph one example of VRFB for grid-scale application is described.
The project is called Yadlamalka Energy, located in Neuroodla in South Australia and announced in December 2020 to realize the largest VRFB energy storage of 2 MW - 8 MWh AC for 20.3 million dollars.

The system incorporates a 6 MW solar photovoltaic array, and it works as storage system for the power plant and participates in the Frequency Control Ancillary Service for the grid.
Beside features as safety, scalability and non-degrading asset, what distinguishes this technology is its ability to discharge at a power of 2 MW for four hours.
This project is a consequence of a low carbon economy strategy implemented by Australia, that will lead to an estimated 4000 to 4300 tonnes of carbon dioxide saved per year [34].

Thus, being an innovative technology, relying on metal usually have environmental implications.
VRFBs have the advantage, differently from other commonly used batteries, to lack of potentially toxic metals, such as lead or nickel. Nevertheless, relying on metals can lead to environmental impacts due the extraction. Specifically, the extraction of vanadium for the VRFBs causes the pollution of topsoil and sediments in the mining areas[35].
Based on this, in Section 4.2.2 a new version of the redox flow battery, entirely organic, will be discussed.

4.2.2 Organic Redox Flow Battery

In April 2020 the University of South California published a study on a new technology for a redox flow batteries with organic materials [36].
In October 2020 the Sweden's Linkoping University claims to have designed the first all-organic redox flow battery; a cheap, recyclable and safe device [37].
The structure of the organic redox flow battery is shown in Fig. 4.2.

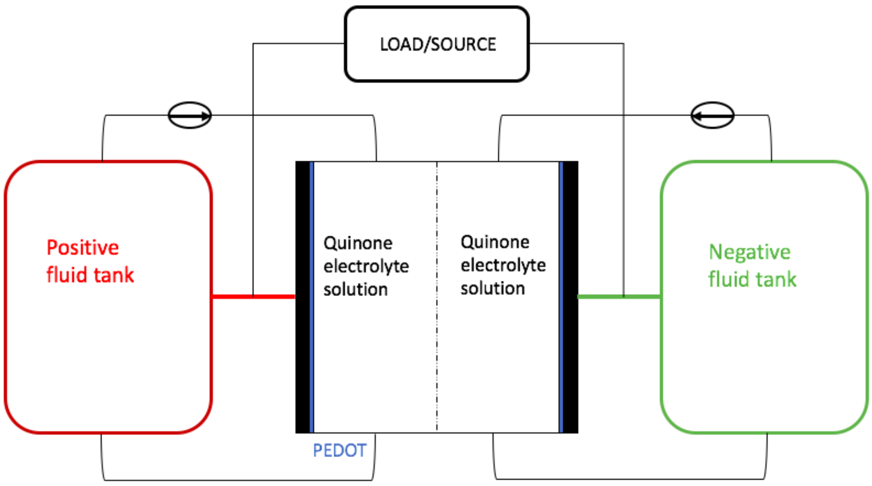

Figure 4.2: Organic redox flow battery

Both electrodes are based on an organic conducting polymer called PEDOT, specifically doped to transport ions. This polymer is the catalyst for the electrocatalysis that takes place between the positive and negative side and can be easily modified in order to promote the desired reaction. In particular, electrodes tend to be porous for creating an effective large specific interface between the electrode and the electrolyte.

The electrolyte is a water-based solution that consists of quinone molecules. Quinones are a derivative from the wood, they present a high discharge capacity and the possibility to be physically adapted. Quinone molecules have resulted to be highly compatible with the cited conducting polymer; in fact quinone itself shows a low electron conductivity, but once combined with the polymer, this helps the quinones switching from the oxidation and reduction state to create the flow of electrons and protons [38].

This mechanism called ion-selective electrocatalysis is what this new organic technology is based on [39].

Compared to the previous technology of redox flow batteries, VRFBs, this kind present a lower energy density. Nevertheless they are relevantly cheaper, completely recyclable and safe.

Germany energy group EWE Gasspeicher announced in July 2017 its plan on creating an organic redox flow battery in underground salt caverns, with a capacity able to supply one day demand of 75000 homes, by the end of 2023.
The battery is called brine4power and it is based on an experimental process developed at the Friedrich Schiller University in Jena. It consists of a metal-free technology which uses saline solution as electrolytes and organic polymers for the active sites, anode and cathode [40].
They are investigating on the possibility of filling two salt caverns, currently used for gas storage, each with a volume of 100000 cubic meter, to achieve a battery with a capacity up to 120 MW and 700 MWh.
The completion of this project can represent a turning point in the storage system field.

Chapter 5

Simulation

The overall system, composed by the solar panels, the load (house and school) and the power electronics needed to connect them, has been simulated with Simulink to track the power flow.
The simulation is made on a daily basis, considering three months as representative of a certain season, therefore hours of light, and different demand. In particular, the demand change based on when the heating or the air conditioning is on.
The followings months have been taken into account:

- January: representative of the winter season with few hours of light and a high consumption due to the heating
- May: no heating or air conditioning are used and the production from the solar panels increases
- July: representative of the summer season with many hours of light and a high consumption due to the air conditioning

The group of buildings have three options for being supplied, therefore three main paths have been simulated:

- Main path that connects the PV panels to the complex of buildings
- Storage path connected to the group of buildings
- Connection to the grid of the group of buildings as last option in case of non availability of renewable energy

5.1 PV - load

The main path is the one connecting the PV panels to the load through power electronics components that adapt and convert the electrical quantities.
In Figure 5.1 the block scheme summarizes the simulated connection.

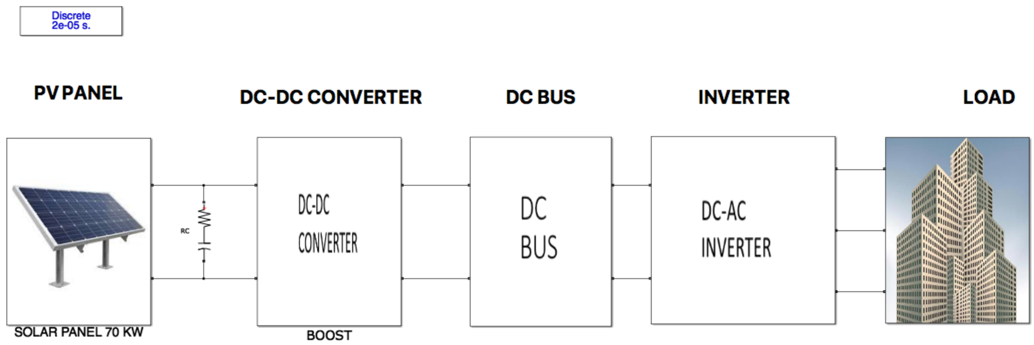

Figure 5.1: Simulink main path block scheme

Every component will now be described as it has been simulated.

5.1.1 PV panels

In the Simulink library the PV panels are present as one block in which it is possible to choose the technology of the cells and their organization into series and parallel structures.
Thanks to the energy profile analysis we know that the power to size the solar plant is 70 kW_p (peak power). The chosen technology is the monocrystalline cell because of its advantage in dimension, in fact they are normally used when the available surface might not be enough with reference to the demand.
Simulink offers a wide choice of different kinds of cells, and the selected one is the PANASONIC-ECO-SOLUTION CANADA PE320M-BBB for its performance and dimension. Each module presents 72 cells with an overall area of 1.96 m^2. In Table 5.1 the main electrical characteristics per module are listed.

Electric dimension	Value
Maximum power	319.68 W
Open circuit voltage	45.35 V
Voltage at maximum point	37.0 V
Short circuit current	8.96 A
Current at maximum point	8.64 A
Shunt resistance	1002.06 Ω
Series resistance	0.35 Ω

Table 5.1: Electric characteristics of the PV module PANASONIC-ECO-SOLUTION CANADA PE320M-BBB

In order to reach the peak power requested, the plant is organized into 22 parallel strings N_p, responsible for the overall current, and 10 series strings N_s, responsible for the voltage.
Figure 5.2 shows a schematic representation of the PV arrays:

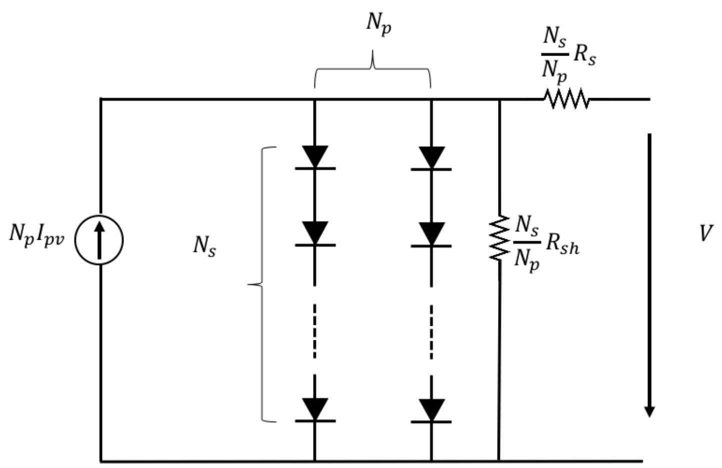

Figure 5.2: PV panels scheme

Based on the chosen organization we can conclude that the overall open circuit voltage and short circuit current are:

$$V_{oc,tot} = V_{oc} \cdot N_s \tag{5.1}$$

$$I_{sc,tot} = I_{sh} \cdot N_p \tag{5.2}$$

The block requires two inputs: the irradiance in W/m^2 and the temperature. For what concerns the temperature we can suppose the cells to work constantly at the standard temperature of 25 °C.
For what concerns the irradiance, a 24 hours table is provided through the signal builder block, indicating the irradiance at each hour. These data were obtained using the European website that bases itself on the database PVGIS-SARAH from 2016, once the exact location of the power plant is given (45.450,10.997) [24].
Once set the basic parameters, Simulink plots the $I-V$ and a $P-V$ graphs corresponding to different values of irradiance.
In Figure 5.3 the curves corresponding to the standard condition (1000 W/m^2, 25 °C) and worst condition (50 W/m^2, 25 °C) are presented:

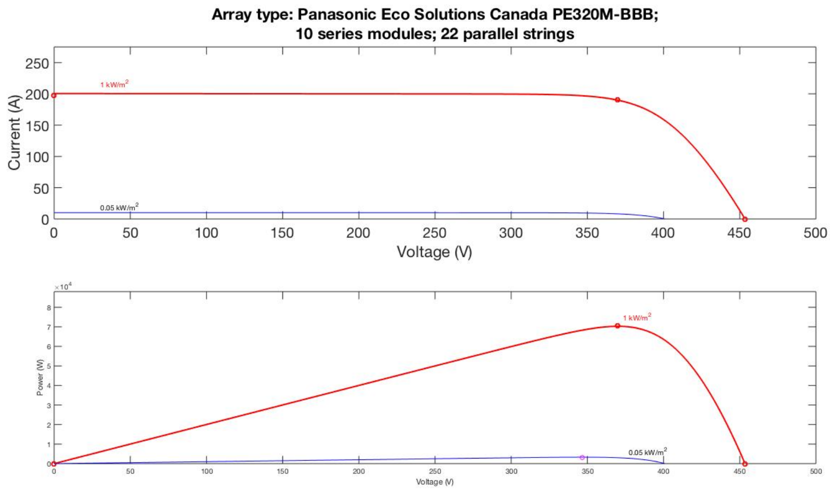

Figure 5.3: I-V and P-V graphs

The dimension related to the two considered conditions are the following:

- Standard condition 1000 W/m^2 at 25 °C
  V_{mps}=370 V
  I_{mps}=190.1 A
  P_{mps}=70330 W

- Worst condition 50 W/m^2 at 25 °C
  V_{mpw}=346.8 V
  I_{mpw}=9.5 A
  P_{mpw}=3294 W

Right after the PV panels a DC-DC converter is required to adapt the voltage that enters the inverter.

5.1.2 DC-DC converter

The DC-DC converter chosen is the Boost Converter which is a static converter that steps up the input voltage.
As shown in Figure 5.4, it consists of two semiconductors, an IGBT controllable switch, a diode, an energy storage element, which is the inductor, and a C filter to reduce the voltage ripple. Both semiconductors are assumed ideal since losses have not been analyzed.

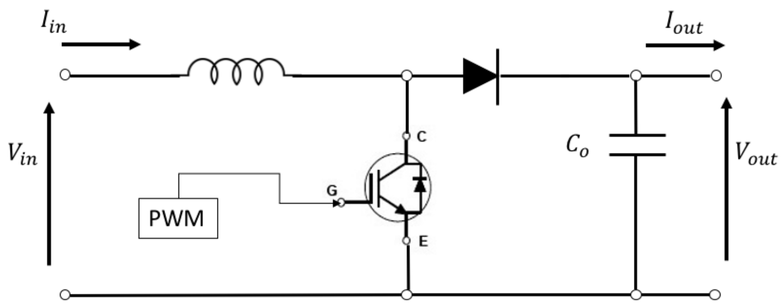

Figure 5.4: DC-DC converter

The IGBT transistor receives a control signal provided by a pulse width modulation generator, based on the duty cycle that the MPPT control (Maximum Power Point Tracking) computes. This control technique will be presented in the next paragraph.
For what concerns the design of the filter, it is important to define the mode in which the converter operates. The design has been made in CCM (continuous current mode) in order to have a better controllability.
Moreover, the sizing is consequent to considering the input voltage equal to the

panel voltage in the standard condition, and an output voltage that has to be greater than the final one at the load. Therefore, the assumed parameters of the converter are shown in Table 5.2:

Parameter	**Symbol**	**Value**
Switching frequency	f_s	10 kHz
Input voltage	V_{in}	370 V
Output voltage	V_{out}	400 V
Ripple current	Δi	10 % I_{out}
Ripple voltage in	Δv_{in}	1 % V_{in}

Table 5.2: Boost converter parameters

In order to define the minimum inductance value to ensure CCM, we need to define the two conditions in which the converter operates.

- Mode ON t_{ON}: the IGBT is conducting and the Diode is open. The inductor's current is ramping linearly and the voltage is equal to the input $V_L = V_{in}$
- Mode OFF t_{OFF}: the IGBT is open and the Diode is conducting. The inductor's current is decreasing because the inductor is discharging and its voltage is equal to $V_L = V_{in} - V_{out}$

In steady state the time integral of the voltage of the inductor must be zero, therefore:

$$V_{in} \cdot t_{ON} + (V_{in} - V_{out}) \cdot t_{OFF} = 0 \tag{5.3}$$

By dividing both sides by T_s the duty cycle appears in the definition

$$V_{in} \cdot D + (V_{in} - V_{out}) \cdot (1 - D) = 0 \tag{5.4}$$

We are now able to determine the relationship between input and output:

$$1 - D = \frac{V_{in}}{V_{out}} \tag{5.5}$$

The inductor is the energy storage element that requires the continuity of the current and that filters the ripple set at 10 %.

In the two mode state the current assumes these two different values:

$$I_{max} = \frac{V_{in} \cdot D \cdot T_s}{L} + I_{min} \tag{5.6}$$

$$I_{min} = \frac{V_{in} - V_{out} \cdot (1 - D) \cdot T_s}{L} + I_{min} \tag{5.7}$$

Starting from the equation (5.6), the ripple current $\Delta i = I_{max} - I_{min}$ must be greater than zero to ensure CCM. Therefore the minimum inductance is:

$$L_{min} \geq \frac{V_{in} \cdot D}{f_s \cdot \Delta i} \tag{5.8}$$

It is adequate to choose a value that is ten times greater than the minimum computed:

$$L = 10 \cdot L_{min} = 4.2 \quad \text{mH} \tag{5.9}$$

For what it concerns the design of the capacitor, the equation (5.10) is used:

$$C_{min} \geq \frac{I_{out} \cdot D}{f_s \cdot \Delta v_{out}} \tag{5.10}$$

Once again, this is the minimum value expected but in this case the final value has been chosen looking at the standard values of capacity, therefore C=4700 μF.
In order to eliminate the ripple from the voltage in output at the switching frequency, the cut frequency of the filter must be at least ten times lower. Based on the values obtained, we can verify this condition:

$$f_s > \frac{10}{\sqrt{LC} \cdot 2\pi} > 1 \quad \text{kHz} \tag{5.11}$$

For this particular application it has to be mentioned that the input voltage cannot be constant because dependent on the available energy source, therefore the output voltage fluctuates, and so does the duty cycle. For this reason it is recommended to place another capacitor at the input in order to smooth the voltage ripples produced by the non linearity of the voltage characteristic of the PV panel.

$$C_{min,in} \geq \frac{V_{in} \cdot (1-d)}{8 \cdot L \cdot f_s^2 \cdot \Delta v_{in}} \tag{5.12}$$

Once again, a standard value of capacity has been chosen equal to C_{in}=1000 μF. The overall scheme is shown in Figure 5.5.

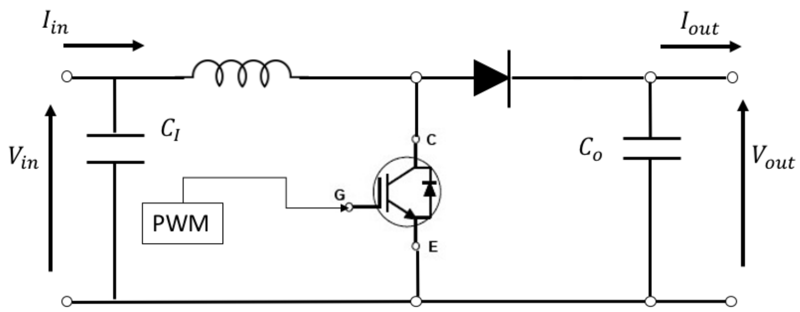

Figure 5.5: Boost converter

Once the design of the electric elements is done, the control technique of the IGBT must be implemented, taking care of the fluctuation of the input voltage. Among the day the sun moves and the solar radiations striking the arrays decrease. In fact, the input is represented by a range of possible voltages and powers:
P [W]: [0, P_{max}]
V [V]: [0, V_{oc}]
Especially with roof mounted panels, that cannot track the sun, a control technique called MPPT is used because it enables to increase the electricity generation up to 30 %.
Matlab has a pre-existent function of this algorithm that optimizes the output power of the panel by instantaneously tracking the maximum power working point. This technique is implemented by adjusting the duty cycle of the DC-DC converter. Multiple logics exist to implement the MPPT control, for this case the least complex has been chosen. The logic is called Perturbation and Observe (P & O); at every step the reference voltage is modified (perturbed) of a defined margin and the resultant power is observed [41].

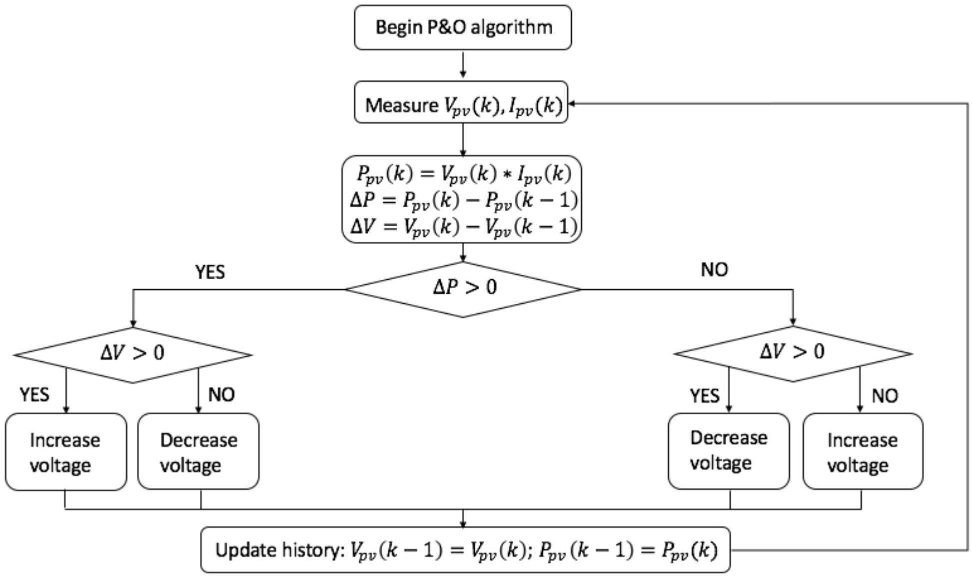

Figure 5.6: Flowchart of the Perturbation & Observe logic

For deciding how to perturb the system we need to know the open circuit voltage, equal to V_{oc}=453.5 V. Assuming a perturbation of 1 %, at each step we apply the following delta:

$$\Delta v = 0.01 \cdot 453.5 = 4.54 \quad \text{V} \tag{5.13}$$

The function returns a value of duty cycle, to impose to the converter, that enters in the PWM block, generating the signal for the gate channel of the IGBT. In the simulation the technique of control was not successful and at the end of the chapter Section 5.4.4 is dedicated explaining it.

Between DC-DC converter and inverter the DC bus is interposed. It is composed by an RL branch that simulates the connection line, and by a capacitor which represents the DC link. The DC link is essential in order to provide a more stable DC voltage at the input of the inverter. The simulation confirmed that in its presence the quality of the inverter's output voltage improves.

5.1.3 Three phase inverter

Knowing the peak power of the solar system, equal to 70 kW, the inverter has to be chosen. A single-phase inverter is suitable for application which peak power is 5 - 6 kW_p, whereas in this case a three-phase inverter is mandatory.
This component is used to convert from direct current to alternate current that the load requires.
The scheme is presented in Figure 5.7.

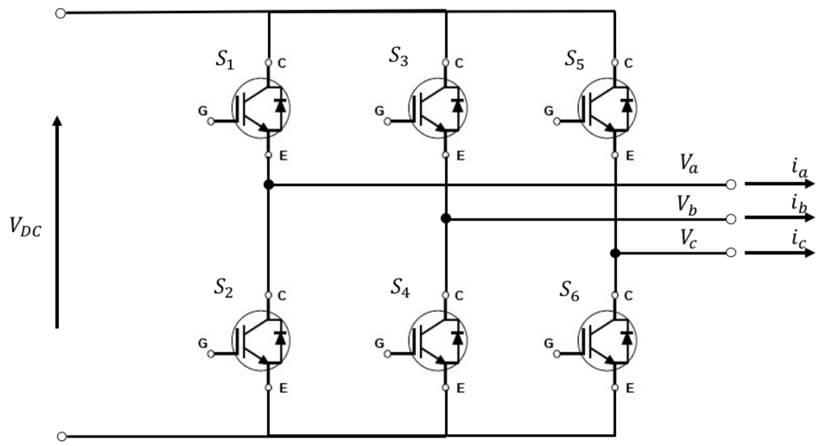

Figure 5.7: Inverter

In order to smooth the output current, obtaining a sinusoidal waveform at the nominal frequency of 50 Hz, a LCL filter is needed as shown in the scheme in Fig. 5.8.

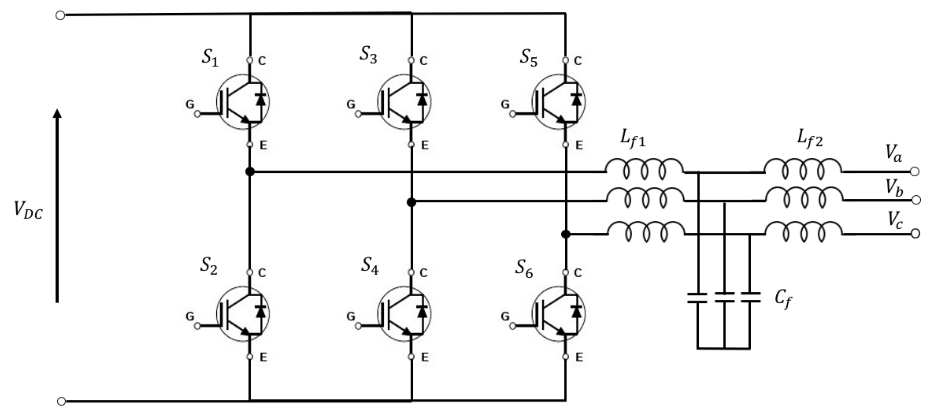

Figure 5.8: Inverter with filter

The filter's element has been sized following a procedure that takes into consideration the standards imposed [42].
The inverter chosen has a switching frequency of 10 kHz, a rated active power of 75 kW and apparent power of 100 kVA. The output waveforms must agree with the low voltage standard of 230 V_{rms} and a frequency of 50 Hz.
The first parameter to calculate is the filter capacity, which can be defined based on the requirements of the reactive power. The reactive power is generally set to 5 % of the rated active power S.
Each branch is responsible for one third of the total power, therefore:

$$P_b = \frac{P}{3} \tag{5.14}$$

The reactive power can be expressed as a function of the capacity:

$$Q = \frac{V_{out}^2}{\dfrac{1}{2\pi \cdot f \cdot C_f}} \tag{5.15}$$

Knowing that $Q = 0.05 \cdot P_b$, the capacity is:

$$C_f = \frac{0.05 \cdot P_b}{V_{out}^2 \cdot 2\pi \cdot f} \tag{5.16}$$

Using the equation (5.16), the resultant value of the filter inductance is 100 μF. For what is concerns the inductance, firstly we need to calculate the basic impedance based on the rated apparent power of the inverter ($S_b = S/2$):

$$Z_b = \frac{V_{out}^2}{S_b} \tag{5.17}$$

In accordance to the standards IEEE 519-1992, the maximum value of inductance, sum of the two filter inductances, has to be less than 10 % of the basic value, obtained through the basic impedance:

$$L_t = 0.1 \cdot \frac{Z_b}{2pi \cdot f} \tag{5.18}$$

We can consider the inductances equals, therefore:

$$L_{f1} = L_{f2} = L_{max}/2; \tag{5.19}$$

At last, the resonance frequency must be checked, it has to be at least ten times lower than the switching frequency, therefore approximately 1000 Hz.

$$f_{res} = \frac{1}{\sqrt{L_t \cdot C_f}} \tag{5.20}$$

The condition is not satisfied and through the simulation the output curve of the inverter present some noise. After many attempts, the inductance L_t has been multiplied by a factor of 30, reaching the value of 45.8 mH in order to remain within the frequency limits and to achieve a smooth sinusoidal output.

Each IGBT/Diode receives a PWM control signal at the gate that defines its state. As usual, the control is implemented on the (d,q,0) reference axis as two parallel channels in which the current wants to be maximized on the d-axis, responsible for the active power, and minimized on the q-axis, responsible for the reactive power.
First, an error is created between the voltage at the DC link (output of the boost converter) and the reference that is assumed at 450 V. The error enters in the PI

regulator, which is triggered only when the voltage at the DC link is higher than the reference to avoid a bad regulation when there is no power available (low solar energy available). The output is a reference value for the current on the d-axis. The values of the PI controllers were chosen based on the experience, many simulations were done. For what concerns the PI used for the voltage control its output is the first required to complete the control, therefore its sample time is set to T_s times 20. The gains are set to:

- k_p=0.15
- k_i=80

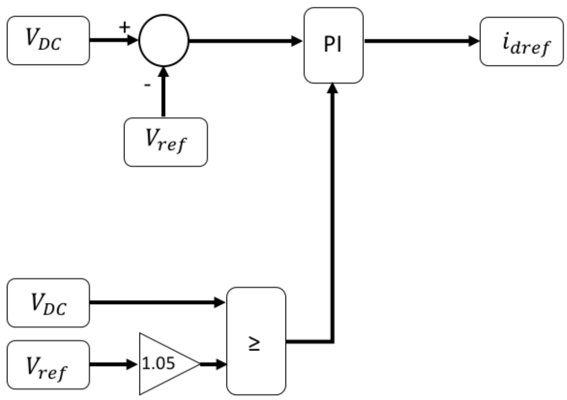

Figure 5.9: PI for the voltage control

In order to regulate the current on the two channels, the measured three-phase current I_{abc} has to be transformed and referred to the (d,q,0) reference system.

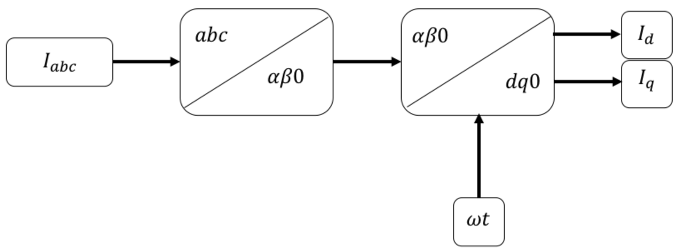

Figure 5.10: Transformation of the I_{abc}

The angle used in the transformation is obtained starting with the value of the three-phase voltage measured at the output of the inverter and through a Phase Locked Loop block (PLL).
Known the value of the real current flowing in the (d,q,0) reference, the control on the two channel can be implemented. For each channel the following values of gain were used for the PI, in particular:

- PI on the d-axis:
  - k_p=0.005
  - k_i=1
- PI on the q-axis:
  - k_p=0.01
  - k_i=1

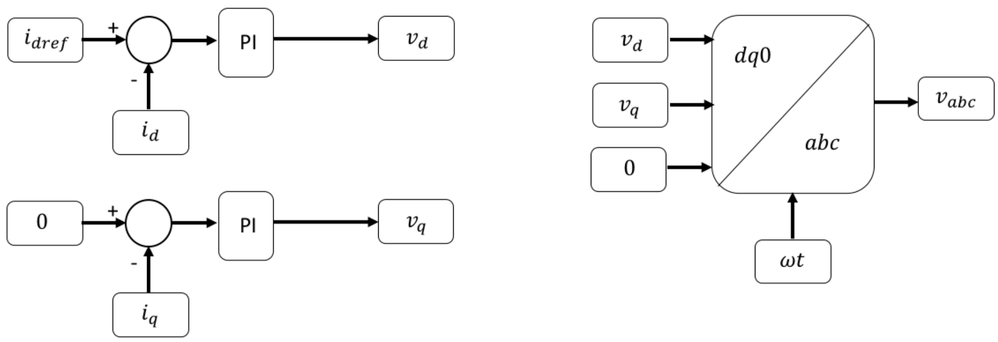

Figure 5.11: Block diagram for the control of the current

As shown in Fig. 5.11 the q channel receives a reference which is zero because we want the d dimension to be maximized, since it is the one responsible for the active power.
The voltage value is then converted into six PWM signals, commanding six switches, by comparing the voltage given by the control with a triangular waveform which period is $T = \dfrac{1}{f_{sw}}$.

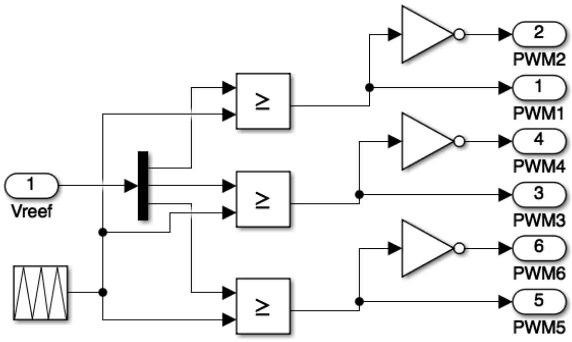

Figure 5.12: Simulink scheme for the PWM generator

5.1.4 Load

The load is representative of the overall consumption.
Both private building and school are single phase loads; the three phases in output of the inverter or the substation are normally used each one for supplying a different load. By considering the overall power consumed, the load is represented by one grounded three-phase RLC.
The load identifies the power meter, knowing that each apartment requires a rated power of 4.5 kW and the school a rated power of 20 kW.
For the grounded three-phase RLC we specify the utility phase to phase voltage 400 V, the frequency 50 Hz, the active power and the reactive power which is set to 100 var either for the inductance and for the capacity.

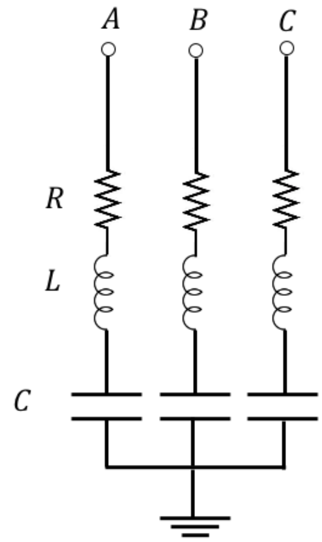

Figure 5.13: Three phase RLC load

5.2 Grid

The system is on-grid, meaning that in case of need for energy, whether the one supplied by the solar plant or the backup storage system is not enough, it can be required from the public grid.
The grid has been modelled as a source of 20 kV connected to a transformer, simulating the substation, that steps the voltage to 230 V_{rms}, value of phase to ground voltage. Moreover, the line of 1 km is considered through its "pi" representation.

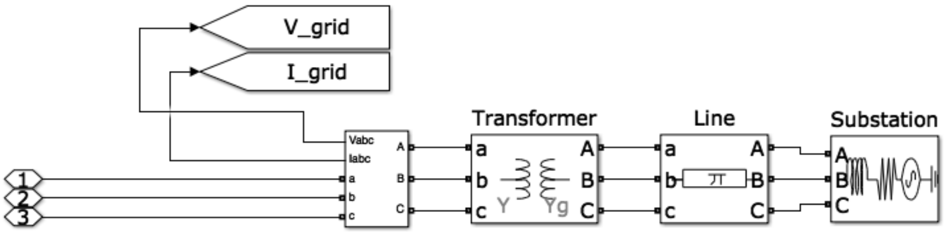

Figure 5.14: Simulink grid representation

Usually after the point of connection there is a pole transformer that converts the output into single phase, since residential loads are all single phase. As already mentioned in the simulation the load is a three phase load, therefore there is no need for the transformer.

5.3 Storage system - load

We have dedicated Chapter 4 to the storage system topic in order to acquire a general framework regarding the technologies most used for storing electricity. In particular, there has been a focus on the redox flow batteries, being an interesting alternative to the lithium-ion based batteries.
In Section 5.3.1 the electrical model of the battery is discussed and so are the power electronics needed for its connection to the load.

5.3.1 Battery

Researches, as the one conduced in the University of South California and in the University of Linkoping, have opened the possibility to create a total organic redox flow battery.
Since the organic configuration is not on the market yet, it is difficult to find the right parameters to represent the materials. Moreover, the available representations of batteries in Simulink do not describe properly the structure of the redox flow battery, which distinguish itself for having external tanks of electrolyte that is pumped inside the cell stack. Therefore, in order to represent the structure of the

battery as most accurate as possible, an electric discharge model of the vanadium redox flow battery is used.
The model was created and published in a scientific article written by Ankur Bhattacharjee and Hiranmay Saha [43]. Starting from this, the parameters were then adapted based on the ones employed in a study conducted in the University of Transilvania [44].
In particular, in Table 5.3 we can find the most relevant parameters used.

Parameter	**Value**
Number of series cell stack	39
Power rating	5 kW
Energy content	20 kWh
Output voltage range	42-56 V
Current output	112 A
$R_{reaction}$	0.045 Ω
$R_{resistive}$	0.02 Ω
$R_{parasite}$	13.889 Ω
$C_{electrode}$	0.15 F

Table 5.3: Battery parameters

The model includes three main blocks:

- Cell voltage stack
- SOC estimator
- Flow pump

For what it concerns the cell voltage stack, for the single cell the calculations are based on the Nernst potential equation.

$$E_{stack} = n \cdot (E_{cell_{at50\%SOC}} + \frac{2RT}{F} \cdot ln(\frac{SOC}{1 - SOC})) \tag{5.21}$$

Where n is the number of series of cells, in our case 39, R is the universal gas constant (8.3144 $\frac{\mathrm{J}}{\mathrm{kmol}}$), T is the ambient temperature, F is the Faraday's number and the value of the voltage of the cell at 50 % of SOC is 1.39.

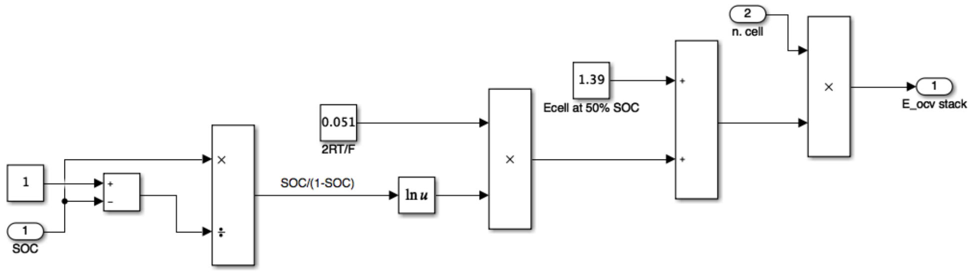

Figure 5.15: Simulink block scheme for the calculation of the stack voltage

The State of Charge (SOC) is the ratio between the current energy in the battery and the total energy capacity. The estimator has to be updated at every step following the equation:

$$\Delta SOC = I_{stack} \cdot V_{stack} \cdot X \tag{5.22}$$

Where X is the constant:

$$X = \frac{Time_{step}}{P_{rating} \cdot T_{rating}} \tag{5.23}$$

The redox flow battery is capable of discharging at its rated power for four hours, reason for which in the simulation the discharge is imperceptible.

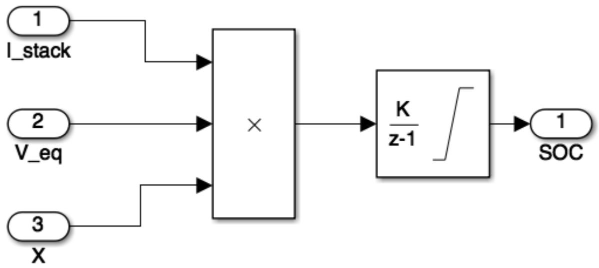

Figure 5.16: Simulink representation of the SOC estimator

At last, there is the block representing the pump and its electrolyte flow rate control. Its mathematical expression is:

$$Q = \frac{I_{stack}}{N \cdot SOC} \tag{5.24}$$

where N is the electrolyte capacity, equal to 1.6 $\frac{\mathrm{As}}{\mathrm{cm}^3}$.

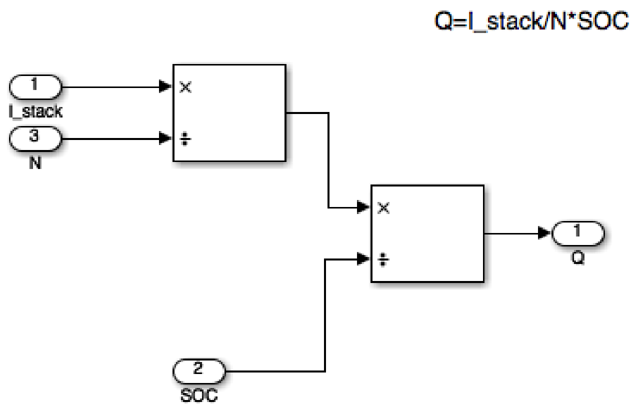

Figure 5.17: Simulink representation for the calculation of the flow rate of the pump

In order to simulate its operation, once the voltage stack is calculated the value is given to a controllable DC voltage source. The source is placed in series with the $R_{reaction}$ to simulate the charge transfer resistance, and in parallel to a capacitor $C_{electrode}$ that defines the capacitive coupling between the two electrodes. Moreover, the $R_{resistive}$ is present to identify the electrolyte solution resistance.
Having two pumps, one for external tank, leads to an additional terms of losses that can be represented by a controlled current source having the value of the flow rate, in parallel with the $R_{parasitic}$. The overall model can be seen in Figure 5.18.

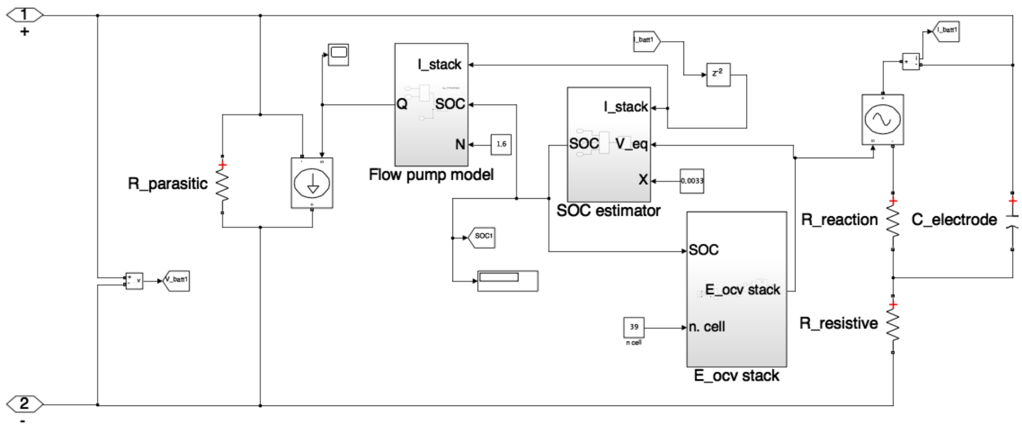

Figure 5.18: Simulink battery model

The battery is used when the solar panel is not working, therefore, in the evening and at nighttime. We can consider a lower load, corresponding only to the meters of the residential building since the school is closed.
For supplying a load of 18 kW, the described battery is not enough. In reality we know that the advantage of this technology is the possibility to be easily scaled. Nevertheless, since the values come from the design of a 5 kW battery, in the simulation we can put four blocks representing the battery's stack in series in order to be able to sustain the power requested by the load.

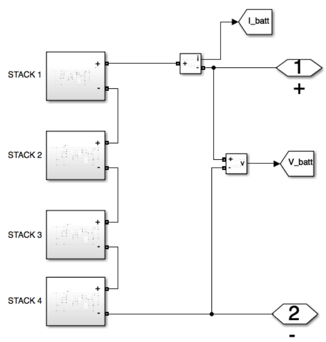

Figure 5.19: Simulink series of battery's stacks

5.3.2 DC-DC converter

The output voltage from the battery has to be stepped up to reach the domestic value of phase to ground voltage of 230 V_{rms}.
Therefore, a Boost converter is used and it has been sized following the same procedure seen in subsection 5.1.2.

Parameter	**Symbol**	**Value**
Switching frequency	f_s	10 kHz
Input voltage	V_{in}	168-224 V
Output voltage	V_{out}	400 V
Ripple current	Δi	10 % I_{out}
Ripple voltage in	Δv_{out}	1 % V_{out}

Table 5.4: Boost converter for the battery parameters

The voltage in input is constant, therefore to modulate the DC-DC converter a pulse generator is used with a set duty cycle and period.
The equations characterizing the converter are the followings:

$$d_b = 1 - \frac{V_{in}}{V_{out}} = 0.43 \tag{5.25}$$

$$L_{boost,b} = \frac{V_i \cdot d_b}{f_{sw} \cdot \Delta i} \tag{5.26}$$

The equation (5.26) returns a value that is the minimum acceptable to guarantee the CCM, a value ten times greater is used, equal to $L_{boost,b}$=19.6 mH.

$$C_{boost,b} = \frac{I_{out} \cdot d_b}{f_{sw} \cdot \Delta v_{out}} \tag{5.27}$$

The standard value chosen for the capacitor is 4700 μF.

The block is indicated in Figure 5.20.

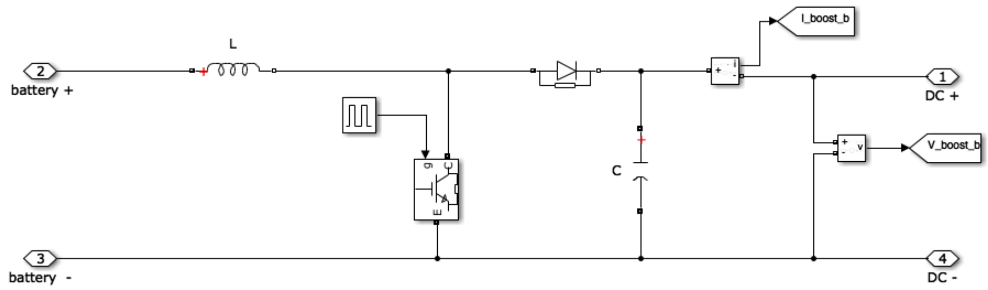

Figure 5.20: Boost converter

The battery to supply the load uses the same inverter described in Section 5.1.3. This is because in the simulation the two path work independently, therefore, there is no moment in which the load is supplied by the solar panels and the battery simultaneously.

5.4 Simulink

The simulation is in a discrete time framework with a sampling time of T_s=20 μs. For every component respectively the voltage and the current have been plotted. The solar panels follow the irradiance characteristic given as an input, therefore, the trends as expected is concentrated in the mid of the day, while in the night and early morning there is no production of energy.
Three months have been taken into consideration as being representative of three different situations during the year; January, May, July.
The whole system can be seen in Figure 5.21.

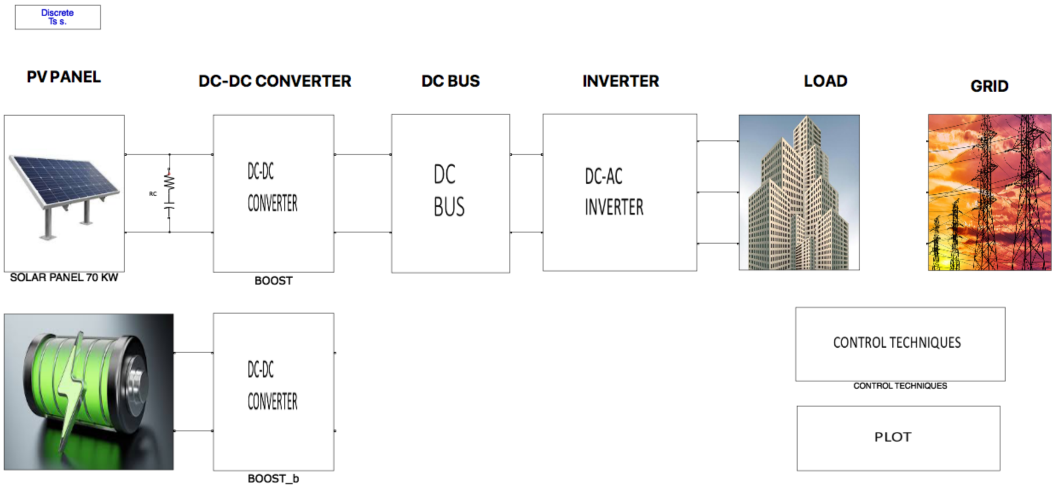

Figure 5.21: Simulink model

5.4.1 January

The PV panels receive the curve of irradiance shown in Figure 5.22.

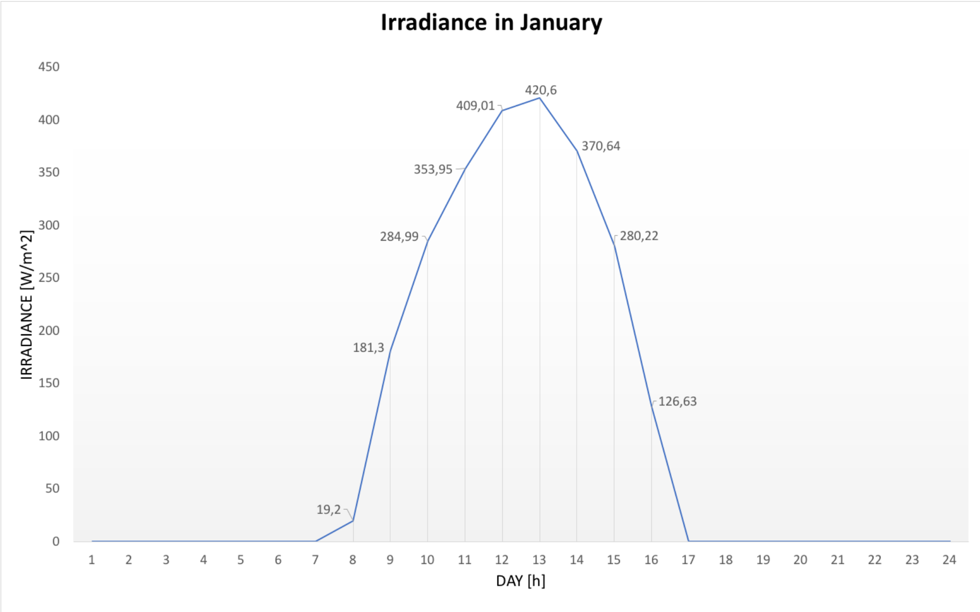

Figure 5.22: Daily irradiance in January

The energy balance results over the month:

- Consumption: 7459.45 kWh
- Production: 4335.68 kWh

$$\Delta E = E_{consumption} - E_{production} > 0 \tag{5.28}$$

The load requires approximately 42 % of energy from the grid.
In this case the storage system is not used because there is not a condition of over generation. Nevertheless, the are instants of over generation among the day in which even a small amount of energy stored can contribute to smooth the rapid demand that is requested from the grid instantaneously.
For each component the $I - t$ and $V - t$ characteristics on a daily basis are shown. Despite the solar panel is not producing energy, in the first instants of the simulation the characteristics are different from zero due to the fact that the capacitor inside the low voltage bus is initialized.

- PV output: the solar panel is supplying only during the hours of light which are from 8 am to 4 pm.

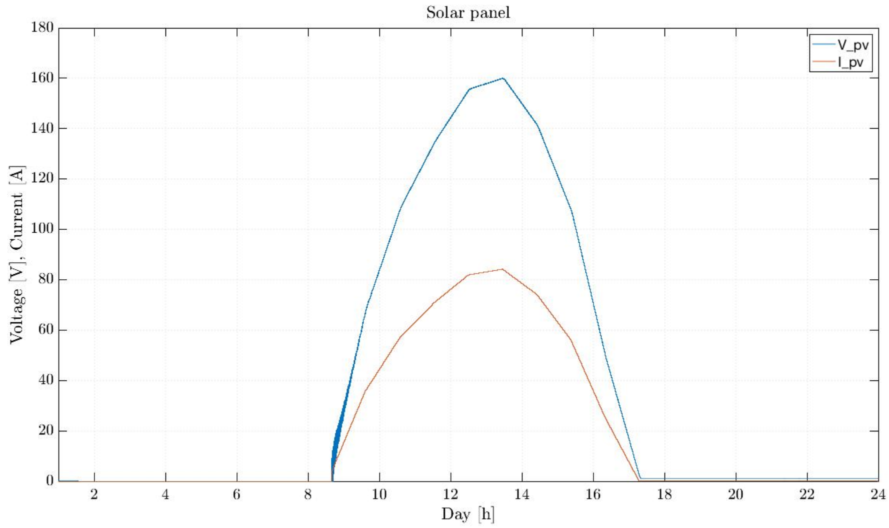

Figure 5.23: Simulink PV voltage and current

- Boost converter output:the boost converter steps up the voltage

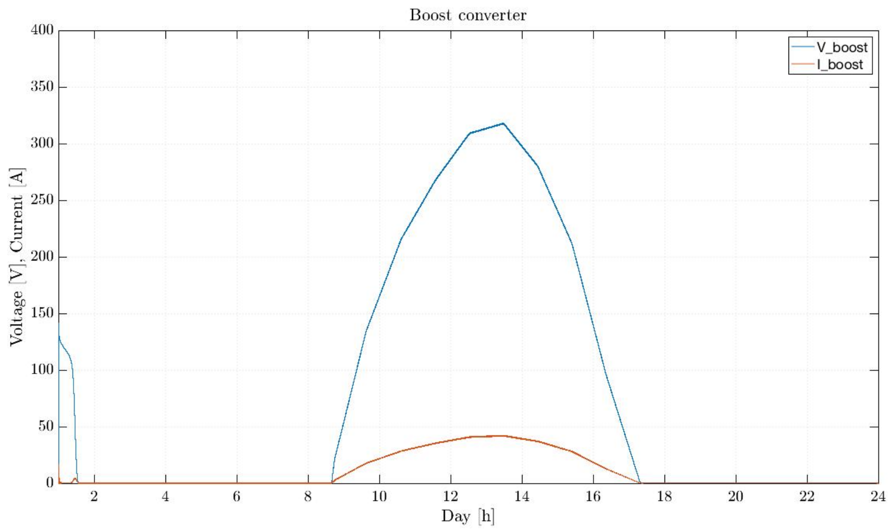

Figure 5.24: Simulink DC-DC converter voltage and current

- Inverter output: the inverter converts the DC signal into a three-phase sinusoidal one

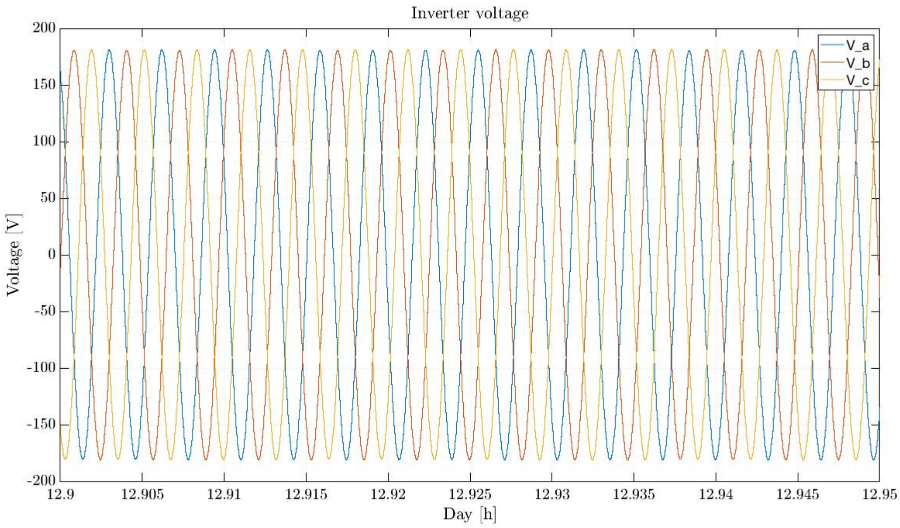

Figure 5.25: Simulink Inverter voltage

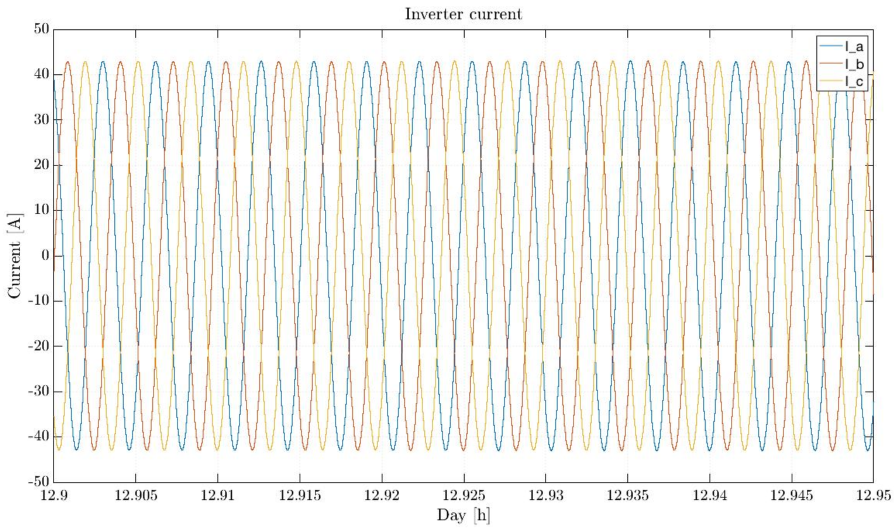

Figure 5.26: Simulink Inverter current

In terms of power, in Figure 5.27 the power provided by the solar panel and the one withdrawn from the load are plotted.

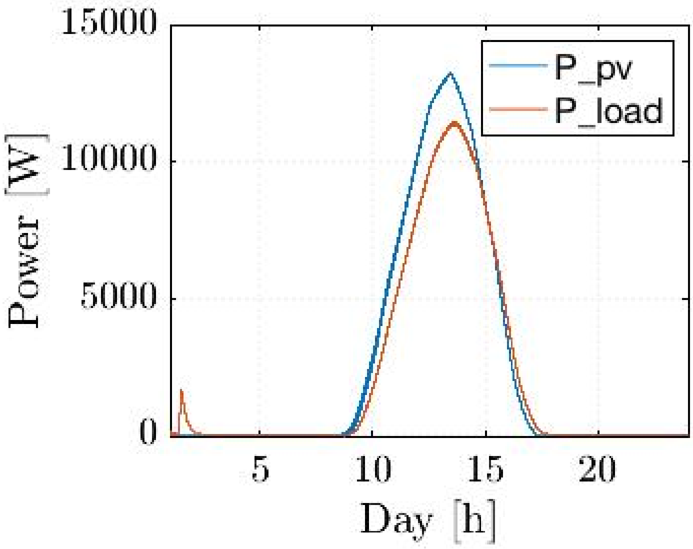

Figure 5.27: PV panel and load power

The load power is set to 38 kW and as we can see from Figure 5.27, the power provided by the PV panel is not enough for supplying our load.
Connecting the grid to the load, the resultant characteristics are the ones shown in Figure 5.28.

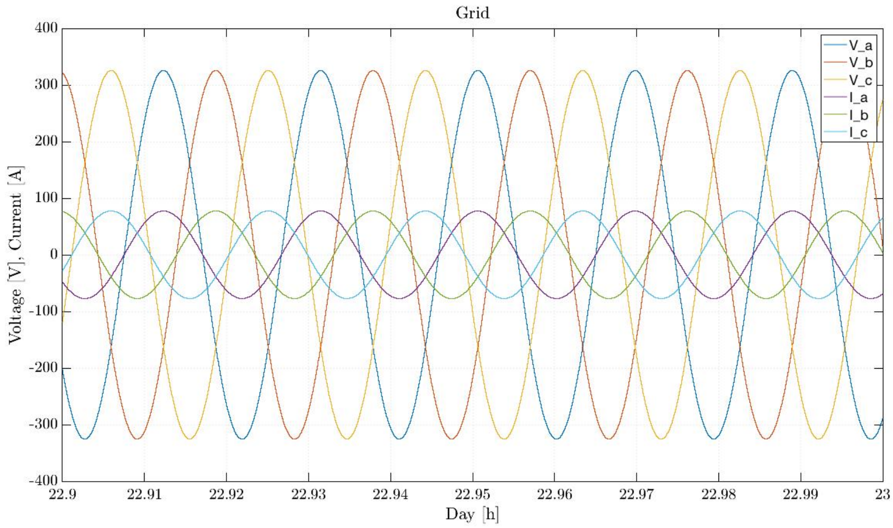

Figure 5.28: Simulink Grid voltage and current

Since the grid is needed in this situation, a solution could be storing the energy in order to let the battery help the grid when high peaks of power are required. Therefore, the winter months as January can be considered grid-dependent with the only difference that the rated power can be lowered due to the presence of the storage system. In fact, the storage system can be used as power curtailer, meaning that higher peaks of power than the rated one can be satisfied by the battery.
January is a month with high consumption due to the heating, therefore, therefore using the storage system to reduce the peaks of power gives benefit to the grid and to the consumers.

5.4.2 May

The PV panels receive the curve of irradiance shown in Figure 5.29.

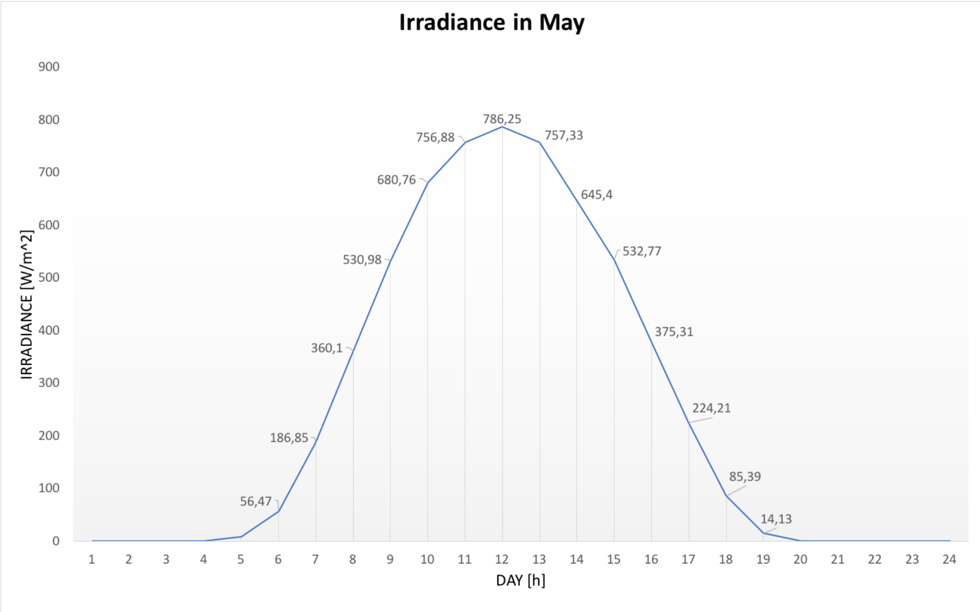

Figure 5.29: Daily irradiance in May

The energy balance results over the month:

- Consumption: 8867.45 kWh
- Production: 9518.86 kWh

$$\Delta E = E_{consumption} - E_{production} < 0 \tag{5.29}$$

The production from the solar panel is enough to fulfill the load demand and to store energy.

For each component the $I-t$ and $V-t$ characteristics on a daily basis is shown.

- PV output: the solar panel is able to supply from 5 am to 7 pm.

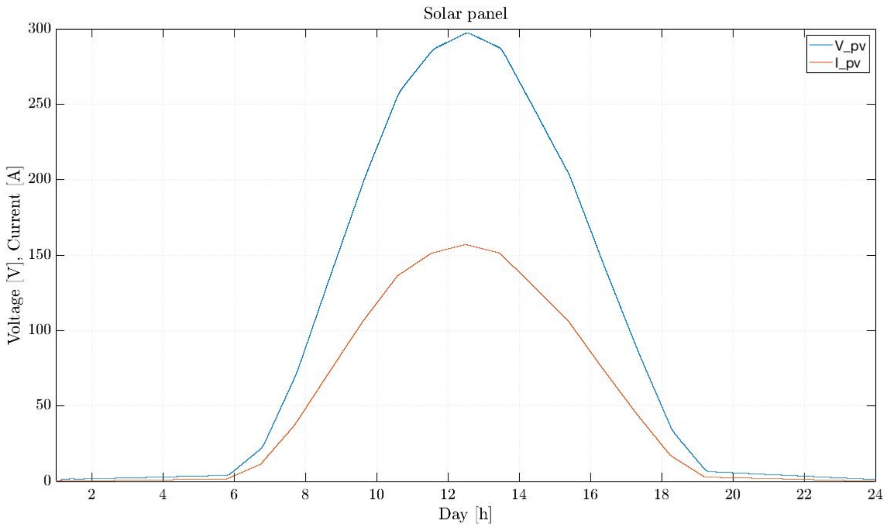

Figure 5.30: Simulink PV voltage and current

- Boost converter output:

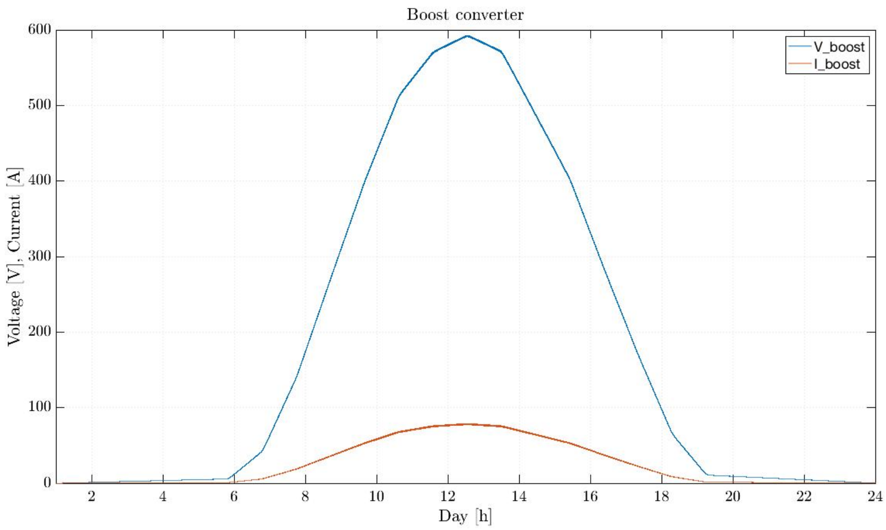

Figure 5.31: Simulink DC-DC converter voltage and current

- Inverter output:

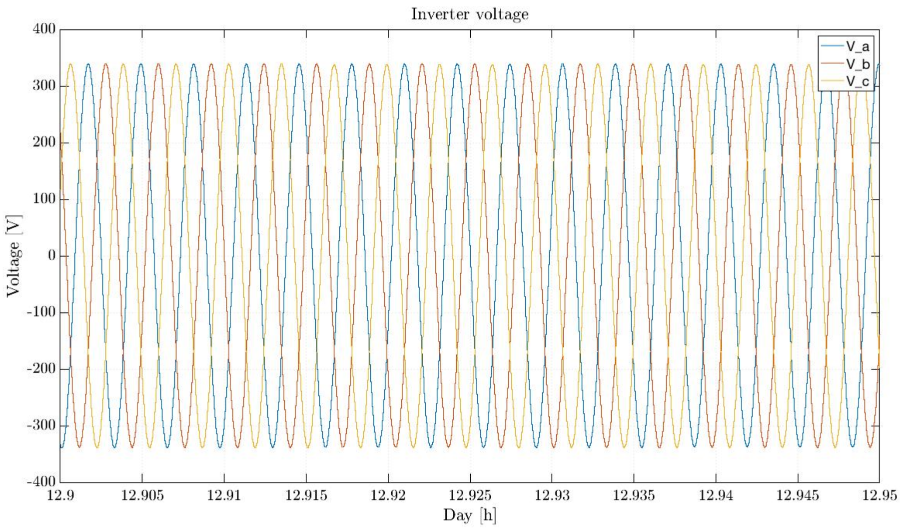

Figure 5.32: Simulink Inverter voltage

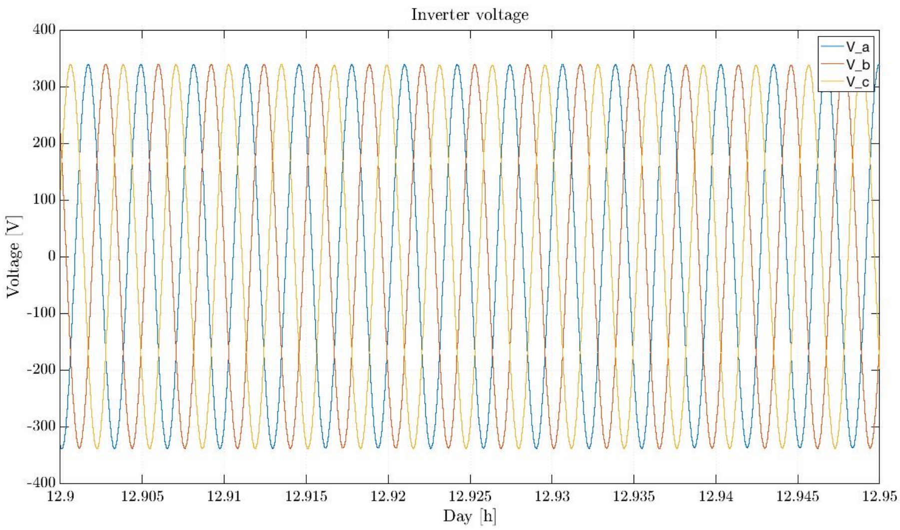

Figure 5.33: Simulink Inverter current

In terms of power flow:

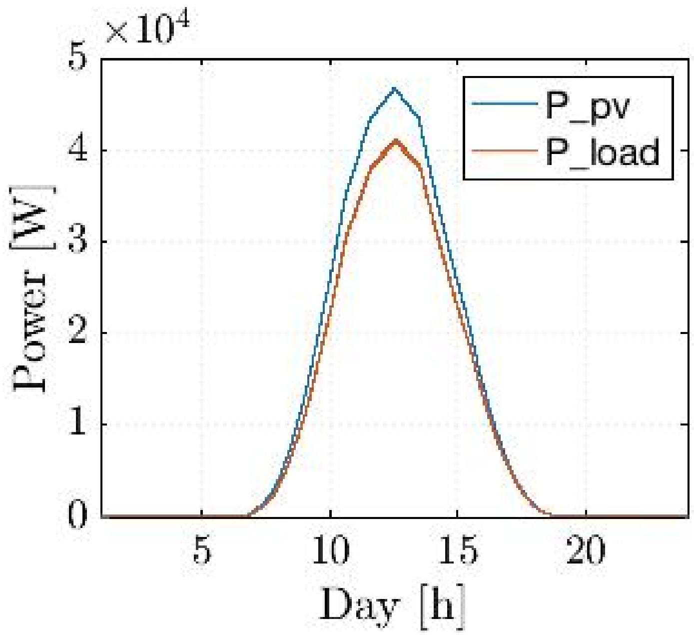

Figure 5.34: PV panel and load power

In the hours with low or zero irradiance, the battery steps in to supply the load. As mentioned, the battery is characterized for being able to discharge at rated power for four hours, therefore we are not able to see its discharge.
The battery is supplying when the solar panel is not producing energy, therefore in the night time and early morning. For the simulation it is appropriate to reduce the power requested from the load since the school is not working. In fact, we can assume that the battery only has to supply the apartment building.
The four blocks of batteries placed in series, as described in Section 5.3.1, are able to sustain a power of 20 kW. By considering only the private building, the peak power requested is 18 kW.

The output of the battery is shown in Figure 5.35.

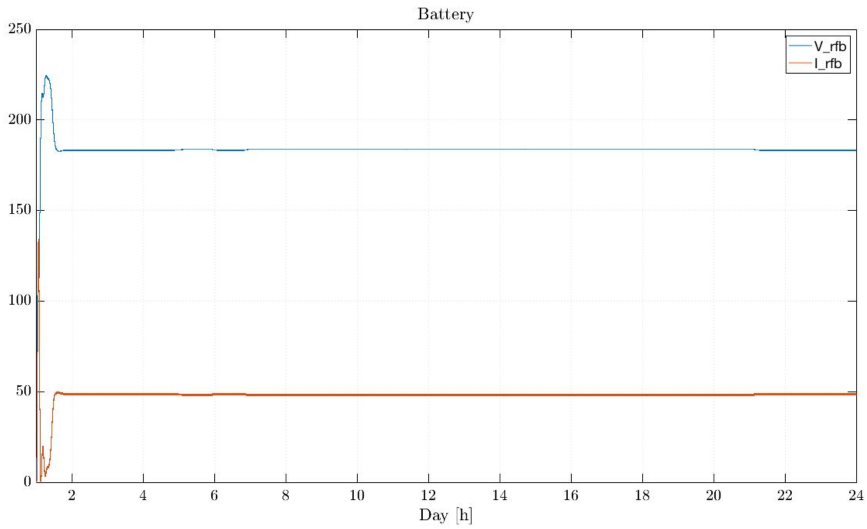

Figure 5.35: Simulink Battery voltage and current

The battery is connected to a step-up DC-DC converter that highers the voltage, as indicated in Figure 5.36.

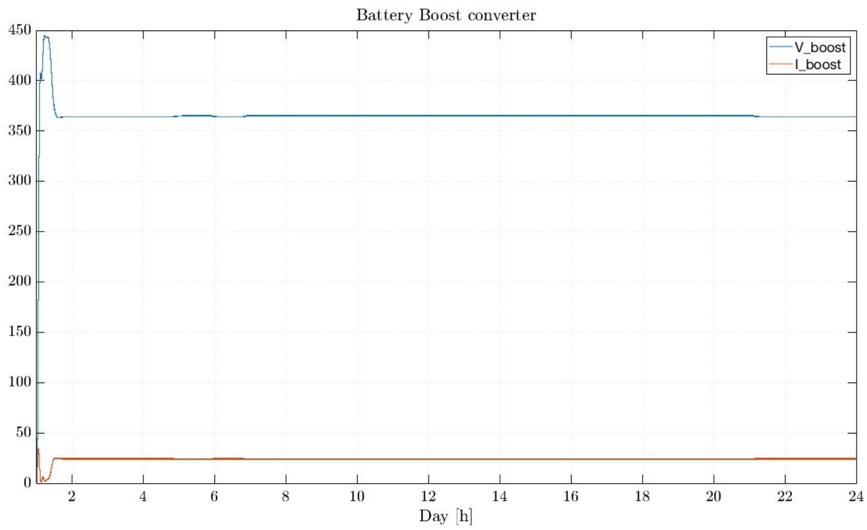

Figure 5.36: Simulink DC-DC converter voltage and current

At last the inverter converts the dimensions into AC.

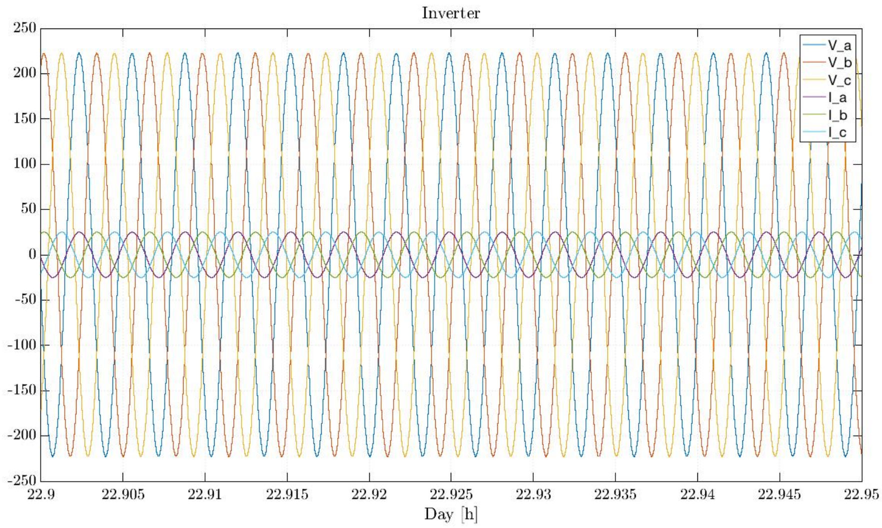

Figure 5.37: Simulink Inverter voltage and current

5.4.3 July

The PV panels receive the curve of irradiance shown in Figure 5.38:

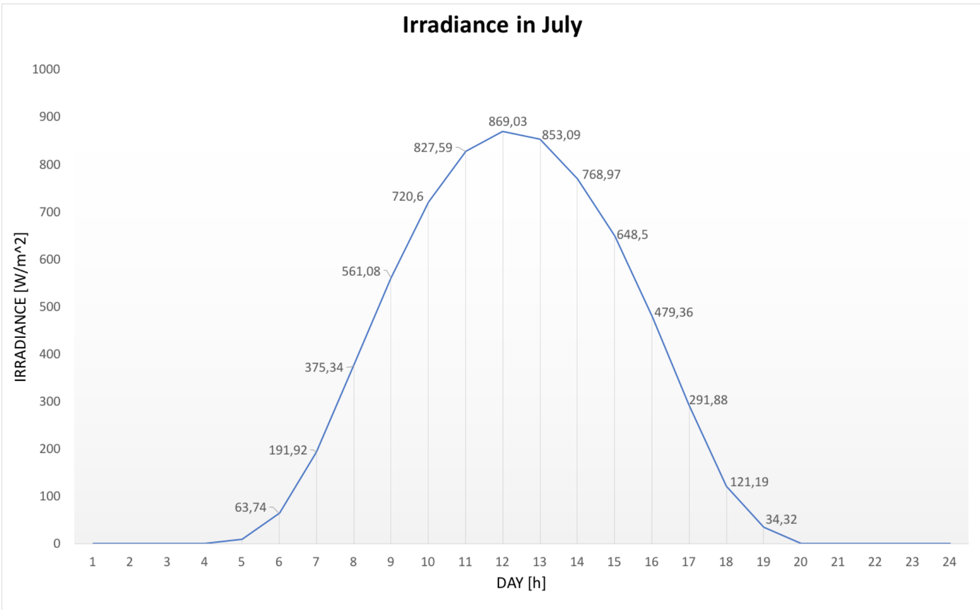

Figure 5.38: Daily irradiance in July

The energy balance results over the month:

- Consumption: 4748 kWh
- Production: 10408 kWh

$$\Delta E = E_{consumption} - E_{production} < 0 \tag{5.30}$$

The PV panel is able to provide the energy needed to the load and to store a relevant amount as well.
For each component the $I - t$ and $V - t$ characteristics on a daily basis are shown below.

- PV output:

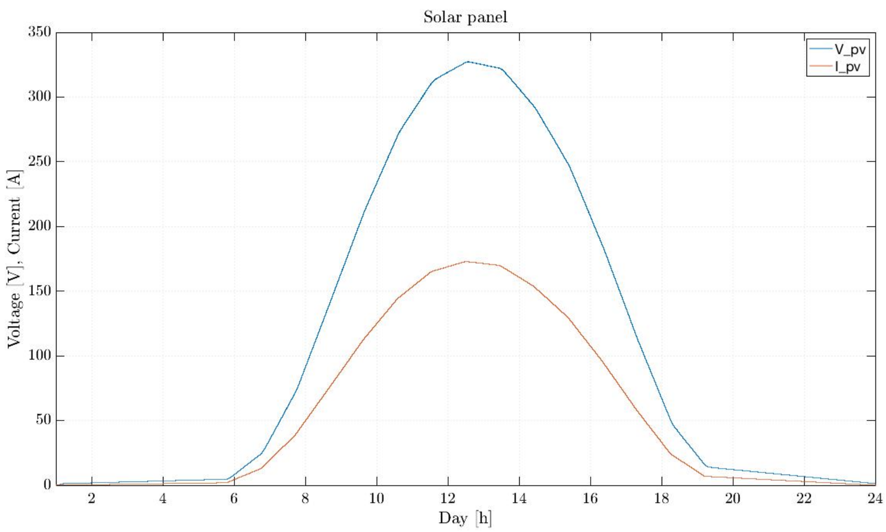

Figure 5.39: Simulink PV voltage and current

- Boost converter output:

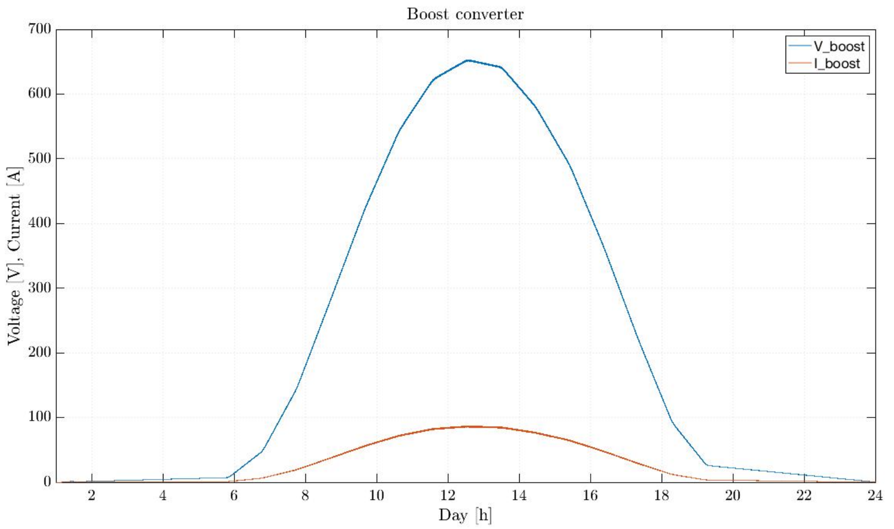

Figure 5.40: Simulink DC-DC converter voltage and current

- Inverter output:

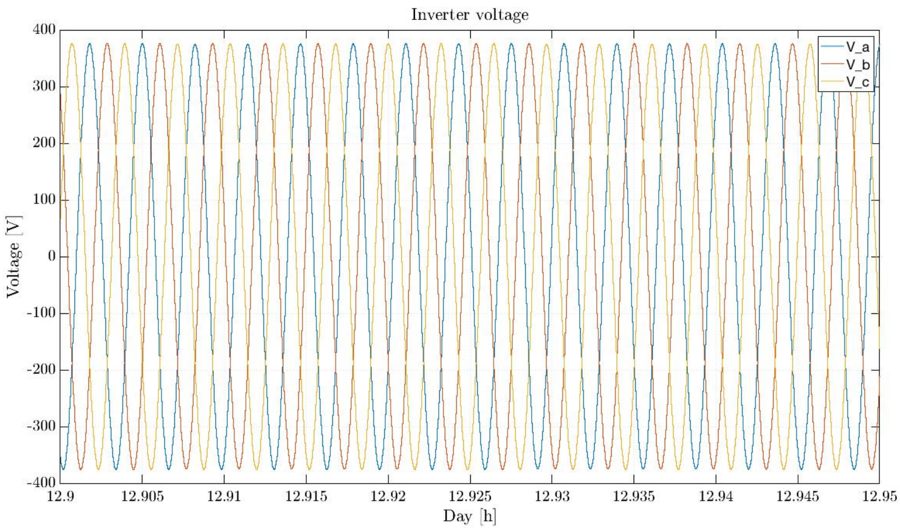

Figure 5.41: Simulink Inverter voltage

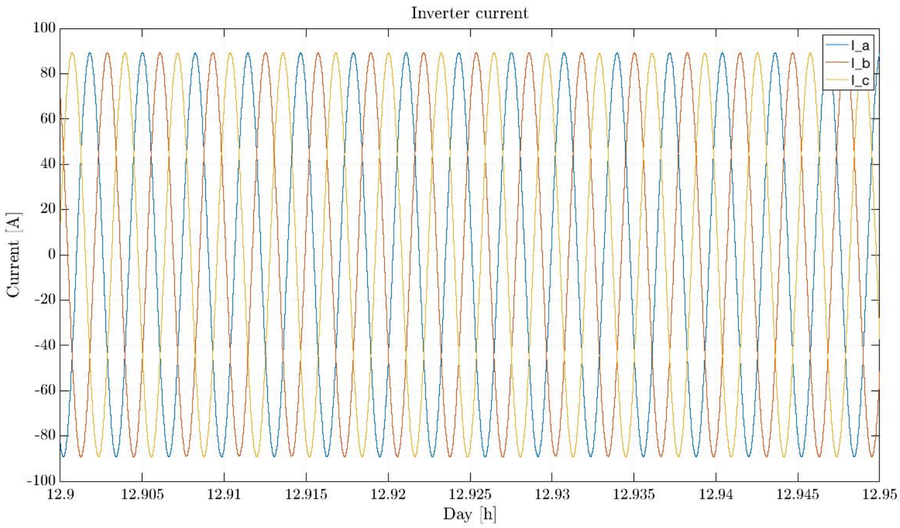

Figure 5.42: Simulink Inverter current

In terms of power flow:

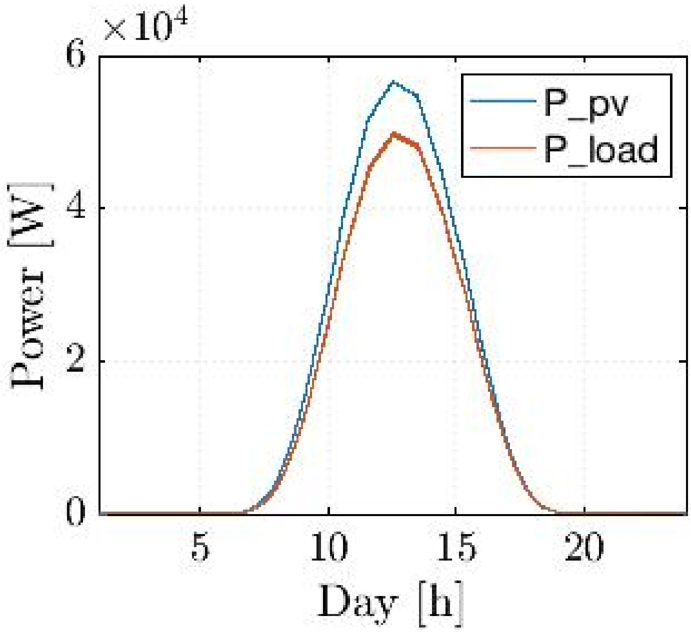

Figure 5.43: PV panel and load power

Similarly to May, described in Section 5.4.2, the storage system is needed to store all the energy that is needed to to supply the load at nighttime and early morning, so that the system can be completely independent of the grid.

5.4.4 MPPT

The Maximum Power Point Tracking function is used to provide the Boost converter a control signal.
The flowchart implemented is based on the conventional logic of Perturbation & Observe. As mentioned, the algorithm compares the power and voltage of time k with the previous sample at time (k-1) [45]. Despite the improvement that the function can provide, both voltage curves from the PV panel and the Boost converter present high oscillations.
Normally, in the simulation this kind of approach works as it should when the irradiance given to the PV panels is constant. In our case, the irradiance follows the real daily variation leading to oscillations of the voltage curve of the PV panels. Starting from this consideration, the flowchart has been altered based on the Modified Perturbation & Observe logic as shown in Fig. 5.45 [45].

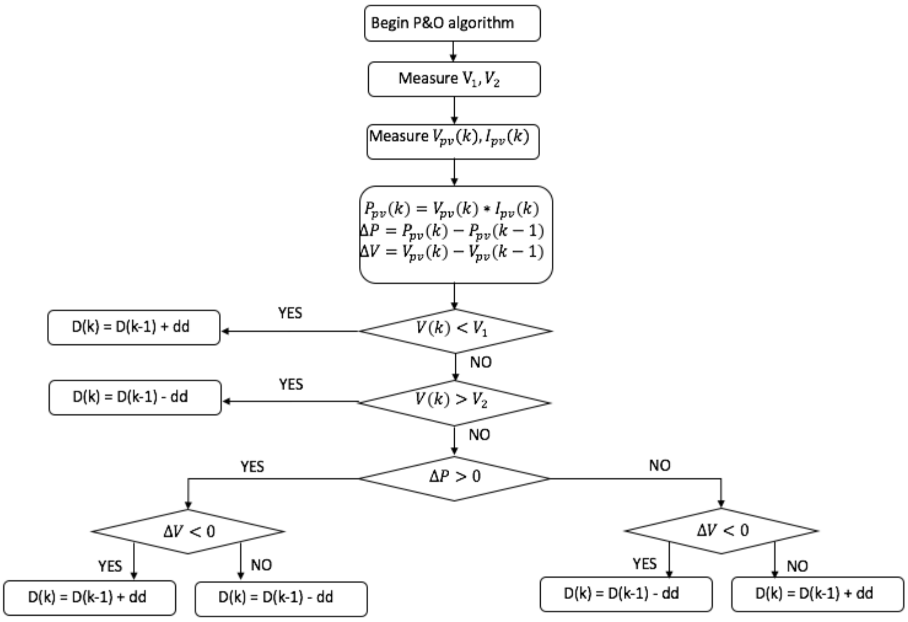

Figure 5.44: Flowchart of Modified Perturbation & Observe logic

In this case, the algorithm is enabled only when reaching the surroundings of the MPP. The $P-V$ characteristic of the PV panel is divided into three areas and the function intervenes in the area between V_1 and V_2, as shown in the Fig. 5.46.

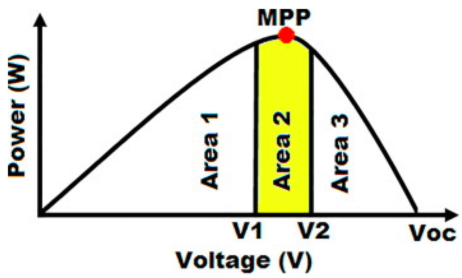

Figure 5.45: P-V divided into areas [45]

Nevertheless, in the simulation we were not able to obtain the wanted outcomes and therefore the function is not implemented. Regardless this problematic, we were mostly interested in the power profiles, which we achieved.

Chapter 6

Conclusion

The thesis focuses on a possible configuration of renewable energy community between an apartment building and a school.
At first, the study case included only one building consisting of four apartments, which consumption were known. Over the year the building requires approximately 25 kWh; according to the surface available we could design a solar plant of 15 kW_p which annual production would be of approximately 20 kWh [24]. Looking at this case we could not justify the employment of the battery, as there is no over generation.
Therefore, the two remaining possibilities were either to take the battery out of the system or to expand the system itself.
In the first case the project would have turned into a situation in which the building is supplied by the solar plant and the grid. This means that when there is no production of solar energy the grid would intervene, and when there is solar production it is used to supply the consumers and it is injected in the grid, when exceeding. This model is also called by the GSE "scambio sul posto", defining the mechanisms for which the energy produced by the plant on site and injected in the grid in a certain moment compensates the energy withdrawn and consumed in an other moment [46].
A relevant part of the thesis is the study regarding the storage system, hence, the decision of expanding the study case to a second building and converting the project into a REC.

Since the enlargement comes from the need of a wider availability of roof surface, instead of choosing a building identical to the first one, a different kind of structure was taken into consideration.
The inclusion of the school aims at solving the problem of the surface available for mounting panels, and it also formulates a different approach when dealing with supply. There are two important aspects to take into consideration that justify the presence of the school in the project. The first aspect is related to the fact that we wanted the power plant to be able to cover for the energy demand, also when panels are not working. In fact, we must be aware that in residential realities the evening is one of the time windows of high energy request. The second aspect is that in order to pursue efficiency it is important to have a load withdrawing energy as it is produced, which means at daylight.
The school allows us to obtain the best performance out of the power plant, since its load profile corresponds to the production one. Moreover, by having the chance to build a bigger solar system we can count on an over generation of energy, that together with the storage system, can cover the evening demand of the private building.

Once we had defined the study case, starting from the overall consumption we were able to design the power plant needed to satisfy the demand, according to the available surface.
After defining the power plant, we investigated on the monthly values in order to evaluate whether it was possible to realize an off-grid system. Due to the winter season and the values of irradiance, the REC is not able to be completely independent from the grid. Nevertheless, with a yearly production of approximately 89000 kWh and a consumption of approximately 85000 kWh, having a storage system allows to save 4.5 % of energy that would otherwise be wasted.
After these first considerations, a deeper analysis was made through the daily profiles of consumption and production.
Chapter 3 is entirely dedicated to explaining how the profiles where obtained, based on the usual patterns that a residential building and a school present. The graphs show clearly the reason why two different types of buildings were included inside the REC, as we wanted to leverage their different behavior among the day. The school

demands high levels of energy and power during the day, approximately in the same time window as the production from the solar panels. The residential building normally presents two peaks during the day, at early morning and lunchtime, and then it presents a peak in the evening. The configuration chosen permits to use most of the energy instantaneously as it is produced, leading to higher efficiency. In case of over production, the energy in excess is stored and used to supply a load at nighttime, corresponding to the apartments.

In the overall system the battery plays different roles.
In the case study, 4.5 % of energy with reference to the overall production is stored. The percentage itself is not very high, and moreover, there are months, as the winter ones, in which the storage system is not even required. What justifies its presence, besides the maximization of self-consumption and reduction of clean energy wasted, is its function for power curtailment. The storage system can help supplying a percentage of power in order to satisfy the peak requested in certain instants. This function translates into a lower rated power for the consumers with an economical benefit, and into a smoother demand to the grid.
As described in Chapter 4, redox flow batteries, regardless their chemical nature, use external tanks for the electrolyte that can be scaled in order to have a higher energy capacity. Supposing that new consumers are willing to join the REC in a future, it is possible to add new panels for a higher production and to use bigger tanks to store more energy.

Chapter 5 is dedicated to the simulation of the overall system, recreating the three main paths of energy flow: solar panels, storage system and grid.
By building the system on the software Matlab/Simulink we obtained the curves of all components within the 24 hours. Besides the technical study regarding the design of the electronic components, the simulation has been created in order to achieve a power profile from the supplier and from the consumer side. Based on this, we were able to understand the battery in its storage function and in its power curtailment function, for the winter months, when the supplier is not able to sustain the peaks required.

In order to accomplish the goals defined to overcome the environmental emergency, we must consider all possible actions that can contribute, no matter how small the impact may be. It is in general more feasible and reasonable to realize RECs in the outside of the cities; looking at the realities that are now present in Italy, the availability of wider spaces for the power plant leads to higher values of energy produced and more diversification in the sources used. Nevertheless, even with more limited choices, it is important to expand the reality of collective self-consumption and RECs in the city environment.
The importance of these realities is demonstrated by the fact that among the years the regulations were implemented, giving the possibility to realize more projects of self-consumption. In the future we expect that the limitations currently defining the terms within the RECs can be realized, will be loosened to continue promoting their construction. It could also be necessary according with the progress regarding the storage systems and the smart grid, in fact the constraints concerning the maximum power and the territoriality might reveal themselves as tight.
The realization of the RECs and smart grids, as suggested by the name, are bonded to a high level of information technologies to achieve the best performance and efficiency. Communication plays a key role; in terms of energy by using smart meters we are able to optimize the consumption, reducing waste of energy, and in terms of operation it helps tracking the power flow to avoid sharp demands to the grid.
Inside the REC, ITs are used to plan a forecast for the next day in terms of production and consumption based on data collected. These profiles are then adjusted on the current day and updated every instant through real time control.

At last, it is relevant to underline that, as mentioned, the starting data are real and they represent the consumption of structures that have not been upgraded in terms of energetic class. In 2005, in fact, it was introduced the certification energetic class for buildings, measured in kilowatt hour per square meter year, defining how the structure is capable of saving energy. The highest level, identified with the level A, corresponds to a building with an energetic impact close to zero. The index takes into consideration air conditioning, heating, sanitary water and mechanical ventilation. Therefore, interventions such as thermal insulation through

a thermal coat and high efficiency heating systems can change the consumption values.
The energetic class A+ defines a consumption inferior to 16.25 kWh/m^{2}year. Considering the apartment in the study case, for 100 m^2 we would expect the consumption related to hot water, air conditioning and heating to be equal to 1625 kWh/m^{2}year. In Chapter 3 where all consumption are listed, we can consider that approximately 2000 kWh/m^{2}year are used by the appliances mentioned. A higher energy class would lead to saving 400 kWh/m^{2}year in one single apartment.
Therefore, in a perspective in which the presented project could be realized, it is essential to take into consideration as a premise the upgrade of the study case in order to obtain a better outcome.

Finally, it is important to investigate and promote new configurations that help optimizing these rising realities. Investing on self-consumption projects can be decisive for the future. In fact, the aim is to engage more citizens and to spread awareness regarding the value of the energy. As we rely more on clean sources, such as solar and wind, we need to develop a higher sensitivity and respect about environmental matters.

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