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Development of Innovative Methodologies for the Aggregation of Distributed Energy Resources in Energy Communities

Department of Astronautical, Electrical and Energy Engineering
PhD in Electrical Engineering (XXXV cycle)

Gianfranco Di Lorenzo
ID number 1149519

Advisor
Prof. Rodolfo Araneo

Academic Year 2021/2022

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PhD thesis. Sapienza University of Rome

This thesis has been typeset by LaTeX and the Sapthesis class.

Author’s email: gianfranco.dilorenzo@uniroma1.it

Abstract

In 2019, the European Union finalized the 'Clean Energy Package for All Europeans', a set of 8 laws covering the crucial aspects and actions needed to reduce greenhouse gas emissions, improve climate resilience and facilitate the energy transition process in a fair and unified manner. The old Renewable Energy Directive 2009/28/EC has been revised and replaced by the new Directive 2018/2001/EU (also known as RED II), which came into force in December 2018. The new directive updates the European targets for renewable energy sources (RES) and energy efficiency in the post-2020 energy framework and looking ahead to 2030, in line with the 2030 Energy and Climate Framework and the ambitious 2050 Long-Term Climate Neutrality Strategy. One of the main innovations of the directive is the introduction of Energy Communities (ECs) as the main vector for realising the energy transition. RED II recognises ownership and proximity as factors that incentivise the acceptance of RES projects. It also defines new and favourable regulatory aspects for the penetration of energy communities that promote collective self-consumption. RED II distinguishes two types of energy communities: Citizen Energy Communities and Renewable Energy Communities. The differences between the two lie in the types of energy used and the requirement for proximity of participants: specifically, the former are limited to electricity and do not require proximity of members, the latter only consider renewable energy but the proximity of members is binding.

This work proposes an innovative power-sharing model, i.e., a power-system architecture for aggregation of users able to share the power produced by common generators and energy services. The model is suitable for both multi-tenant buildings and groups of multiple buildings and it is applicable for both existing and new buildings. It is scalable for larger systems and suitable for an easier integration with storage systems. The novel principle of the model is that the energy produced by common generators can be shared among the end-users in a unidirectional way, so that each user remains passive towards the distributor, except a single active user that assumes the role of balance node. This key feature allows for easily implementing the model in all the residential and tertiary multi-units buildings in full compliance with national regulations, with the adoption of power sharing contracts as well. This work discusses the feasibility of the model through a dynamic Matlab/Simulink model, which is used to show its effectiveness in several case studies. The significance of this work consists of approaching the energy sharing in buildings with a completely new strategy, based on an innovative system architecture that can be effectively implemented.

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Chapter 1

Energy Communities: Formation Process and Regulatory Framework

1.1 Introduction

Energy communities are born in the spirit of the energy transition, driven by the European Union's AGENDA30, specifically Goal 7 'Clean and Affordable Energy', which raises the challenge of doubling the global rate of energy efficiency by 2030 by increasing the share of renewables in energy consumption, Goal 12 'Responsible Consumption and Production', in favour of achieving sustainable energy management by (multinational) industries and also by public administrations with regard to energy procurement. This last goal is very important as it also pushes for making sure that "all people, everywhere in the world, have the relevant information and awareness about sustainable development and a lifestyle in harmony with nature" and in this regard, Energy Communities can help a lot, also in making cities themselves sustainable (Goal 11). The energy transition, understood as the construction of a new model of social organisation based on the production and consumption of energy from renewable sources, is necessary and urgent. For it to be effective, cultural changes, both material and immaterial, based on energy saving and consumption efficiency must be triggered. In such a scenario, the activation of new forms of collective action and collaborative economies (in which production and consumption give rise to new exchange systems), together with the opportunities offered by new digital technologies, constitute the cornerstones of the energy transition, as well as an opportunity for the creation of new green economy models. If the energy transition is necessary in terms of environmental sustainability, it will not be fully realised without a joint management of environmental, social and economic issues using a co-evolutionary and interactive approach, given the inseparability and mutual influence of social and technological change. An energy transition requires cultural changes, both material and immaterial, based on energy saving and consumption efficiency. This raises an important question that concerns us closely, with the concept of community at the centre of our discussions and actions. How can we today rethink being in common? How can we live together? The question, which borrows its title from Roland Barthes (1977), is a provocation to reflect on the possibilities of living together with each other and with the environment, on the complexity of 'living with' in an increasingly complex and interconnected world. Recognising oneself in a community is the first step in the direction of an ethic of peaceful cohabitation with people and the environment.

Figure 1.1. Key aspects of sustainable development

The transition to more sustainable modes of production and consumption has become one of the great contemporary challenges. The end of energy localism and the rise of a high-carbon society have determined international geopolitics and generated instability, inequalities and social inequity. The effects of a social and economic model dominated by the principle of profit maximisation 'at any cost' are tangible on the earth's ecosystem and populations. Global warming, climate change, the loss of biodiversity, environmental

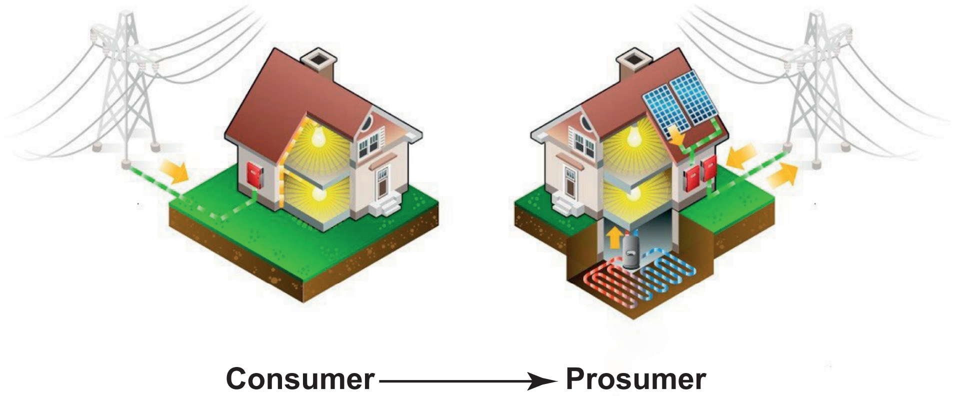


Figure 1.2. Consumer VS Prosumer

and social injustices that drive new hordes of ’climate migrants’ to leave their homelands, confront us with a profound rethinking of the way governments, corporations, financial systems and individuals interact with our planet. Seizing the opportunities offered by new technologies, citizens around the world are already uniting to regain relevance in the energy sector, through direct and participatory actions aimed at building a more equitable and sustainable society. This trend is growing. In fact, in view of the reduction of carbon emissions in the electricity sector planned for 2050, it is estimated that 254 million EU citizens will join the energy market as prosumers, generating up to 45% of the total renewable electricity in the system. The term prosumer is used to refer to the user who is not limited to the passive role of consumer (Fig. 1.2), but actively participates in the different stages of the production process (producer). In practice, the prosumer is the one who owns his own energy production plant, of which he consumes a part. The remaining energy can be fed into the grid, exchanged with consumers physically close to the prosumer or even stored in a special system and thus returned to the consuming units at the most opportune time. Therefore, the prosumer is an active player in the management of energy flows, and can enjoy not only a relative autonomy but also economic benefits.

Innovative forms of prosumption can be implemented through energy communities (ECs), i.e., a coalition of users who, through voluntary adherence to a contract, collaborate with the aim of producing, consuming and managing energy through one or more local energy plants. This is a broad concept that identifies a variety of experiences including communities of interest and communities of place that share the development of a renewable energy project and the resulting economic and social benefits. With due distinctions and differences between them, energy communities all share a common goal: to provide affordable renewable energy to their members, rather than to give their members, rather than prioritising economic profit like a traditional energy society. traditional energy society. Decentralisation and localisation of energy production are the principles on which an energy community is based. energy community that, through the involvement of local citizens, businesses and enterprises is able to produce, consume and exchange energy with a view to self-consumption and collaboration. collaboration. The concept of self-consumption refers to the possibility of consuming on site the electricity produced by a local generation plant to meet its own energy needs. Producing, storing and consuming electricity at the same site produced by a local local generation plant allows the prosumer to actively contribute to the energy transition and sustainable sustainable development of the country, fostering energy efficiency and promoting the development of renewables. Today, self-consumption can be implemented not only as an individual but also as a collective form within apartment blocks or local energy communities. The increase in distributed generation, especially through the spread of photovoltaic systems, makes the integration of energy production and consumption within neighbourhoods and districts, within medium and low voltage grids, relevant. To enable the national electricity system to function optimally, it is necessary to match energy supply with consumption demand. One way to achieve this is to superimpose the individual spatial dimension on the collective spatial dimension, for example, by matching local energy production with the demand of the circuit consisting of house, apartment block and neighbourhood or company-building/shopping centre. The figure 1.3 illustrates the conformation of individual self-consumption, collective condominium self-consumption and collective self-consumption through energy communities, under the same low-voltage electrical cabin. In Italy, the last two types (collective self-consumption and energy community) will be legally recognised from 2020.

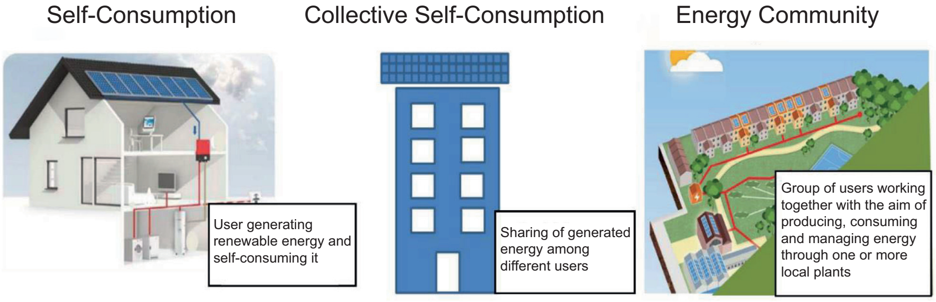


Figure 1.3. Main differences among Self-Consumption, Collective Self-Consumption and Energy Community

1.2 Energy Communities in the World and in Europe

The birth of an energy community involves the aggregation of a number of prosumers willing to share power generation plants based on renewable energy sources (RES). At present, various collective self-consumption and energy community initiatives are active in many countries around the world, demonstrating their potential as social transformers by facilitating the adoption of eco-sustainable behaviour. Some cases of energy communities implemented between 1999 and 2016, worldwide and in Europe, are described below. What they have in common is the local dimension of renewable energy production and exchange systems.

1.2.1 Grupo Creluz, Rio Grande do Sul (Brasile) – 1999

It is a small-scale EC, consisting of 6 small hydroelectric plants capable of providing 600 poor families with free electricity. The plants, located in several river courses, are able to supply up to 4MW, about 27% of the energy needs of 80,000 people. The cooperative members who generate the energy are also the members who consume it.

1.2.2 The Brooklyn Microgrid (BMG), New York (USA) – 2016

BMG was founded as a benefit corporation by its parent company, LO3 Energy, in an attempt to reimagine the traditional energy grid model by incorporating the concept of a municipal energy grid in which Brooklyn's residential and commercial citizens can buy and sell locally generated renewable energy. Participants access the local energy market through BMG's mobile app. In the app, people can choose to buy local solar energy, renewable energy and/or grid energy. They can set their daily budget for purchasing local energy on the market. Once installed a BMG smart meter system, which collects and records energy data for use within the energy markets, professionals can choose whether to sell excess solar energy to the market or continue using grid energy.

1.2.3 Bioenergy Village Juhnde, Germany – 2004

A 700 kW co-generation system running on biogas is used to produce electricity that is supplied to the public grid. A 550 kW woodchip boiler is used in winter to provide heating that circulates around the local grid. The community produces 70% of the heat and twice as much energy as required. The bio-energy plant is locally and collectively owned by the residents of Jühnde. Residents can buy shares in the cooperative society that owns the plant. Currently almost 75 % of the inhabitants of Jühnde are members of this society. Once they have bought shares and become members, they can purchase heating and electricity from the company, this means that the consumers of energy are also the producers of that energy.

1.2.4 Localised Energy Systems - Community Energy Generation, Aggregation and Demand Shaping (LES-CEGADS), United Kingdom – 2015

The project involves a cluster of villages in Oxfordshire, Shrivenham, Watchfield and Longcot and envisages the participation of 48 households. The success of the CEGADS process led to a first fully commercial implementation of the community concept in the small town of Bethesda.

1.2.5 ACCESS Project Mull and Iona Islands, Scotland - 2015

This is a project funded by the Scottish Government through the Local Energy Challenge Fund, 2015. The total cost of the project was approximately £2.5 million, with a grant of £1.8 million from the Scottish Government, £0.3 million from Ofgem's Electricity Network Innovation Allowance (NIA) through SSE Networks and approximately £0.4 million from project partners as in-kind contributions. It demonstrates how aggregated load can be used to control the amount of energy imported and, if necessary, exported from the island.

1.2.6 LIGHTNESS PROJECT, Poland, France, Italy, Netherlands, Spain - 2021

Currently, the Lightness Project, whose main targets are shown in Fig. 1.4, is one of the most interesting projects in the ECs landscape in Europe, with a duration of 36 months and about 3 million of euros in funding. Involving 13 pilot sites in 8 European countries for a total of about 70,000 people, it aims to:

- analyse the needs and opportunities of the various contexts in which an EC can operate,
- facilitate contacts between the various realities and support citizens in the generation of energy from renewable sources and self-consumption,
- develop new technologies for monitoring energy flows and optimisation in order to reduce CO_2 emissions,
- provide guidelines to governments and local administrations to facilitate the establishment of Energy Communities.

Figure 1.4. Lightness Project targets

The most important pilot sites are five, chosen for different legislation, current use of renewable resources, climate areas, social welfare of citizens and available incentives:

- **Poland**: Wroclaw is the largest city in south west Poland, with 650,000 inhabitants. Although there is a large thermal district heating plant (co-generation) in the city, it is not available for all inhabitants. Coal-fired boilers are still commonly used, often supplied with all kinds of waste and releasing substantial amounts of CO_2 emissions. In Poland, electricity is mostly produced in coal-fueled power plants, which makes projects like Lightness an important part of the energy transition.

  Less than half of Poland's population lives in large blocks of flats. As a result, there is very little common roof area per capita, an important factor in determining the potential for installation of solar photovoltaic cells. There are two types of housing associations: Spółdzielnia mieszkaniowa (housing cooperative) and Wspólnota mieszkaniowa (housing community), which can manage building communities. This case study will focus on the first type. The Spółdzielnia mieszkaniowa's legal framework allows for decisions to be made by a few members regarding facility management, infrastructure, and maintenance in the respective facilities. Two locations and 2 apartment blocks have been selected in one of the biggest communities, Spółdzielnia-Południe. Those two apartment blocks give the potential of 2 energy communities, potentially within 142 households and 66 households.

  In those two locations a different scenario can be verified. At one of the locations PV panels are installed on the roof, but produced energy is used only to cover the energy needs in the common area. The LIGHTNESS project will verify the possibility of providing residence opportunities to consume locally produced energy. Under current Polish law the energy generated by photovoltaics cannot be consumed by the inhabitants of the block building, it needs to be resold to the distributor or used only for consumption in the common areas (elevators, pumps, light).

- **Netherlands**: The Dutch case study will combine two pilot sites in two different locations: Woerden and Badhoevedorp. The pilot in Woerden is located in the area “Schilderkwartier”, which consists of social housing, and is in fact an energy community between ZOM-houses (Zero-On-Meter), that went through a net-zero retrofitting by BAM, and non-ZOM-houses (not Zero-On-Meter). The second pilot is the new urban development “Quatrebras”, located in Badhoevedorp. For the pilot, one of the three parts of Quatrebras will be used, i.e., “Quatrebras Park”, which consists of single-family houses.

The use of multiple pilot sites has the potential to provide greater economies of scale, offer a variety in the learnings that will be achieved and allow for the development of multi-community forming strategies.

i.LECO will be a technical aggregator and Local Energy Community (LEC) provider, and as a cross-pilot overall provider will sub-contract tasks to the pilot site locations.

For provision of true community energy services, the regulations still have to be changed. This will help advance the value of community service in relation to lower costs of energy distribution. Furthermore, the current system of incentives in the Netherlands is based on a “net-metering” system, which substantially lets the prosumer use the electrical grid as a “free” battery. This system, very convenient for small PV prosumers, represents however an obstacle for energy communities, since it makes the advantage of an energy community (that of being able to maximise the self-consumption) useless.

Engagement of people that want to participate in the energy communities is crucial. Energy communities can offer many benefits and the general idea can be explained in a way that is comprehensible to the general public. However, the real functioning and details regarding different energy community services is often rather complex. Communication and, especially in the early stages, interaction with the citizens in the Citizen Energy Communities (CECs) will be of key importance.

- **France**: Savoie Technolac is a business park located in southeastern France, built close to the lake of Le Bourget.

  The park development (urbanism, economy, energy, etc.) is led by the Grand Chambery area, the regional community council representing a group of 38 municipalities and 138,677 people.

Since its creation, the park is oriented towards energy efficiency and solar technologies for buildings. With more than 1000 researchers and 230 enterprises.

ALBEDO has worked with Savoie Technolac since 2008 and has developed a partnership with the University and INES (national Solar energy research center).

- **Italy**: The Via Bolzano 4 condominium was built in 1966 and has eight, four-room, 85 square meters apartments.

  It has an energy rating of G (the lowest possible). There is no central heating, only individual heating units with no energy monitoring or control systems.

  The building currently has envelope water/air leakage and a maintenance/retrofit is scheduled by R2M Energy independently of the Lightness Project.

  Given this planned renovation, there is the opportunity to retrofit and showcase a “smart condo” concept consisting of interventions like:

  - Formation of a Citizen Energy Community at the building-level;
  - Installation of 20kWp solar system on a rooftop;
  - Change of energy supply contract to AXPO with new contractual options and flexibility;
  - Blockchain-enabled energy management;
  - Real-time analytics and data available to prosumers.

  An ENER2CROWD crowdfunding campaign was conducted in December 2021 to finance the retrofit of the Smart Condo. 151,010 € were raised within few hours from the campaign opening.

  There is a lack of confidence and a proven track record on how to implement new EU energy regulations regarding energy communities and collective self energy consumption. However, showcasing this pilot site will send an important signal to the market and other energy actors. The engagement process assumes that before the start of the project, there are already solid informal relationships between the community members, as the residents live in the same building and meet from time to time.

- **Spain**: The village of Alginet is located 25km south of Valencia and has a population of 13,000 inhabitants. Its energy distribution network is owned by the end users through the form of a cooperative by the Electric Cooperative of Alginet.

  Alginet's electric cooperative was created in 1930 by a group of citizens, due to the need for electricity supply in the town and the lack of interest from the electric companies to electrify small population centres, such as Alginet, at that time. Besides the commercialization and distribution of electric energy, the cooperative also plays a major social role in the town by investing and redistributing benefits among the end users. This role includes initiatives to mitigate energy poverty, promote culture and sports, and support the energy transition and climate change adaptation.

  Alginet is interested in exploring the advantages and possibilities of implementing a Demand Response Management System, and also to develop a strategy to transition from a basic retailer to an Energy Services Company, as well as empowering their end users.

  There are many constraints and barriers in the Spanish regulatory framework, especially for small electric entities like Alginet. The particularity of this pilot is that the members of the future community are part of the energy supply cooperative and live in the same village. The energy community can help intensify the cooperatives' ties with and between its members, instead of understanding end-users as passive consumers and customers.

1.3 Energy Communities in Italy

In Italy, there are already many energy communities and cooperatives located mainly in the North of the peninsula.

FUNES was founded in 1921 in South Tyrol under the name ’Società Elettrica Santa Maddalena’. Even today, the electricity used locally is produced by three hydroelectric power plants (San Pietro 775 kW, Meles 2,698 kW and Santa Maddalena 225 kW), a photovoltaic plant (170 kW) and two biomass district heating plants (1,100 kW and 700 kW). A veritable revolution, which has made this valley a flagship in the search for completely sustainable territories, where the role of the citizens who members, united in the form of a cooperative, has made the valley capable of producing, 100% renewable, more electricity than is consumed. The remainder is fed into the national grid and revenues are reinvested on the same territory, translating them into bill discounts or investment in new plants.

EWERK PRAD, a cooperative in Prato allo Stelvio, operates 17 renewable energy plants (4,000 kW of hydroelectric, 103 kW of PV, 1,600 kW biomass). A model of excellence that has its roots in 1923 in Prato allo Stelvio, when a group of young men decided to build a mini hydroelectric power station and, to bear the costs, started a cooperative with 40 local families. Today it has 1350 members, i.e., the total number of families in the small municipality who, in addition to being users, are, thanks to the cooperative formula, owners of the production of electricity and gas. In this case, the savings on the bill is 30% in the first case (electricity) and 20% in the second case (gas).

The **COOPERATIVA ELETTRICA GIGNOD** is located in Saint Christophe, in the Aosta Valley. The energy produced by the cooperative is sold to its members. This demonstrates the centrality of the mutual purpose in the qualification of the cooperative society and in the objectives set by the statutes. In compliance with the regulations of the ARERA authority and the integrated text for historical electric cooperatives (TICOOP), the C.E.G. sells surplus energy for members’ consumption to a trader and purchases, from the same, the energy necessary for the members if production is not sufficient. The cooperative manages to guarantee its self-sufficiency calculated over a period of one year.

The **COOPERATIVA ELETTRICA ALTO BUT** was founded in Friuli in 1911. It represents the first company in Friuli for the production and distribution of hydroelectric energy established as a cooperative (5 plants for a total of 10.8 MW). In 1913 the Fontanone plant was inaugurated, intended for the production of electricity for industry and private consumption. The cooperative form characterises the company's work on all fronts. The production, purchase and distribution of electricity generated from renewable and conventional sources, the supply of fuel gas and water resources, the operation of shops for wholesale and retail sales, and social lending activities represent the core of the initiative, in application of the statute, according to the principles of free mutual cooperation.

SEM - SOCIETÀ ELETTRICA DI MORBEGNO, was founded in Valtellina in 1897. The company produces electricity through the exploitation of eight hydroelectric plants located in Valtellina / Alto Lario with an installed capacity of 11 MW and supplies 13,000 users.

The **COOPERATIVA DI MELPIGNANO** was founded in Melpignano in 2011, from the collaboration between Legacoop and municipal administration, with the aim of producing energy using photovoltaic panels placed on the roofs of public and private buildings in the town (33 installations for a total of 179.67 kW). The cooperative has the responsibility for installing the photovoltaic systems and their maintenance and management, producing energy and taking into account user demand and reselled surplus.

The **COOPERATIVA FTI** of Dobbiaco-San Candido was founded in 2003 and was able to cover the needs of 1300 users. With a 1500 kW biomass power plant, it supplies energy to the two municipalities of Toblach and Innichen. It represents a model of energy community pioneer in the production of energy from renewable sources in South Tyrol: The module uses a special technology called ORC (Organic Rankine Cycle) to transform heat into energy electricity. It is one of the largest plants of this type in Europe and was the first to be installed in South Tyrol.

Founded in 2010, **WEFORGREN** uses three photovoltaic plants in the province of Lecce and Verona, shared by 462 self-producing members, which produce energy for 1,471 households. The three plants, with a total of 3,000 kW installed, allow to produce more than 3,460,000 kWh per year. In addition, thanks to a mini-hydroelectric plant of 112 kW, a production of 700,00 kWh is guaranteed, capable of supplying an additional 260 homes. Choosing to join this cooperative has meant for members, in the period 2012-2016, an average saving of 14% on the energy component of the bill compared to the tariffs of the

"Maggior Tutela" market. In addition, the members who purchased plant shares received an average return over the same four-year period deriving from self-production of 530 euro per household, useful to cover the average bill cost of 2,700 kWh, which to date amounts to approximately EUR 500.

The **COOPERATIVA ENERGIA POSITIVA** was founded in 2015 in Nichelino, in the province of Turin. Here the member can, through a computer platform, buy shares in available plants and build his own 'virtual plant' with which to produce energy. 'virtual plant' with which to produce clean energy. The activity started by sharing three plants photovoltaic plants in Piedmont, with a total capacity of more than 250 kW and an annual production of more than 260 MWh, equal to 260 MWh, equal to the average consumption of about 100 households. In its first year, 70 members joined, distributed in eight Italian regions, with an average investment of around 7,000 euro per person; each user on on average saved 350 euro a year.

The **COOPERATIVA ÈNOSTRA** was founded in 2014 in Milan to provide renewable energy to households, businesses and third sector organisations. It currently serves 969 users, including 922 members, thanks to 5 photovoltaic plants installed in the Cuneo area (400 kW total) and a 99 kW photovoltaic plant located in the municipality of Sorbolo.

The **PINEROLESE COMMUNITY** is another recent energy community project, implemented in the territory of Pinerolo, Piedmont. The creation of a cooperative is planned. Municipalities and companies are included in this community, and of these 8 out of 11 are prosumers. The community includes: 15 non-household photovoltaic plants; hydroelectric power plants (450 kW) and biogas production. Natural gas is also used, but in this case, there is a high-efficiency cogeneration system that produces heat and electricity.

In the panorama of Italian experiences, it is worth mentioning the project 'Photovoltaic roof for the Fantini primary school in San Lazzaro di Savena' undertaken in 2011 by the **ASSOCIAZIONE COMUNITÀ ENERGETICA** of San Lazzaro di Savena, in collaboration with the municipal administration. The first phase of the project (aimed at residents and non-residents) consisted in the construction of a photovoltaic system for the production of electricity on the roof of the Fantini Primary School in San Lazzaro Savena.

Interested citizens purchased one or more shares of the plant (at a cost of 250 euro for each share) with which the photovoltaic plant was built, subsequently transferred by the Association to the Municipality of San Lazzaro. The proceeds of the state contribution collected by the municipal administration were passed on to the Energy Community Association, which in turn distributed it proportionally among the citizens participating in the initiative, allocating any surpluses to the municipality. The project, which is still ongoing, continued with the collection of new shares and associates for the construction of a future plant, also based on the principle of shared ownership.

Chapter 2

The Legal Dimension: European and Italian Regulatory Framework

2.1 European Directive: the Clean Energy Package (CEP) for all Europeans

In 2019, the European Union concluded the approval of the Clean Energy Package for all Europeans, consisting of eight directives regulating energy topics including: energy performance in buildings, energy efficiency, renewable energy, market electricity. The EU directives, established by the CEP, seek to put in place appropriate legal frameworks to enable the energy transition and give citizens a leading role in the energy sector. The directives should be followed by national laws on the respective topics. The deadline for transposition of the directives by the EU Member States, and consequently for the drafting of national legislation, was June 2021. Among the various topics of interest, we will only examine two of the CEP directives here:

- the Renewable Energy Directive (EU Directive 2018/2001), also known as RED II, in which the definitions of collective self-consumption and Renewable Energy Community (REC) are given,
- the Directive on the internal electricity energy market (EU Directive 2019/944), also

referred as IMD II which defines the Citizens Energy Community (CEC).

Article 21 of the Renewable Energy Directive (2018/2001) defines collective self-consumption realised within a building by a system that supplies electricity to more than one consumer ('one-to-many'). The classic example is that of a multi-unit building with a system in the common area that is able to meet the energy needs of both the condominium consumers and the autonomous units. When collective self-consumption transcends the scope of a single building or condominium, we are dealing with an energy community. Although the Directives present different definitions, they both define the energy community as "a legal entity" based on "open and voluntary participation", whose primary purpose is not the generation of financial profit, but the achievement of environmental, economic and social benefits for its members or associates or the territory in which it operates. To ensure the non-profit character of energy communities, energy companies cannot participate as members of the community but can provide supply and infrastructure services.

A REC is based on the principle of autonomy between members and the need for proximity to generation facilities. The REC can manage energy in different forms (electricity, heat, gas) as long as they are generated from a renewable source. The CEC does not provide for the principles of autonomy and proximity and can only manage electricity, produced either from renewable or fossil sources.

Furthermore, it is important to note that the two directives set different transposition periods for the member states. In the case of the Electricity Directive 2019/944, which established the ECC, the transposition deadline is 31 December 2020; whereas for the Renewable Energy Directive 2018/2001, which established the CER, the transposition deadline is 30 June 2021. This discrepancy, however, does not prevent the directives from being transposed by the Member States in a single law on energy communities.

The new national law should also allow energy communities to act as aggregators, creating a new energy business. The aggregation scheme allows the coordination of different units to control generation output and demand, exploiting flexibility. Aggregation will also allow small users to join together to participate in the wholesale energy market.

2.1.1 European Directive 2018/2001 RED II

In the introduction the RED II Directive (EU 2008/2001) promotes the use of energy from renewable sources, in accordance with Article 194 of the Treaty on the Functioning of the European Union (TFEU), promoting renewable forms of energy is one of the goals of the Union energy policy. That goal is pursued by this Directive. The increased use of energy from renewable sources or 'renewable energy' constitutes an important part of the package of measures needed to reduce greenhouse gas emissions and comply with the Union's commitment under the 2015 Paris Agreement on Climate Change following the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (the 'Paris Agreement'), and with the Union 2030 energy and climate framework, including the Union's binding target to cut emissions by at least 40 % below 1990 levels by 2030

For this reason, the use of energy from renewable sources can play an indispensable role both in ensuring security of energy supply and in ensuring that prices do not rise to the detriment of the end consumer, and in fostering technological and social development by bringing together different people with the common goal of energy sustainability.

2018/2001 repeals Directive 2009/28/EC, which established a regulatory framework for the promotion of the use of energy from renewable sources which set binding national targets on the share of renewable energy in energy consumption and in the transport sector to be met by 2020. The Commission Communication of 22 January 2014 entitled 'A policy framework for climate and energy in the period from 2020 to 2030', established a framework for future Union energy and climate policies and promoted a common understanding of how to develop those policies after 2020.

The Commission proposed that the Union 2030 target for the share of renewable energy consumed in the Union should be at least 27 %. The establishment of a binding Union renewable energy target for 2030 would continue to encourage the development of technologies which produce renewable energy and provide certainty for investors. A target defined at Union level would leave greater flexibility for Member States to meet their greenhouse gas reduction targets in the most cost-effective manner in accordance with their specific circumstances, energy mix and capacity to produce renewable energy.

In order to ensure consolidation of the results achieved under Directive 2009/28/EC, the national targets set for 2020 should constitute Member States' minimum contributions to the new 2030 framework. Under no circumstances should the national shares of renewable energy fall below those contributions. If they do, the relevant Member States should take appropriate measures as provided for in Regulation (EU) 2018/1999 to ensure that baseline share is regained. If a Member State does not maintain its baseline share over a 12-month period, it should, within 12 months of the end of that period, take additional measures to regain that baseline share. Where a Member State has effectively taken such additional measures and has fulfilled its obligation to regain the baseline share, it should be deemed to have complied with the mandatory baseline share requirements under this Directive and under Regulation (EU) 2018/1999 for the entire period in question. The Member State in question cannot therefore be considered to have failed to fulfil its obligation to maintain its baseline share for the period in time where the gap occurred. Both the 2020 and 2030 frameworks serve the environmental and energy policy objectives of the Union.

To this end, of course, a financial framework should be set up to encourage investment in renewable energy projects in the member states, including through the use of financial instruments: allocation of funds for renewable energy projects, development of essential infrastructure for the use of the energy produced, fostering the exchange of best practices between the competent authorities and national and supranational bodies, streamlining the necessary bureaucracy that discourages citizens from taking action to improve and upgrade the energy efficiency of buildings.

The legislation sets out the following roles:

- **renewable self-consumer** defined as *a final customer operating within its premises located within confined boundaries or, where permitted by a Member State, within other premises, who generates renewable electricity for its own consumption, and who may store or sell self-generated renewable electricity, provided that, for a non-household renewables self-consumer, those activities do not constitute its primary commercial or professional activity;*;

- **jointly acting renewables self-consumers**, defined as *a group of at least two jointly acting renewables self-consumers in accordance with point (14) who are located in the same building or multi-apartment block*;
- **Renewable energy community** is a *legal entity*:
    - *which, in accordance with the applicable national law, is based on open and voluntary participation, is autonomous, and is effectively controlled by shareholders or members that are located in the proximity of the renewable energy projects that are owned and developed by that legal entity*;
    - *the shareholders or members of which are natural persons, SMEs or local authorities, including municipalities*;
    - *the primary purpose of which is to provide environmental, economic or social community benefits for its shareholders or members or for the local areas where it operates, rather than financial profits*.

At point 65 of European Directive 2018/2001 describes the opportunity for a transition to decentralised energy production, which has many advantages, including the use of local energy sources, greater local security of energy supply, shorter transport distances, and reduced energy transmission losses, while also fostering community development and cohesion through the availability of income sources and the creation of local jobs. At the points 66 and 67, the granting of rights to self-consumers is also discussed, in order to enable renewable energy communities to increase the energy efficiency of households and to help combat energy poverty by reducing consumption and supply tariffs. Member States should appropriately seize this opportunity, also considering the possibility of allowing the involvement of households that might, otherwise, not be able to participate, including vulnerable consumers and tenants.

Renewables self-consumers should not face discriminatory or disproportionate burdens or costs and should not be subject to unjustified charges. Their contribution to the achievement of the climate and energy target and the costs and benefits that they bring about in the wider energy system should be taken into account. Member States should therefore generally not apply charges to electricity produced and consumed within the same premises by renewables self-consumers. However, Member States should be allowed to apply non-discriminatory and proportionate charges to such electricity if necessary to ensure the financial sustainability of the electricity system, to limit the support to what is objectively needed and to make efficient use of their support schemes. At the same time, Member States should ensure that renewables self-consumers contribute in a balanced and adequate way to the overall cost-sharing system of producing, distributing and consuming electricity, when electricity is fed into the grid.

RED II emphasises in point 70 that the participation of local citizens and authorities in renewable energy projects through renewable energy communities has resulted in significant added value in terms of local acceptance of renewable energy and access to additional private capital, which translates into local investment, more choice for consumers and greater citizen participation in the energy transition.

The specific characteristics of local renewable energy communities, in terms of size, ownership structure and number of projects, may hinder their equal competitiveness with larger operators, notably competitors with larger projects or portfolios. Member States should have the possibility to choose any form of entity for renewable energy communities provided that this entity can, acting in its own name, exercise rights and be subject to certain obligations. To avoid abuse and ensure broad participation, Renewable Energy Communities should be able to maintain their autonomy from individual members and other traditional market actors participating in the community as members or shareholders, or cooperating by other means, such as investment. Participation in renewable energy projects should be open to all potential local members on the basis of objective, transparent and non-discriminatory criteria. Suitable measures also include the possibility for energy communities to operate in the energy system and facilitate their integration into the market. Renewable energy communities should be able to share among themselves the energy produced by the plants they own. However, community members should not be exempt from relevant costs, charges, levies and taxes, and should maintain their rights as consumers including the right to have a contract with the supplier of their choice and to change supplier at any time.

Article 21 of RED II defines self-consumption by asserting that:

1. Member States shall ensure that consumers are entitled to become renewables self-consumers, subject to this Article,
2. Member States shall ensure that renewables self-consumers, individually or through aggregators, are entitled:
    a) to generate renewable energy, including for their own consumption, store and sell their excess production of renewable electricity, including through renewables power purchase agreements, electricity suppliers and peer-to-peer trading arrangements, without being subject:
        - in relation to the electricity that they consume from or feed into the grid, to discriminatory or disproportionate procedures and charges, and to network charges that are not cost-reflective;
        - in relation to their self-generated electricity from renewable sources remaining within their premises, to discriminatory or disproportionate procedures, and to any charges or fees;

    b) to install and operate electricity storage systems combined with installations generating renewable electricity for self-consumption without liability for any double charge, including network charges, for stored electricity remaining within their premises;

    c) to maintain their rights and obligations as final consumers;

    d) to receive remuneration, including, where applicable, through support schemes, for the self-generated renewable electricity that they feed into the grid, which reflects the market value of that electricity and which may take into account its long-term value to the grid, the environment and society.

Member States may apply non-discriminatory and proportionate charges and fees to renewables self-consumers, in relation to their self-generated renewable electricity remaining within their premises in one or more of the following cases:

a) if the self-generated renewable electricity is effectively supported via support schemes, only to the extent that the economic viability of the project and the incentive effect of such support are not undermined;

b) from 1 December 2026, if the overall share of self-consumption installations exceeds 8 % of the total installed electricity capacity of a Member State, and if it is demonstrated, by means of a cost-benefit analysis performed by the national regulatory authority of that Member State, which is conducted by way of an open, transparent and participatory process, that the provision laid down in point (a)(ii) of paragraph 2 either results in a significant disproportionate burden on the long-term financial sustainability of the electric system, or creates an incentive exceeding what is objectively needed to achieve cost-effective deployment of renewable energy, and that such burden or incentive cannot be minimised by taking other reasonable actions; or

c) if the self-generated renewable electricity is produced in installations with a total installed electrical capacity of more than 30 kW.

In accordance with Article 22 of European Directive 2018/2001 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 or procedures that would prevent their participation in a renewable energy community, provided that for private undertakings, their participation does not constitute their primary commercial or professional activity.

Article 22 also establishes that Member States will have to guarantee RECs the right to:

- produce, consume, store and sell renewable energy, including through renewables power purchase agreements;

- share, within the renewable energy community, renewable energy that is produced by the production units owned by that renewable energy community, subject to the other requirements laid down in this Article and to maintaining the rights and obligations of the renewable energy community members as customers;
- access all suitable energy markets both directly or through aggregation in a non-discriminatory manner.

In this context, it is therefore necessary for Member States to streamline bureaucracy in order to make the RECs sustainable, eliminating all those unjustified steps that discourage citizens, especially the less well-off, from taking this big step towards the energy transition.

Last but not least, the directive stipulates that RECs can be open to cross-border participation, which is very important in order to break down distances bringing the EU States even closer together.

in summary, EU Directive 2018/2001:

- ensures that the binding EU target is achieved in a cost-effective manner
- establishes a stable, market-oriented European approach to renewable electricity
- provides long-term certainty for investors and accelerates the licensing procedures necessary for the realisation of projects
- enables consumers to take part in the energy transition with the right to produce their own renewable energy
- promotes the use of renewable energy in the heating, cooling, and transport sectors;
- reinforces the EU sustainability criteria for bioenergy,

and includes:

- an overall binding target for the EU for 2030 requiring the use of no less than 32% of energy from renewable sources;

- the rules for cost-effective and market-based financial support for electricity from renewable sources;
- the protection of support systems from changes that jeopardise existing projects;
- cooperation mechanisms between EU and non-EU countries;
- the simplification of administrative procedures for renewable energy projects (including time limits and digitalisation).

2.1.2 European Directive 2019/944

European Directive 2019/944 was approved by the European Parliament and Council on 5 June 2019 and regulates the internal market for electricity, amending Directive 2012/27/EU and repealing Directive 2009/72/EC. In particular, the text focuses on consumers' rights regarding self-generated electricity stating that: *consumers should be able to consume, to store and to sell self-generated electricity to the market and to participate in all electricity markets by providing flexibility to the system, for instance through energy storage,such as storage using electric vehicles, through demand response or through energy efficiency schemes. New technology developments will facilitate those activities in the future. However, legal and commercial barriers exist, including, for example, disproportionate fees for internally consumed electricity, obligations to feed self-generated electricity to the energy system, and administrative burdens, such as the need for consumers who self-generate electricity and sell it to the system to comply with the requirements for suppliers, etc. Such obstacles,which prevent consumers from self-generating electricity and from consuming, storing or selling self-generated electricity to the market, should be removed while it should be ensured that such consumers contribute adequately to system costs. Member States should be able to have different provisions in their national law with respect to taxes and levies for individual and jointly-acting active customers, as well as for household and other final customers*.

Energy communities are an effective and cost-efficient way to respond to citizens' needs and expectations regarding energy sources, services and local participation. Energy community initiatives mainly focus on the affordable supply of energy from specific sources, such as renewables, for members or associates, rather than on profit purpose like traditional power companies. Energy community initiatives demonstrate that they have the potential to support the deployment of new technologies and new forms of consumption, including smart distribution networks and demand-side management, in an integrated manner. They also make it possible to increase the energy efficiency at household level and reduce energy poverty by decreasing consumption and supply tariffs. The energy community also enables certain groups of household customers to take part in the electricity market, which they might otherwise not be able to access. In cases of good management, these initiatives have brought economic, social and environmental benefits to the community which beyond the mere benefits of providing energy services.

This Directive aims to recognise certain categories of citizen energy initiatives at EU level as Citizen Energy Communities (CECs) in order to provide them with a supportive framework, fair treatment, a level playing field and a well-defined list of rights and obligations. The CEC is defined as a legal entity:

- 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;
- whose primary purpose is 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
- 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.

Citizen energy communities are therefore a different kind of entity by virtue of their membership structure, governance requirements and purpose. They should be able to operate in the market on a level playing field, without distorting competition, and the rights and obligations applicable to other electricity undertakings in the market should be applied to citizen energy communities in a proportionate and non-discriminatory manner. These rights and obligations should apply in accordance with the roles assumed, e.g. that of final customer, producer, supplier or distribution system operator. Citizen energy communities should not be subject to regulatory restrictions when they apply existing or future information and communication technologies to share among their members or associates, on the basis of market principles, the electricity produced using generation facilities within the citizen energy community, for example by offsetting the energy component of the members or partners with the production available within the community, even if the sharing takes place on the public grid, as long as both measurement points belong to the community. The sharing allows members or partners to be supplied with electricity from generation facilities within the community without being in direct physical proximity to the generation facility or under a single metering point. Where electricity is shared, the sharing should not affect the collection of network charges, tariffs and fees related to electricity flows. The sharing should be facilitated by existing regulations.

This directive also regulates electromobility, stipulating that Member States shall define the regulatory framework necessary to facilitate the connection of electric vehicle charging points to the distribution networks, while distribution system operators (DSOs) may only own, develop, manage or operate charging points if no other body has expressed an interest in an open tender procedure, subject to approval by the regulator and in line with third-party access rules.

2.1.3 Differences and Similarities between European Directives 2018/2001 and 2019/944

Table 2.1 summarises the definitions of RECs and CECs.

The prosumers' discipline is contained in article 21 of the REDII which takes the form of a series of obligations born by the States so that self-consumers of renewable energy, individually or through aggregators, are authorized to produce, store and sell surplus energy production. renewable electricity, also through renewable electricity purchase and sale

Table 2.1. RECs and CECs definitions.

RECs are defined in paragraph no. 16 of Article 2 as a legal entity:	**CECs are, on the other hand, defined in the IMDII Directive in paragraph 11 of article 2 as a legal entity that:**
in accordance with the applicable national law, is based on open and voluntary participation, is autonomous, and is effectively controlled by shareholders or members that are located in the proximity of the renewable energy projects that are owned and developed by that legal entity	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
the shareholders or members are natural persons, SMEs or local authorities, including municipalities;	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
the primary purpose is to provide environmental, economic or social community benefits for its shareholders or members or for the local areas where it operates, rather than financial profits	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

agreements, electricity suppliers and agreements for peer to peer exchanges, without being subject to discriminatory or disproportionate procedures and charges and network charges that do not take into account the costs incurred. At the same time, the regulation provides for the right of the prosumer to maintain rights and obligations as final consumers.

CEC is a wider concept that is free from several restrictions and its organizational structure can be used by citizens, small businesses and local authorities to participate across the energy sector. In this concept, there is a strong analysis on the non-discriminatory access to the electricity markets through aggregation. In turn, RECs have more stringent requirements: there is a stronger obligation for private undertakings that their participation must not constitute their primary commercial or professional activity; the shareholders or members must be located in the proximity of the RE projects that are owned and developed by the REC. Member states are invited to incentivize primarily the development of RECs, to support real aggregation services rather than to provide a playing field in the energy market (as for CECs). Despite these differences, both types of ECs share some similarities, that can be summarized as follows:

- They require a legal entity as a community umbrella;
- They must be voluntary and open;
- They should be primarily value driven rather than focusing on financial profits;
- They require a specific governance.

A list of similarities and differences is reported in Table 2.2.

Table 2.2. Similarities and differences between CECs and RECs.

Similarities:	**Differences:**	
	CECs	RECs
They require a legal entity	They don't have geographic limitation (also open to cross-border participation)	There must be a proximity to the source and an effective control under a defined in national law
They must be voluntary and open	There is no limitation on the membership	There are limitations on the membership: large companies are not allowed as shareholders or members
They should be primarily value driven rather than focusing on financial profits	They must be focused only on electricity but not necessarily focused on renewable energy	They are open only to renewable energies but of any kind (e.g., also heat)
They require a specific governance	The purpose is to create a new market actor	The purpose is to promote a way to expand the share of renewable energy at national level.

2.2 The Italian Regulation: Article 42-bis of the Milleproroghe Decree

Although Italy has not yet enacted national legislation to transpose the Renewable Energy Directive (EU Directive 2018/2001) and the Internal Electricity Market Directive (EU Directive 2019/944), it has started a trial phase on the former.

To date, the Italian regulation on collective self-consumption and renewable energy communities consists of Article 42-bis, included in the Milleproroghe Decree (converted into Law no. 8/2020 on 29 February 2020).

According to this Article, it ’s permitted to activate collective self- consumption from renewable sources or to realise renewable energy communities in the manner and under the conditions laid down in the Article 42-bis. The monitoring of such realisations shall be functional for the acquisition of useful elements for the implementation of the self-consumption provisions of the aforementioned Directive (EU) 2018/2001 and Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 concerning common rules for the internal market in electricity and amending Directive 2012/27/EU.

This article refers to Article 21 of the RED II stating that electricity consumers may join together to become self-consumers of renewable energy acting collectively within the meaning of paragraph no. 4 of Article 21 of Directive (EU) 2018/2001 in particular by complying with the following conditions:

a) in the case of self-consumers of renewable energy acting collectively, persons other than households are associated only if the activities mentioned in letters a) and b) of Article 42-bis, paragraph 4, do not constitute the main commercial or professional activity;

b) in the case of energy communities, the shareholders or members are natural persons, small and medium enterprises or local authorities, including municipalities, and participation in the renewable energy community may not constitute the main commercial or industrial activity;

c) the main objective of the association is to provide environmental, economic or social benefits at to its shareholders, members or to the local areas where the community operates, rather than financial profits;

d) participation in renewable energy communities is open to all consumers located within the perimeter of paragraph 4(d), including those belonging to low-income or vulnerable households.

Legal entities set up to establish energy and self-consumption communities must act in accordance with the following conditions, some of which are very restrictive and will certainly have to be updated in the final transposition law:

a) the participating entities produce energy for their own consumption with plants powered by renewable sources with a total capacity not exceeding 200 kW, which came into operation after the date of entry into force of the law converting this decree and within sixty days following the date of entry into force of the measure transposing RED II,

b) the participating entities share the energy produced using the existing distribution network. The shared energy is equal to the minimum, in each hourly period, between the electricity produced and fed into the grid by renewable energy plants and the electricity withdrawn by all associated end-customers,

c) the energy is shared for instantaneous self-consumption, which may also take place through storage systems installed in the perimeter referred to d) or at the buildings or condominiums referred to e),

d) in the case of renewable energy communities, the consumers' pick-up points and the feed-in points of the plants referred to a) are located on low-voltage grids connected, on the date of creation of the association, to the same medium voltage/low voltage transformer substation,

e) in the case of self-consumers of renewable energy acting collectively, they are located in the same building or condominium.

The customers associated with the above configurations maintain the right to choose their seller and withdraw from the self-consumption configuration at any time. In addition, a **delegated subject** is identified as responsible for allocating the shared energy; customers may also delegate to this subject the management of payment and collection items towards sellers and the Gestore dei Servizi Energetici (GSE). The Regulatory Authority for Energy, Networks and Environment (ARERA) must adopt the measures necessary to ensure the immediate implementation of the measures discussed so far, supervising the tariffs applied and making the aggregation procedure simple, as well as establishing a continuous monitoring system of the configurations implemented.

Another key issue is the identification of an incentive tariff for the remuneration of renewable energy plants. The incentive tariff is provided by GSE Spa and rewards instantaneous self-consumption and the use of storage systems. The mechanism is implemented taking into account the principles of simplification and ease of access and it provides for a system of reporting and monitoring of economic and energy flows in order to acquire useful elements for the general reform of the on-site exchange mechanism, in the context of the transposition of EU Directive 2018/2001. The incentive tariff is granted for a maximum utilisation period and is modulated among the different incentive configurations to ensure the profitability of the investments. The mechanism is realised taking into account the overall balance of the charges in the bill and the need of not increasing the trend costs compared to those of the existing mechanisms.

To summarise, the collective self-consumption is done by a plurality of consumers located within a building in which there is one or more plants powered exclusively by renewable sources. The plants can be owned by third parties and take advantage of specific benefits, such as tax deductions. The provision for energy communities stipulates that the participating entities must produce energy for their own consumption with plants powered by renewable sources with a total power not exceeding 200 kW. In order to share the energy produced, users can use existing distribution networks and use forms of virtual self-consumption.

The most restrictive part of the standard is certainly the one that stipulates that the renewable energy community must consist of consumers linked to the same medium/low-voltage substation, but members still retain the right to enter and exit at will and choose their supplier.

While collective self-consumption in buildings may be managed by one's own condominium, energy communities may take the form of any entity capable of acting in its own name and be the recipient of obligations and rights. In both cases, participation must be open, based on objective, transparent and non- discriminatory criteria. This means that if a condominium installs a generation plant in the building, all interested condominiums must be able to participate in collective self-consumption. Similarly, in an energy community that is being created, all interested users belonging to the same medium/low-voltage electrical substation have the right to join the community (cooperative/association/etc.). Fulfilment of condominium obligations is one of the objective criteria for community membership. It is also possible to create distinct membership categories, which differ in that they are user members (those who do not participate in the investment for the installation of the generation or storage system) and user/investor members (those who financially support the installation of the generation or storage system). In both cases, users retain their electricity supplier and can leave the collective self-consumption or energy community scheme at any time. In the case of early withdrawal, the sharing of the investment incurred must be fair and proportionate.

Crucially, the energy shared within the community is equal to the minimum, in each hourly period, between the electrical energy produced and fed into the grid by the community's plants and the electrical energy withdrawn by all associated members.

To access the incentives provided, shown in detail in table 2.3, it needs to be underlined that the system must be new, i.e., installed after first March 2020; these incentives will be cumulative with tax deductions where available, according to the two types:

- Shared energy for collective self-consumption (same building or condominium): 100 €/MWh;
- Shared energy within renewable energy communities (same medium/low voltage electrical substation): 110 €/MWh.

Table 2.3. Scheduled incentive tariffs for Collective Self-Consumption and Renewable Energy Communities

Remuneration:	**Collective Self-Consumption:**	**Renewable Energy Community:**
UNITARY REMUNERATION ARERA	LV transmission tariff (equal to 7.61 €/MWh) + BTAU distribution variable component value (equal to 0.61 €/MWh) + grid losses (equal to 1.3 €/MWh for LV and 0.6 €/MWh for MV)	LV transmission tariff (equal to 7.61 €/MWh) + BTAU distribution variable component value (equal to 0.61 €/MWh)
BONUS of MiSE	100 €/MWh	110 €/MWh

The regulation also provides for the refund of some items in the bill for the avoided energy transmission to the grid that these plants allow, with consequent relief that ARERA quantifies at 10 €/MWh for Collective Self-consumption and 8 €/MWh for RECs on shared energy. The remuneration of energy fed into the grid at the Hourly Zonal Price must also be considered, which according to RSE is assumed to be about 50 €/MWh. So the sum of all benefits would amount to about 150-160 €/MWh.

2.3 Associated Complementary Regulations

In the wake of the Covid-19 pandemic, the Italian government issued the Decreto Rilancio (D.L. 34/2020), which consists of a series of measures to facilitate the country's recovery on several fronts. Among the various measures, particular attention is paid to the energy efficiency of structures through the Ecobonus 2020, which closely concerns energy communities. In particular, Article 119 of the aforementioned decree introduces a deduction equal to 110% of the expenses related to specific energy efficiency and earthquake-proof measures on buildings, incurred from 1 July 2020 until 31 December 2021, but recently extended to 30 June 2022 with the Budget Law of 2021 (L. no. 178 of 30/12/20). The tax relief consists of deductions from gross tax for earthquake-proof interventions or that increase the energy efficiency of existing buildings. These measures apply exclusively to interventions carried out by condominiums and individuals, excluding those engaged in business, arts and professions; the Autonomous Institutes for Popular Housing (AIPH), however denominated, indivisible housing cooperatives, Third Sector entities, and amateur sports associations and societies are covered for certain types of intervention. The prerequisite for obtaining the tax relief is that the interventions must undergo a special procedure that certifies the regularity of the interventions through qualified professionals, who must also certify the congruity of the expenses incurred with the subsidised interventions. To access the 110 % benefits, at least one of the following leading interventions must be carried out, which bring about an improvement of at least two energy classes of the building:

- Intervention of thermal insulation of opaque structures on vertical, horizontal and inclined surfaces affecting at least 25% of the gross dispersion surface of the building. The building concerned may be a condominium, a building consisting of two to four separately registered building units owned by a single owner or co-owned by several individuals, a single-family building, or a building unit located within multi-family buildings as long as it is functionally independent and has one or more independent accesses;
- intervention on the common parts of the building for the replacement of existing winter air-conditioning systems with centralised systems equipped with:
  - water condensing boilers with a seasonal energy efficiency of room heating at least equal to product class A in accordance with Commission Delegated Regulation (EU) No. 811/2013 of 18 February 2013 ($\eta_s \geq 90$ %),
  - heat pumps and factory-assembled hybrid systems also with geothermal probes and eventually combined with photovoltaic plants and related storage systems,
  - micro-cogeneration plants,
  - solar collectors for the production of hot water, used for winter and summer air

conditioning, in the case of reversible heat pumps, and for the production of domestic hot water,

- In addition, for interventions on the common parts of the building for the replacement of the existing winter air-conditioning systems with centralised systems, and exclusively for municipalities mountain municipalities not affected by European infringement procedures no. 2014/2147 of 10 July 2014 or no. 2015/2043 of 28 May 2015 for Italy's non-compliance with its obligations under Directive 2008/50/CE, it will be possible to connect to efficient district heating systems,
- moreover, again for interventions on single-family buildings or on units located within multi-family buildings as long as they are functionally independent and have one or more independent accesses, and exclusively for non-methanised areas in municipalities not affected by the European infringement procedures no. 2014/2147 of 10 July 2014 or no. 2015/2043 of 28 May 2015 for Italy's non-compliance with its obligations under Directive 2008/ 50/CE, the replacement of existing winter air-conditioning systems may be carried out with biomass boiler systems having emission performance with the values envisaged for at least class 5 stars. Finally, exclusively for mountain municipalities not affected by the European infringement procedures no. 2014/2147 of 10 July 2014 or no. 2015/2043 of 28 May 2015 for Italy's non-compliance with the obligations under Directive 2008/50/CE, it will be possible to connect to systems of efficient district heating systems.

As far as energy communities are concerned, it has been said that by moving up two energy classes it will be possible to take advantage of the 110% deduction for interventions involving the installation of PV systems up to 20 kWp, storage systems related to the photovoltaic system (€1,000/kWh) and charging stations for electric cars, up to a maximum total expenditure of € 48,000. In particular, the application of the higher rate is envisaged when there is a transfer to the GSE of energy not self-consumed on site or not shared for self-consumption, where a decree of the Minister of Economic Development, in accordance with paragraph 9 of Article 42-bis , identifies the limits and procedures regarding the use and valorisation of shared energy produced by incentivised plants.

If renewable energy communities consisting of non-commercial entities or condominiums install plants up to 200 kW, which adhere to the configurations referred to Article 42-bis of Decree-Law 162/2019, the Superbonus applies to the portion of expenditure corresponding to the maximum power of 20 kW, while for the portion of expenditure corresponding to the power exceeding 20 kW, the ordinary deduction established by the Testo Unico delle Imposte sui Redditi (TUIR) applies, up to a maximum overall expenditure limit of €96,000 referred to to the entire system.

Chapter 3

The Forming Process of an Energy Community

Within the reference regulatory framework mentioned in Chapter 2, ARERA's Resolution 318/2020/R/eel emerges, transposing RED II (EU) with the transitional character of Article 42-bis of Decree-Law 162 and disciplining the modalities and economic regulation of renewable energy shared in buildings or condominiums by a group of self-consumers, whether they act collectively or as part of a renewable energy community.

This resolution introduces a virtual regulatory model for new configurations of self-consumption or CERs, making it possible to recognise the benefits of in-situ consumption of locally produced electricity avoiding, however, the creation of new closed networks (with highly complicated technical solutions) and keeping separate the benefits associated with self-consumption (which do not depend on sources, types of networks and/or company structures) and the explicit incentives (which, as such, can be appropriately calibrated according to sources and/or technologies).

This virtual model envisages that the GSE provides the service of 'valorisation and incentivisation of shared energy') through the Configuration Referent. However, the GSE is called upon to perform the following tasks for the purposes of managing the mechanism:

- prepare and transmit, for positive verification by the Director of the Wholesale

Energy Markets and Environmental Sustainability Directorate of ARERA, the instance scheme, the contract outline and the Technical Rules containing, among other things, the precise calculation criteria that may be required, the methods for communicating to the Referent the configurations that benefit of the service of valorisation and incentivation of shared electricity and the methods of data profiling and its use,

- provide local assistance services to public administrations,
- set up a special informatic platform operating with the Gestione delle Anagrafiche Uniche Degli Impianti (GAUDI) system, for the purpose of accessing the shared electricity valorisation and incentive service, as well as for the technical and economic management of the same service.

The incentives provided for the shared energy service are defined by the Minister of Economic Development through the aforementioned decree of 16 September 2020 on "Identification of the incentive tariff for the remuneration of renewable energy plants included in the experimental configurations of collective self-consumption and renewable energy communities, in compliance with Article 42-bis, paragraph 9, of D.L. No. 162/2019, converted by Law No. 8/2020", which came into force on 17 November 2020. According to the provisions of the Decree, the energy produced and fed into the grid remains in the availability of the Configuration Referent, with the option of sale to the GSE in the manner described in Article 13, paragraph 3, of the legislative decree 387/2003, notwithstanding the obligation of transfer envisaged for those who access the tax deduction of 110 %.

The configurations admitted to the shared electricity valorisation and incentive service managed by the GSE are two: a group of self-consumers of renewable energy acting collectively and a renewable energy community. According to the GSE, a group of self-consumers *is a set of at least two self-consumers of renewable energy acting collectively and located in the same apartment block or building. A self-consumer of renewable energy is an end-consumer who, operating on its own sites within defined boundaries, produces renewable electricity for its own consumption and may store or sell self-produced renewable electricity as long as, for a self-consumer of renewable energy other than households, such* *activities do not constitute its main commercial or professional activity. The production plant of the self-consumer of renewable energy may be owned and/or managed by a third party, provided that the third party remains subject to the instructions of the self-consumer of renewable energy. The self-consumer of renewable energy may realise, independently or jointly with a third party producer, a configuration of Efficient Utility Systems (EUS) or Self-Production Systems (SPS) within the meaning of the Integrated Text on Simple Production and Consumption Systems, in compliance with the relevant definitions.* The GSE also incorporates the definition provided by RED II about REC as a legal entity:

- which is based on open and voluntary participation, is autonomous and effectively controlled by shareholders or members who are located in the proximity of the renewable energy community's production plants,
- whose shareholders or members are natural persons, small and medium enterprises, territorial entities or local authorities, including municipalities, provided that, for private enterprises, participation in the energy community is not their principal commercial and/or industrial activity,
- whose principal objective is to provide environmental, economic or social benefits at community level to its shareholders or members or to the local areas in which it operates, rather than financial profits.

In accordance with Paragraph 4, Article 11 of Legislative Decree 28/2011, plants installed for the purpose of fulfilling the obligations for the integration of renewable energy sources in new buildings and existing buildings undergoing major renovations, access to state incentives provided for the promotion of renewable energy sources within the limit of the quota exceeding that required to comply with the same obligations.

According to Annex 3 of the aforementioned Decree, the obligatory power P_o is defined according to 3.1:

$$P_o = \frac{1}{K} S \tag{3.1}$$

where S is the floor area of the building at ground level, measured in m^2, and K is a coefficient (expressed in m^2/kW) which assumes the following values:

- $K = 80$, when the request for the relevant building permit has been submitted between 31 May 2012 and 31 December 2013,
- $K = 65$, when the request for the relevant building permit has been submitted between 1 January 2014 and 31 December 2016,
- $K = 50$, when the request for the relevant building permit has been submitted on 1st January 2017.

The GSE states that for public buildings the previously defined mandatory quota is increased by 10%, while for zones A of the Decree of the Minister of Public Works No. 1444 of 2 April 1968, the mandatory quota is reduced by 50%. Regional laws may establish increases of the percentage values as defined above. The premium tariff, therefore, cannot be granted to the shared electricity attributable to the Po mandatory power quota, notwithstanding the right to the fee set by the Resolution for the whole power of the power plant and the right to transfer the electricity from the plant to the GSE. If a renewable energy plant with a power output P greater than the obligatory power output P_o is built, it is possible to access the premium tariff limited to the power (P - P_o). In such cases, for the only purpose of calculating the incentives related to the premium tariff, the shared electricity is multiplied by a reduction factor equal to (P - P_o)/P.

On the other hand, with regard to photovoltaic systems with modules placed on the ground (i.e., not physically installed on buildings, greenhouses, noise barriers, rural buildings, pergolas and canopies) in agricultural areas, according to Article 65 of D.L. 1/2012, converted by Law 27/2012, it is forbidden to access state incentives. This restriction, however, in accordance with D.L. no. 76 of 16 July 2020, converted by Law 120/2020, does not apply to solar photovoltaic plants to be installed on areas declared as sites of national interest or on landfills and landfill lots closed and restored, quarries or quarry lots not susceptible to further exploitation for which the competent authority issuing the authorisation has certified the completion of the environmental recovery and restoration activities specified in the authorisation title in compliance with the applicable regional regulations, as long as they have been authorised pursuant to Article 4, paragraph 2, of Legislative Decree no. 28 of 3 March 2011, and in any case access to the incentives for such plants does not require any further attestations and declarations.

For these plants to which the prohibition applies, the premium tariff cannot therefore be recognised, without prejudice the right to the remuneration envisaged by the Resolution for the whole capacity of the production plant and the right to sell the electricity to the GSE.

For photovoltaic systems built in rural areas, for which access to the incentive and valorisation service is requested, and installed on greenhouses, noise barriers, pergolas and canopies , it is necessary, at the time of the request, to attach appropriate documentation proving the actual function of the supporting structure (e.g. declaration of start of activity, building permit or land registry certificate).

Having said this, the requirements for access to shared electricity incentive and valorisation services will be explained in the following chapters.

3.1 Technical Rules for Access to the Valuation and Incentive Service of Shared Energy

The GSE specifies that the requirements for access to valorisation and incentive services for shared electricity in both configurations, self-consumption and RECs, must be compulsorily met not only at the time of access, but also throughout the entire period of validity of the configuration.

3.1.1 General Requirements

The relations between the parties belonging to one of the two configurations described above are governed by a private law contract:

- provides for the preservation of end-customer rights, including the right to choose one's own seller;

- unambiguously identifies a delegated subject responsible for allocating the electricity shared to which the parties may, in addition, delegate the management of payment and collection towards the sales companies and the GSE;

- allows the parties to recede at any time and exit from the configuration, notwithstanding any fees agreed upon in the event of early withdrawal for the sharing of the investments made, which must in any case be fair and proportionate.

In the case, for example, of apartment blocks, the contract may also consist of the minutes of the shareholders' meeting decision signed by the tenants joining the group of renewable energy self-consumers acting collectively. For renewable energy communities, the contents listed above are an integral part of the statute and/or deed of incorporation of the same community, which will be discussed below.

Basically, the stipulation of a contract containing at least the contents listed above, integrated into the articles of association of the CER or into the community's deed of incorporation must take place before the request for access to the shared electricity valorisation and incentive service.

The power plants admitted to the shared electricity valorisation and incentive service must be fuelled by renewable sources and come into service from 1 March 2020 and within 60 days from the date of entry into force of the measure transposing European Directive 2018/2011. A renewable energy plant is defined as a plant capable of converting wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogas into other forms of energy . Hybrid production plants, as defined in Annex 1 of the GSE Document, are not eligible for the shared electricity valorisation and incentive service in which, on the other hand, plants that incidentally produce electricity through the combustion of non-renewable sources (e.g. for engine start-up), but for which the share of electricity produced from non-renewable sources is less than 5% per year, participate: in fact, the electricity produced by the plant is considered as renewable overall.

A plant is classified as new if it is installed on a site on which, before the start of works, there had not been for at least five years another electricity production plant fuelled by the same renewable source or the main parts of it. The presence on-site of "main parts" of a pre-existing plant, still identifiable and recoverable in their function, according to ordinary technical-scientific and economic criteria, does not allow the recognition of the category of new construction and consequently access to the evaluation and incentive service. Therefore, if only the modules (even if completely or partially new) are replaced on a site, it is not possible to recognise the category of new construction or access to the various incentives. This also applies to the case where an intervention has been implemented for which the main components (modules, DC-AC converters and other minor electrical components) have also been replaced in their entirety, where the same or part of them have previously been installed in other plants.

The GSE document also mentions the case of plant upgrades. In this case, the part of the plant installed as a result of the upgrade (added portion) must be linked to the same grid connection point as the pre-existing plant and the intervention must be registered on the GAUDI portal by creating a new section.

In the case of upgrades, only the electricity injected into the grid, referred to the upgrading section, contributes to the definition of the shared electricity and, for the purposes of verifying the requirements for access to the shared electricity valorisation and incentive service relating to the entry into operation and the power, the date of entry into operation of the upgrading section and the overall power of the production plant, respectively, is taken as a reference. As established by the Resolution, it is then necessary that the new section is equipped with suitable measuring equipment that allows the measurement, separately, of the electrical energy produced by the new section of the plant with respect to the existing ones: therefore, upgrades that involve the replacement of photovoltaic modules or alternators with others of greater power are not allowed.

Installed photovoltaic modules shall be tested and verified by accredited laboratories for the specific tests in accordance with UNI CEI EN ISO/IEC 17025, in order to demonstrate the quality of the product and the electrical and mechanical safety of the component during its expected lifetime.

Within the configurations entitled to access the shared energy valorisation and incentive service, there may also be recharging infrastructures (commonly referred to as charging stations).

The (citare regole tecniche) define the subjects referred to as producer and final customer.

The producer is a natural or legal entity that produces electricity, which does not necessarily coincide with the owner of the generation plant. The producer is the holder of the electrical production workshop licence or company code, where provided for by the legislation in force, as well as of the authorisations for the construction and operation of the production plant, and is also the signatory of the operating regulations. In order to have access to this measure, the producer must have obtained the electrical workshop licence or the company code, where provided for by the regulations in force, and have signed the operating regulations.

The end customer is the person who draws electricity from the grid, for the amount of his own end use, in order to supply the consumers belonging to the consumption unit of which he has the availability. To this end, the end customer is the owner of the connection point of the consumption unit and therefore the holder of the electricity bill. In order to verify the ownership of the connection point by the end customer, the GSE shall refer to the master data reported in the Official Central Register (OCR) of the Integrated Information System (IIS) of the Single Buyer S.p.A.

3.1.2 Specific Requirements for Self-Consumer Configurations

According to ARERA Resolution 318/2020/R/eel, the configurations of a group of self-consumers must include at least two end customers and one plant/section of a production plant. The entities must be end customers and/or producers with the following requirements:

- be holders of connection points located in the same building or condominium;
- do not carry out as their main commercial or professional activity the production and exchange of electricity (in this respect it is necessary, in the case of persons other than private households, that the prevailing ATECO code of the self-consumer is different

from codes 35.11.00 and 35.14.00);

- having subscribed to a private law contract meeting the requirements discussed in Chapter 3.1.1;

- having given a mandate to the Referent to constitute and manage the configuration and for the request to the GSE and obtain the benefits provided by the shared energy valorisation and incentive service.

The final customers that are part of the configuration must provide, through the Referent, a release to the GSE for the use of the data related to their connection points for the purposes of verifying the requirements and for the valorisation and incentivisation of the shared energy, as well as to achieve all the objectives provided for Article 42-bis of D.L. 162/2019 and by the ARERA Resolution. Other end customers with withdrawal points located in the same building or condominium to which the configuration refers but not associated with them (without a contract) may issue a release to the GSE, again through the Referent, for the purpose of using the measurement data relating to their connection points in order for them to be taken into account in the calculation of the shared electricity. The GSE, as autonomous data controller for the recognition of benefits deriving from self-consumption, will adopt the most appropriate methods for the processing of such data in compliance with the provisions of EU Regulation 679/2016 (GDPR), interfacing where necessary with the GSE group, Ministries and Regulatory Authorities, as well as with energy distribution companies and/or sellers, without prejudice to the responsibilities of the latter regarding the processing and data in their ownership.

The connection points of the end customers and/or producers and the generation plants, including any storage systems or charging stations, whose electricity is relevant for the determination of the electricity shared in the self-consumption group, must be located in the area pertaining to the same building or condominium (as surveyed by the cadastre according to the specific designations). This verification must be carried out by the Referent.

3.1.3 Specific Requirements for Renewable Energy Communities

According to ARERA Resolution 318/2020/R/eel, RECs must have at least two end customers, shareholders or community members, and a production plant/section of plant. The REC must meet the following requirements:

- be an autonomous legal entity that, acting in its own name, can exercise rights and be subject to obligations;
- have as its main social purpose (as reflected in its Statute and/or Memorandum of Association) that of providing environmental, economic or social benefits at community level to its shareholders or members or to the local areas in which it operates, rather than financial profits;
- have a statute or memorandum of association that provides for:
    - open and voluntary participation in the community;
    - that the community is autonomous and effectively controlled by the shareholders or members belonging to the configuration;
    - respect of all the conditions set out by the ARERA Resolution, with particular regard to those set out in the private law contract;
- have shareholders or members that are natural persons, small and medium enterprises(SMEs),local authorities, including municipalities, provided that, for private enterprises, participation in the renewable energy community is not their main commercial and/or industrial activity;
- being the owner, i.e., having full availability of the production plants belonging to the configuration.

Subjects that are part of the REC must also meet the following requirements:

- being shareholders or members of the same legal entity (the renewable energy community), meeting the requirements described above;

- be holders of connection points located on low-voltage networks linked to the samemedium/low-voltage transformer substation (secondary substation);

- having mandated the renewable energy community for the request to the GSE and to obtain the benefits provided by the shared energy valorisation and incentive service.

These subjects must also issue, through the Referent, a release to the GSE for the use of the data relating to their connection points for the purposes of verifying requirements and for the valorisation and incentivisation of shared energy, as well as to achieve all the objectives set forth in Article 42-bis of D.L. 162/2019 and in ARERA Resolution.

The connection points of the members or shareholders of a renewable energy community and of the production plants must be linked to the same secondary cabin. The Resolution provides for grid operators to implement tools enabling them to identify, also on a conventional basis, the connection points tied to the same secondary substation. The perimeter defined by the Grid Manager on the basis of the same secondary substation remains unaffected in order to protect different users (end customers and/or producers) belonging to the same renewable energy community in the event that the distribution company, due to technical requirements, subsequently has to change the secondary substation to which the consumption units and/or production plants of the same users are connected.

Before sending to the GSE the request for access to the shared energy valorisation and incentive service, the Referent shall verify that the connection points of the end customers and of the production plants, whose electricity is relevant for the configuration, identified by their respective Point Of Delivery (POD) codes, are connected to the same secondary substation, according to the information made available by the reference grid operator. They will then transmit to the GSE, in accordance with the provisions of the Resolution, the information relating to the secondary substation to which the connection points which they detect for the configuration are connected, according to the modalities defined by the GSE: the answers or information provided by the grid operators to the Referent will be considered valid, for a period of 180 days, after which new verifications will have to be carried out.

3.1.4 Request for Service Activation

According to Resolution 318/2020/R/eel of ARERA, a Referent is defined as the entity to which the producers and end customers, present within one of the configurations mentioned in chapter 3.1.2, jointly confer the mandate for the technical and administrative management of the request for access to the valorisation and incentive service, the processing of the data and the signing of the relative contract with the GSE for obtaining the benefits provided by the aforementioned service.

The Referent is identified as follows:

- in the case of a group of self-consumers of renewable energy acting collectively is:
  - the condominium, acting through its administrator or representative where there is no obligation to appoint an administrator,
  - the owner of the building, if the connection points of the aforementioned group are located within the same building whose units belong to a single entity, who in the case of legal entities acts through its legal representative,
  - an electricity producer managing one or more generation plants whose produced electricity is relevant in the configuration of a group of self-consumers of renewable energy acting collectively;
- in the case of a renewable energy community, it is the community itself.

According to the GSE document, all communications relating to the incentive eligibility procedure will be sent to the Referent, including any requests for supplementary documentation or any communications containing the reasons preventing qualification. All active invoices issued by the GSE relating to the administrative costs due to the same GSE will be addressed to the Referent who shall then be responsible for issuing invoices to the GSE in respect of the amounts due. In order to carry out the envisaged verification and control activities, the Referent is required to allow access to the production plants and consumption units that are relevant for the purposes of the configurations, informing the relevant end customers and producers in advance. Any recoveries resulting from audits and sample checks shall be applied to the Referent only, who shall transfer them to the members of the configuration (or some of them) in the manner that he deems most appropriate. The Referent, within the limits of the declarations made pursuant to D.P.R. 445/20008 and of the data communicated to the GSE, shall be liable for any unlawful acts committed, with particular reference to the cases provided for Article 76 of the aforesaid decree. In such cases, without prejudice to the actions for damages of the injured parties against those responsible, the GSE shall proceed to the cancellation/revocation of the admission to the contributions.

In order to submit the request for access to the service, the Referent must register with the GSE's electronic portal; the request for access must be received exclusively electronically from the aforementioned portal, by entering his credentials. The GSE will validate the request received, comparing the data communicated by the Referent with those present in GAUDì regarding the plants included in the configuration and those of the connection points.

The effective date of the valorisation and incentive service corresponds with the date on which the request for access to the service is sent to the GSE, but the Referent may indicate a different effective date. Obviously, this date cannot be lower than the subscription date of the community of self-consumers on the contract or the deed of incorporation of the REC.

In order to receive the amounts due, the Referent that falls within the subjects under anti-mafia verification, in accordance with D.L. 159/2011 and ss.mm.ii., shall submit to the GSE the documentation required by the same Legislative Decree, through the special section of the Customers Area, called "Anti-mafia Documentation": the absence of such documentation is a reason for refusal of the request.

3.2 Request for Access to the Service for Self-Consumers of Renewable Energy Who Act Collectively

In the case of a request for access to the shared energy valorisation and incentive service for a group of self-consumers of renewable energy acting collectively, the Referent must operate exclusively by means of the GSE Electronic Portal through his personal area. The Referent will have to answer a series of questions in order to verify the presence of the necessary requirements, to indicate the type and address of the configuration (building or condominium), to enter the date of formation of the association of subjects and a possible effective date of the contract/service different from that of submission of the request. Finally, it is also required to enter information on all end customers, producers, installations and PODs detected for the configuration.

After providing all the required information, the Referent shall download and print out the service access request and the customer and producer mandates automatically generated by the Electronic Portal on the basis of the data entered and, following the verification of the correctness of all the data and information contained therein, subscribe the request and have the end customers and producers sign the mandates and upload them in digital format on the Electronic Portal, together with a digital copy of the valid identity document of the signatories and the relevant attachments, taken from the GSE document and listed below:

1. request for access to the service presented in the form of a declaration in lieu of affidavit, drafted pursuant to Articles 46 and 47 of DPR 445/2000, and privacy policy for data processing, pre-filled from the portal, accompanied by a copy of a valid identity document of the signatory;

2. mandates of end customers and/or producers forming part of the configuration pre-filled by the portal, accompanied by a copy of a valid identification document of the signatories;

3. mandates of producers that are not part of the configuration but are relevant for the purposes of the configuration, pre-filled by the portal, accompanied by a copy of a valid identification document of the signatories;

4. releases of end customers not forming part of the configuration whose withdrawn electricity is relevant for the calculation of the shared electricity, pre-filled by the portal, accompanied by a copy of a valid identification document of the signatories;

5. planimetric layout on a cadastral map extract showing the perimeter of the building/-condominium to which the configuration refers and the positioning of the plants;

6. single-line electrical diagram of the production plant with evidence of any storages and the positioning of the meters (for each production/upgrading plant);
7. minutes of activation of the meter for the electrical energy fed in, of the production meter (in the case of an upgrade) and of the meter relating to the storage system (only in the case of the installation of storage systems for which the regulation in force requires the installation of the relevant meters), issued by the competent network operator (for each production/upgrading plant);
8. a copy of the electricity workshop licence(s)/company code issued by the Customs Agency, in the case of plants with a power output greater than 20 kW, or a copy of the operating regulation for plants with a power output less than or equal to 20 kW (for each production/expansion plant);
9. photo of the photovoltaic module label (one for each model), of the inverter label (one for each model) or, in the case of systems different from photovoltaic systems, of the alternator/generator label (one for each model) and of the mechanical component (one for each model of hydraulic turbine, wind turbine, internal combustion engine, etc.), and of the storage systems where present, affixed by the manufacturer on the component showing the main technical data of the same (for each production/power plant);
10. list of photovoltaic module serial numbers (for each plant or plant upgrade);
11. destination of use certificate of the building (for each plant or upgrading of photovoltaic system located on a building realised on farming area);
12. declaration of the area as a site of national interest or certification by the competent authority of the completed environmental recovery and restoration activities in the case of closed and rehabilitated landfills and landfill lots, quarries or quarry lots that cannot be of further exploitation (optional, for each plant or plant upgrading located on the ground in farming areas);

13. substitute declaration of the specialised workshop concerning the regeneration activity or of the Referent concerning the use of refurbished components (for each production plant/upgrade with refurbished components).

The Referent must, in any case, keeps all documents and make them available for checks and verifications.

3.3 Request for Access to Service for Renewable Energy Communities

In the case of the request for access to the shared energy valorisation and incentive service for a renewable energy community, the Referent shall follow the same procedure described in Chapter 3.2, operating through the GSE's Electronic Portal, verifying the presence of the necessary requirements and entering all the information about the end customers, producers, plants and PODs detected for the configuration. Before sending the request, moreover, the Referent has to verify, through the competent grid operator, that all the connection points of the end customers and of the generation plants detected for the configuration are subtended to the same LV/MV secondary substation. Once the required information has been provided, the Referent shall again download the customer mandates and get them signed, and then upload them into the system together with the following attachments:

1. request for access to the service presented in the form of a declaration in lieu of affidavit, drafted pursuant to Articles 46 and 47 of DPR 445/2000, and privacy policy for data processing, pre-filled from the portal, accompanied by a copy of a valid identity document of the signatory;
2. mandates of end customers and/or producers forming part of the configuration pre-filled by the portal, accompanied by a copy of a valid identification document of the signatories;
3. mandates of producers that are not part of the configuration but are relevant for the

purposes of the configuration, pre-filled by the portal, accompanied by a copy of a valid identification document of the signatories;

4. articles of association and/or statute of the renewable energy community, with highlighted passages from which it is possible to find that:
   a) the primary social purpose of the community is to provide environmental, economic or social benefits at community level to its shareholders or members or to the local areas in which it operates, rather than financial profits;
   b) shareholders or members may only be natural persons, small and medium enterprises (SMEs), territorial authorities or local authorities, including municipalities, provided that, for private enterprises, participation in the renewable energy community does not constitute the main commercial and/or industrial activity;
   c) the community has open and voluntary participation, is autonomous and effectively controlled by the shareholders or members of the configuration;
   d) the participation of members/shareholders in the community provides for the preservation of their rights as end-customers, including the right to choose their own seller, and it is possible for them to leave the configuration at any time, subject, in the event of early withdrawal, to any fair and proportionate fees agreed upon for co-participation in the investments incurred;
   e) a delegated entity has been identified as responsible for the allocation of the shared electricity;
5. single-line electrical diagram of the production plant with evidence of any storages and the positioning of the meters (for each production/upgrading plant);
6. minutes of activation of the meter for the electrical energy fed in, of the production meter (in the case of an upgrade) and of the meter relating to the storage system (only in the case of the installation of storage systems for which the regulation in

force requires the installation of the relevant meters), issued by the competent network operator (for each production/upgrading plant);

7. a copy of the electricity workshop licence(s)/company code issued by the Customs Agency, in the case of plants with a power output greater than 20 kW, or a copy of the operating regulation for plants with a power output less than or equal to 20 kW (for each production/expansion plant);

8. photo of the photovoltaic module label (one for each model), of the inverter label (one for each model) or, in the case of systems different from photovoltaic systems, of the alternator/generator label (one for each model) and of the mechanical component (one for each model of hydraulic turbine, wind turbine, internal combustion engine, etc.), and of the storage systems where present, affixed by the manufacturer on the component showing the main technical data of the same (for each production/power plant);

9. list of photovoltaic module serial numbers (for each plant or plant upgrade);

10. licence authorisation of the building on which the photovoltaic system is installed with attached approved project (only in the case of a photovoltaic plant or photovoltaic plant upgrade located on a building other than a listed building erected on farming area);

11. destination of use certificate of the building (for each plant or upgrading of photovoltaic system located on a building realised on farming area);

12. declaration of the area as a site of national interest or certification by the competent authority of the completed environmental recovery and restoration activities in the case of closed and rehabilitated landfills and landfill lots, quarries or quarry lots that cannot be of further exploitation (optional, for each plant or plant upgrading located on the ground in farming areas);

13. substitute declaration of the specialised workshop concerning the regeneration activity

or of the Referent concerning the use of refurbished components (for each production plant/upgrade with refurbished components).

Once again, the Referent must carefully preserve and make available all documents for verification and consultation.

3.4 Request Assessment Procedure

According to ARERA Resolution 318/2020/R/eel, the process of evaluating the request starts when the request is received electronically. It consists of several steps:

a) a technical-administrative exam of the information and documentation sent with the request, in compliance with the regulatory framework in force on the date at which the request was sent, and with the provisions of ARERA Resolution and the Decree;

b) the identification of the starting date of the shared electricity service and, if required, the starting date of the withdrawal of the fed-in electricity, and the related fees;

c) communication of the outcome of the request to the Referent;

d) the sending to Terna of the information flow containing the type of configurations for which the shared electricity valorisation and incentive service has been activated, specifying the related effective date.

With regard to requests for access to the valorisation and incentive service, the GSE concludes the inquiry within 90 days from the request, net of the time attributable to the Referring Entity or to other entities called upon by the GSE. Any delay by the GSE does not constitute a case of tacit consent, since the procedure is concluded by an express measure.

Once the above steps have been completed, the GSE notifies to the Referent:

1. **the direct acceptance of the request** the direct acceptance of the request, sent to the Certified Electronic Mail (PEC) address indicated by the Referent in the request for access to the service or, in the absence of such, by registered letter with advice of

receipt, containing: the unitary contributions that will be recognised, the start date of the contract and the relative period of validity, the main technical characteristics of the configuration (power, POD, etc.). If the request is accepted, the contract is activated with the communication to the Referent, by the GSE, of the admission to the benefits through the aforementioned measure;

2. **the request for additions**, if the documentation sent with the qualification request is incomplete with respect to the provisions of the Resolution and the Decree. In such cases, the Referent must send the integration within 30 days of receipt of the aforesaid request. In accordance with the provisions of Law 241/90, the request for integration suspends the 90-day time limit, which starts to run again from the date of receipt of the requested integrations or, failing that, from the expiry of the 30-day time limit. If the documentation is still incomplete or contains technical inaccuracies or discrepancies, or if the Referent fails to send the requested integrations, the GSE, where the requirements are met, shall notify the reasons preventing the application from being accepted (notice of rejection). If, on the other hand, the integrations sent are exhaustive and the GSE verifies that the configuration meets the requirements for access to the service, the order of acceptance is issued.

3. **the impediments to granting of the application**(rejection notice), pursuant to Article 10-bis of Law 241/1990. In the event that the requirements set forth in the Resolution and/or the Decree are not met and/or if there are impediments to the acceptance of the request for access, the GSE sends the notice of rejection, granting to the Referent a period of 10 days to submit its observations, possibly accompanied by documents. If the observations provide a remedy to the rejection notice, the GSE will issue the acceptance decision.

3.5 Contract for the Recognition of the Service and Any Changes

Having verified the fulfilment of the requirements shown in Chapters 3.3 and 3.4, the GSE shall proceed to the activation of the contract at the same time as sending the acceptance measure bearing the signature of its Legal Representative, reporting the references and the period of validity of the Contract.

The incentive period, where provided, has a duration of 20 years considered net of any stops pursuant to Article 3, paragraph 4 of the Decree. At the end of the incentive period the Contract may be tacitly renewed annually with respect only to those parts pertaining to the valorisation of the shared electricity.

A change in the Referent's person may also occur. In the case of collective self-consumption groups, the change of the Referent must be promptly notified to the GSE by means of the Electronic Portal; the latter will verify the requirements of the new person on the basis of which the configuration was admitted, reserving the right to terminate the contract.

3.6 Criteria for the Calculation of Recognised Economic Contributions

The economic contributions due to accepted configurations can be of three types:

- Valorisation of Shared Electricity by returning the tariff components according to the Resolution,
- Incentivisation of Shared Electricity in accordance with the Decree,
- Withdrawal of electricity fed into the grid by the GSE, where required.

Table 3.1 show the algorithms used for the calculation of contributions (defined in Article 7 of Annex A to the Resolution), in €, applied according to the type of configuration and contribution.

As mentioned above, the E_{AC} shared electricity is equal to the minimum (one-hour basis) between the electrical energy fed into the grid by plants powered by renewable sources and the electrical energy withdrawn by means of the connection points that meter for a group of self-consumers or a REC.

Table 3.1. Algorithms for the calculation of economic contributions recognised by the GSE

SELF-CONSUMERS OF RENEWABLE ENERGY ACTING COLLECTIVELY	
Refund of tariff components (C_{AC})	$C_{AC} = CU_{Af,m} \cdot E_{AC} + \sum_{i,h} (E_{AC,i} \cdot c_{PR,i} \cdot P_z)$
Incentives for shared energy (I_{AC})	$I_{AC} = TP_{AC} \cdot E_{AC}$
Energy withdrawal (R_{AC})	$R_{AC} = P_R^3 \cdot E_{injected}$
RENEWABLE ENERGY COMMUNITIES	
Refund of tariff components (C_{CE})	$C_{CE} = CU_{Af,m} \cdot E_{AC}$
Incentives for shared energy (I_{CE})	$I_{CE} = TP_{CE} \cdot E_{AC}$
Energy withdrawal (R_{CE})	$R_{CE} = P_R^3 \cdot E_{injected}$

The electricity shared per voltage level ($E_{AC,i}$, where i can take the values of low and medium voltage) is, in each hour, equal to the minimum between the sum of the electricity fed into the grid and the sum of the electricity withdrawn via the connection points having a voltage level equal to or lower than the voltage level, to which the generating plant is connected and that are metering for a group of self-consumers of renewable energy acting collectively. Where there are several production plants whose production is fed in at different voltage levels, the shared electricity shall be calculated from the inputs of the plants connected at the lowest voltage level and up to the amount of the withdrawals at the same or lower voltage level. In the case of a group of self-consumers, for the purposes of determining the shared electricity, the withdrawals of end customers not forming part of the configuration may also be taken into account, as long as they connection points are located in the same building or condominium. In this case, such end customers shall issue a release to the configuration Referent for the purpose of using their own metering data of the electricity withdrawn. Withdrawals for which the transmission and distribution tariff components do not apply, i.e., where the power is intended only for the operation of auxiliary generation services, are not relevant.

The Equation 3.2 allows us to calculate the shared electricity E_{AC}:

$$E_{AC,m} = \sum_{h=1}^{n} E_{AC,h} \tag{3.2}$$

of which:

$$E_{AC,h} = min[\sum_{y=1}^{n} E_{inj\_into\_y}; (\sum_{y=1}^{n} E_{withdrawn\_from\_y} - \sum_{y=1}^{n} E_{withdrawn\_from\_exempt\_y})] \tag{3.3}$$

where:

- $E_{AC,m}$: monthly shared electricity (kWh);
- $E_{AC,h}$: hourly shared electricity (kWh);
- $E_{AC,i,h}$: hourly shared electricity per voltage level (kWh);
- i: voltage level;
- m: month;
- h: hour of the month;
- y: connection point pertaining to the configuration;
- $E_{inj\_into\_y}$: electrical energy actually injected through the connection point y expressed in kWh, net of the conventional loss coefficients referred to Article 76, paragraph 1, letter a) of the "Integrated text of the provisions of the Authority for Electricity and

Gas concerning the regulation of the physical and economic items of the dispatching service (settlement)" (TIS)

- $E_{withdrawn\_from\_y}$: electricity withdrawn by means of the connection point y (kWh);
- $E_{withdrawn\_from\_exempt\_y}$: electricity withdrawn through the connection point y, expressed in kWh, for which the transmission and distribution tariff components are not applied in accordance with Article 16 of the TIT or Resolution 574/2014/R/eel.

The unitary monthly flat-rate self-consumption fee ($CU_{Af,m}$), expressed in c€/kWh, is equal to the algebraic sum, rounded to the third decimal place according to the commercial criterion, of the variable unitary parts, expressed in c€/kWh, of the transmission tariff ($TRAS_E$) defined for low-voltage users and of the highest value of the variable distribution component defined for users for other low-voltage uses ($LVAU$) in force in the m-th month.

$$CU_{Af,m} = TRAS_E + MAX(LVAU_m) \tag{3.4}$$

The grid losses coefficient (C_{PR}) is equal to 1.2 % in the case of shared electricity due to the production plants connected to the MV distribution grid, and equal to 2.6 % if the generation plant is connected to the LV distribution grid.

Shared electricity (E_{AC}) is entitled, for a period of 20 years from the date of entry into operation of each plant whose electricity is relevant for the configuration, to a premium tariff of:

- (TP_{AC}) - 100 €/MWh if the generation plant involves a group of self-consumers;
- (TP_{CE}) - 110 €/MWh if the generation plant involves a REC.

The premium tariff does not apply to shared electricity attributable:

- to the power rate of PV systems that have access to the 110 % deduction,
- to the quota of obligatory power P_o,

- to PV systems for which there is a ban on access to state incentives, i.e., with modules located in defined areas.

The GSE calculates on a monthly basis for each configuration the contribution due in € of the energy shared and withdrawn, providing a specific detail. In case of unavailability of non-validated data, the grid operator will inform the Referent and the GSE. The latter will apply in this specific case standard profiles defined for each type of end customer in accordance with Annex A to the Resolution.

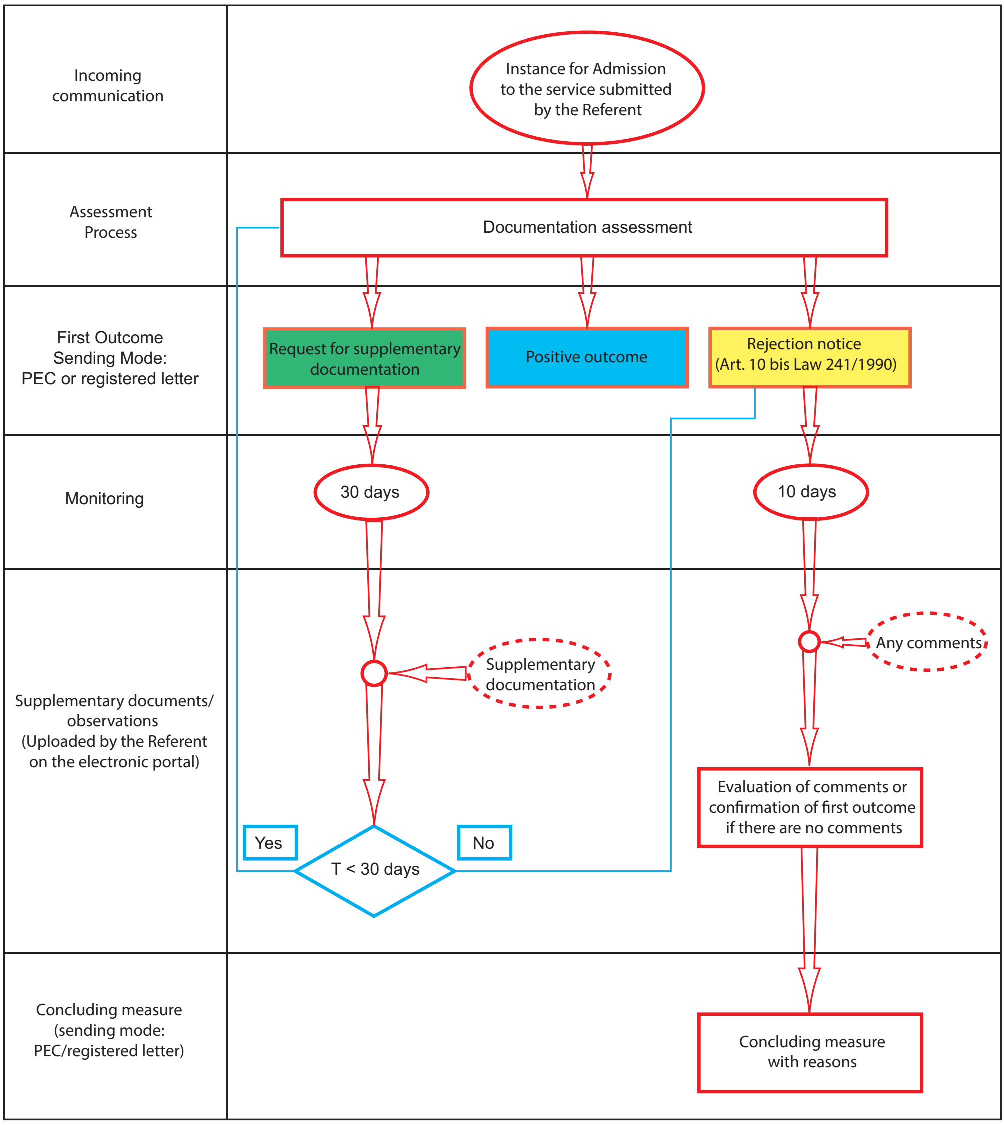


Figure 3.1. Outline of the procedure for admission to the shared electricity valorisation and incentive service

The Fig. 3.1 shows the summary outline of the procedure for admission to the shared electricity valorisation and incentive service, from the GSE document attached to 318/2020/R/eel of ARERA.

Chapter 4

Modelling and Design of a Renewable Energy Community in Matlab/Simulink

4.1 Introduction

In Europe, it is estimated that 40% of total energy consumption is attributable to the commercial and tertiary sectors and to residential buildings. New national and international policies on energy and sustainability have introduced the use of new technologies in different sectors (e.g. internet of things [1], internet of energy [2], blockchains [3]) to promote rational energy use [4]. The approach is based on smart-grids [5] where renewable Energy Storage Systems (ESSs) and loads work in synergy thanks to Demand Side Management (DSM) techniques [6], with the ultimate goal of achieving Nearly Zero Energy Buildings (NZEBs), i.e., dwellings with very low energy demand and covered for the most part by renewable sources [7]. Net-zero energy is a transversal concept applicable to dwellings and more broadly to neighbourhoods: for example in [8] a multivariate regression model is proposed for the management of net-zero energy residential test facilities; in [9] a review of co-planning models in multi-energy systems for sizing and scheduling resources in neighbourhoods approaching zero-energy condition is made. In this context, the transition in heat generation from gas-fired heaters/furnaces to electric heat pumps plays a significant role, which significantly increases the electrical load demand for common building services (CSs). In [10] a resistor-capacitor model is used to develop a model for predicting thermal energy consumption for smart buildings that are modelled as flexible resources of active distribution networks.

Nowadays, one of the most exciting challenges is the aggregation of users into ECs [11], which allows an optimised use of power and energy. The key to this strategy lies in including generation from renewable sources in Technical Building Systems (TBSs) [12] to reduce the impact of users in terms of grid-power demand. The principle behind the creation of virtuous systems is the active role that users must play in order to obtain important economic benefits [13].

The work carried out focused on two important energy aspects::

- A Multi-Unit Building (MUB) with energy aggregation capabilities;
- A collection of neighbouring dwellings willing to share energy resources as ECs.

Most buildings in Europe consist of several units. Depending on the end use of the units, it is possible to distinguish between:

- Multi-unit construction, where the structure consists only of residential units.
- Multi-unit residential and commercial construction, where the structure consists of residential units and units for commercial and tertiary activities.

Access to individual units may be internal or external to a common area. The set of units forms the condominium for which the entire community is responsible for managing the common areas and Common Services (e.g. lighting, central heating, lifts). In condominiums, the CSs are supplied by a Point of Connection (POC) with the Distributor System Operator (DSO), which is independent of the one for private users.

According to current European standards, every newly built structure must comply with the NZEB model. The individual units of NZEBs require the adoption of energy management systems, specific DSM models and operation in a microgrid configuration [14].

The NZEB model applied to a MUB increases the complexity of the entire system when compared to a single dwelling system. The application of the NZEB model requires the design and operation of technical systems with the building as a whole in mind and not only considering individual units [15]. In particular, small-scale networks should serve a cluster of units, which, however, introduces legislative and economic problems. The analysis performed shows a new solution to improve the small-scale network approach: a MUB, although recognised as a group of independent units, from a technical point of view should be considered as one large system.

Recently, the European Directive 2018/2001, also referred to as the Renewable Energy Directive (RED-II), introduced ECs as new forms of end-users. These are legal entities formed by the aggregation of users, municipalities, etc., who are willing to share the energy produced by a common renewable generation plant with the aim of increasing the social welfare of the community. The introduction of ECs into the current electricity grid configuration may allow for a better utilisation of the renewable energy produced [16], and a reduction of the energy drawn from the grid with a consequent reduction of costs for users. ECs act as MUBs (when the cluster of units corresponds to individual structures) and the condominium becomes an aggregator, which is in charge of managing the energy community and energy exchange [17]. In both approaches, members retain their rights as end-users, even though they are part of aggregation entities [18].

There are many analyses of community-based cooperative energy consumption in the literature, with a focus on networks. In [19]a customer community-based game is proposed that considers the dynamic nature of community members, with the aim of reducing energy consumption costs for customers. In [20], Fina et al. develop a model to estimate the cost-optimal large-scale economic potential of shared rooftop PV systems based on neighbourhood ECs by allocating buildings in characteristic settlement patterns and then in ECs by an upscaling approach. The concept of energy sharing is further extended in [21], where the author proposes a peer-to-peer approach for the energy exchange in buildings. Furthermore, the community-cooperative concept is extended in the framework of a transactive energy market to multi-interconnected microgrids [22] and microgrid clusters [23]. The energy consumption is closely linked to optimal grid operation, in terms of distributed energy resources management (DERs), a topic addressed in [24] using holistic methods and an Analytical Target Cascading (ATC) algorithm in [25]. Finally, in [26], the authors also apply the energy management system to buildings through a multi-agent based approach.

In the well-established context of cooperative energy consumption, following the implementation idea presented in [27], we introduce a new approach, called Power Sharing Model (PSM), which promotes the optimised integration of renewable and energy sources. PSM can be well adapted to multi-tenant buildings and multi-tenant groups and can be applied to existing or new buildings alike. Furthermore, the PSM is scalable for larger smart grids and allows for easy integration of generation and storage systems. The proposed PSM is based on an innovative idea while also respecting what is already present in the literature: energy produced by common renewable plants can only be shared between end-users in a unidirectional manner and each user cannot receive more than his current energy demand; thus, each user remains passive towards the DSO. In order to feed the excess power produced into the grid, the system architecture has a balance node whose role is represented by the common building services and acts as an active node; this node is called Balance User (BU). This key feature allows PSM to be easily implemented in existing and new MUBs, in full compliance with national regulations, with the support of appropriate power-sharing contracts. At this stage, we are not designing any DSM program to encourage end-users to change their energy consumption profiles, but deliberately analysing the effectiveness of a simple PSM that shares power democratically, following the natural variations of end-user profiles in a dynamic and responsive manner. Obviously, the proposed architecture is able to exploit load scheduling/shifting algorithms to maximise the on-site energy consumption of the PV system and also the users' profits.

This makes it possible to install and integrate generation and storage systems serving the building and connected to all tenants/users. The system architecture includes a DC bus called Power Sharing Link (PSL) that connects the common generators to the users, who have an independent connection point with the DSO. The energy produced reaches the users, equipped with one-way inverters, via the PSL. Therefore, the entire system functions as if it had several generators (one for each user) without energy exchanges between the users. The only active user towards the grid is the balance node for the common building services, equipped with a bi-directional inverter. To investigate the feasibility of the PSM, a dynamic model was developed in Matlab/Simulink and used for the only purpose of illustrating the basic details for implementing the new EC model and demonstrating its great capabilities.

4.2 Power-Sharing Model

4.2.1 Regulatory Barriers

Today, the critical aspect for the realisation of MUBs and ECs is the national legislation that does not encourage the aggregation of consumers into common power systems. The national regulatory code for the electricity grid does not include a configuration that recognises a system consisting of a single generating plant and several consumers, but only a single generator with a single consumer. In the particular case of MUBs, the generation system can be installed in the building but can only supply the common services, making this configuration economically inconvenient. In the current legislative scenario, each unit must be provided with a POC and, consequently, a system consisting of several units connected to the grid with only one POC cannot be realised. Furthermore, the use of the existing distribution network to share the energy produced in MUB systems can create problems related to the payment of overhead costs that are included in the electricity bill and are currently not considered in the case of self-consumed energy. However, individual states are beginning to recognise these forms of aggregation as a transposition of European Directives.

For example, in Italy, Law n. 8 was passed on 28 February 2020 recognising ECs at national level. Although a law recognising the REDII Directive is still missing, Law n. 8 opens up opportunities for experimental cases where energy can be shared through the existing distribution network, paying electricity charges both on energy supplied by the grid and on energy shared in the building or community. However, as legislative scenarios are beginning to include these new forms of end-user, it is important to understand how they should work and how to optimise energy exchange.

4.2.2 Novel PSM Model

The new PSM model is based on the ability of users to consume electrical energy that is locally generated and managed by a Common Power-Sharing System (CPSS) based on a dc bus, avoiding energy exchanges between the units themselves. In the proposed architecture, users remain passive towards the DSO and the role of active user is only played by the BU for which the direction of energy in the POC can be reversed. It should be noted that by doing so no regulatory constraints are broken, making this the preferred solution for ECs as introduced by the EU. As discussed in [28], to connect a renewable generator to the grid it is necessary to become an active grid user. This can only be achieved by interacting with the DSO because several technical conditions required for access to the distribution networks have to be met (access should be non-discriminatory). The main requirements concern the limitation of injected active power that could generate abnormal over-frequencies, compensation of reactive power and resilience to voltage drops, through the so-called Low Voltage Fault Ride Through curve. In the proposed model, common generators and storage systems act as a multiple generator with variable power. Locally generated power can only flow from the common generator to the users and never from user to user. Therefore, for each user and at any time, the locally generated and absorbed energy can never exceed the load. At the POC with the distributor, the direction of energy is always from the grid to the user and can never be reversed, so that the user is always passive.

Since users have usually independent POCs to the power grid, the PSM can easily be implemented in special power-sharing contracts in full compliance with national regulatory systems. The energy is delivered to the users through the PSL by means of secondary connection points (sharing points of connection) with a one-way inverter managed by a local control. The main rule of PSM is that the users can only consume the power/energy coming from the CPSS and they can never supply energy to the CPSS (Fig. 4.1).

The control logic is simple: moment by moment the power is divided among all users and, when possible, the portion not consumed by users is fully fed into the grid through the BU.

The scheme in Fig. 4.1 explains how the system works. A photovoltaic system installed

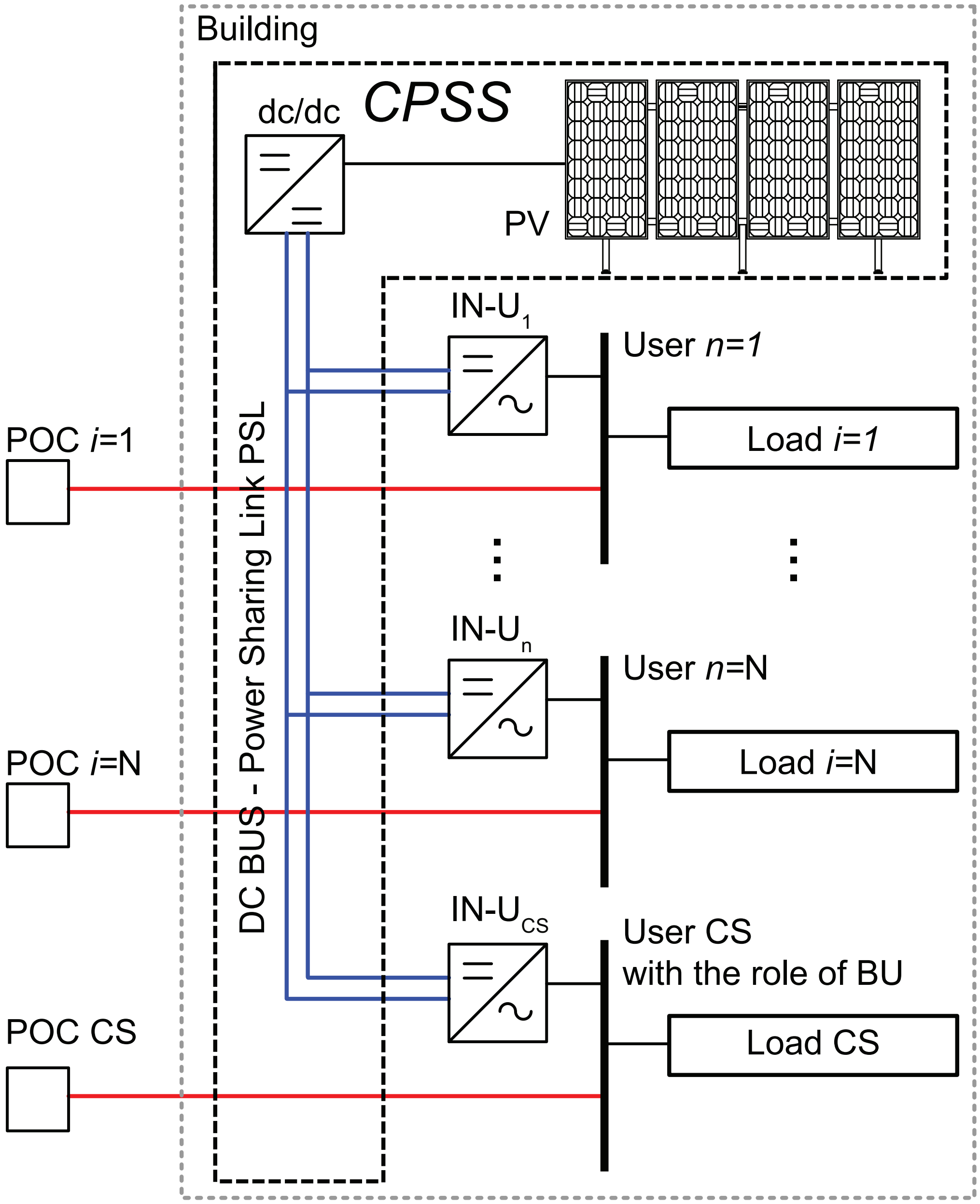


Figure 4.1. Scheme of power-sharing model (PSM).

on the roof of the building is connected to the CPSS via a dc/dc converter and feeds a dc bus for energy sharing with all users. A dc/dc converter (step-up/boost converter) is installed downstream of the photovoltaic system, controlled by means of a Maximum Power Point Tracking (MPPT) algorithm to extract maximum power from the system under all environmental conditions. Each user (U_1-U_N) has its own POC. The user CS for the building (i.e., lighting, elevator, parks, etc.) has an independent POC with the grid (POC-CS). The users are connected to the PSL through a special dc/ac inverter (IN-U_n) controlled by the CPSS, which allows power flow only from PSL to the users. The inverter installed for the CSs of the building (IN-U_{CS}) has been identified as the balance node of the system and is the only active user for the DSO. The CPSS control system also prevents the users (U_1-U_N) from feeding power into the public power grid; therefore, the units are not active components of the system.

To allow the DSO to have access to the data needed for electric charges, each user is equipped with an electric meter at the inverter. If the CPSS is owned by users, they can stipulate a power-sharing with the contributing community. If, on the other hand, the CPSS belongs to a third party, the users can stipulate a power purchase contract with such party. The model, in this case designed for a MUB, can be applied if there are at least two users (one passive user and one BU) and extended to multi-buildings (with several active balance nodes).

There are several reasons for users to adopt the proposed model:

- Users can take advantage of a single generator installed in a common building area, without the need to build their own system, which would have to be located in a private area that is very often unavailable, especially in existing apartment buildings;
- The utilisation of renewable energy sources improves when several users, with different load profiles, interact with each other resulting in a reduction of installed peak power and unbalance;
- The system architecture, based on a backbone dc link , allows the integration of several distributed resources with a high level of efficiency [29].

4.2.3 MUB for Existing Buildings

With regard to heating systems in existing buildings, it's recommended the installation of electrically powered heat pump generators coupled with the existing gas-fired heater. The heat pump is supplied by the building's common services and connected to the grid via the

POC-CSs. The heating system then becomes a hybrid as it consists of a central thermal storage (i.e., a boiler) fed by both the gas-fired heater and the heat pump.

The terminals of the heating system, i.e., traditional radiators, are not replaced. Domestic Hot Water (DHW) production will be supported by electric heat pumps replacing traditional gas boilers. In this configuration, the hobs (cookers) will remain the only gas-powered components.

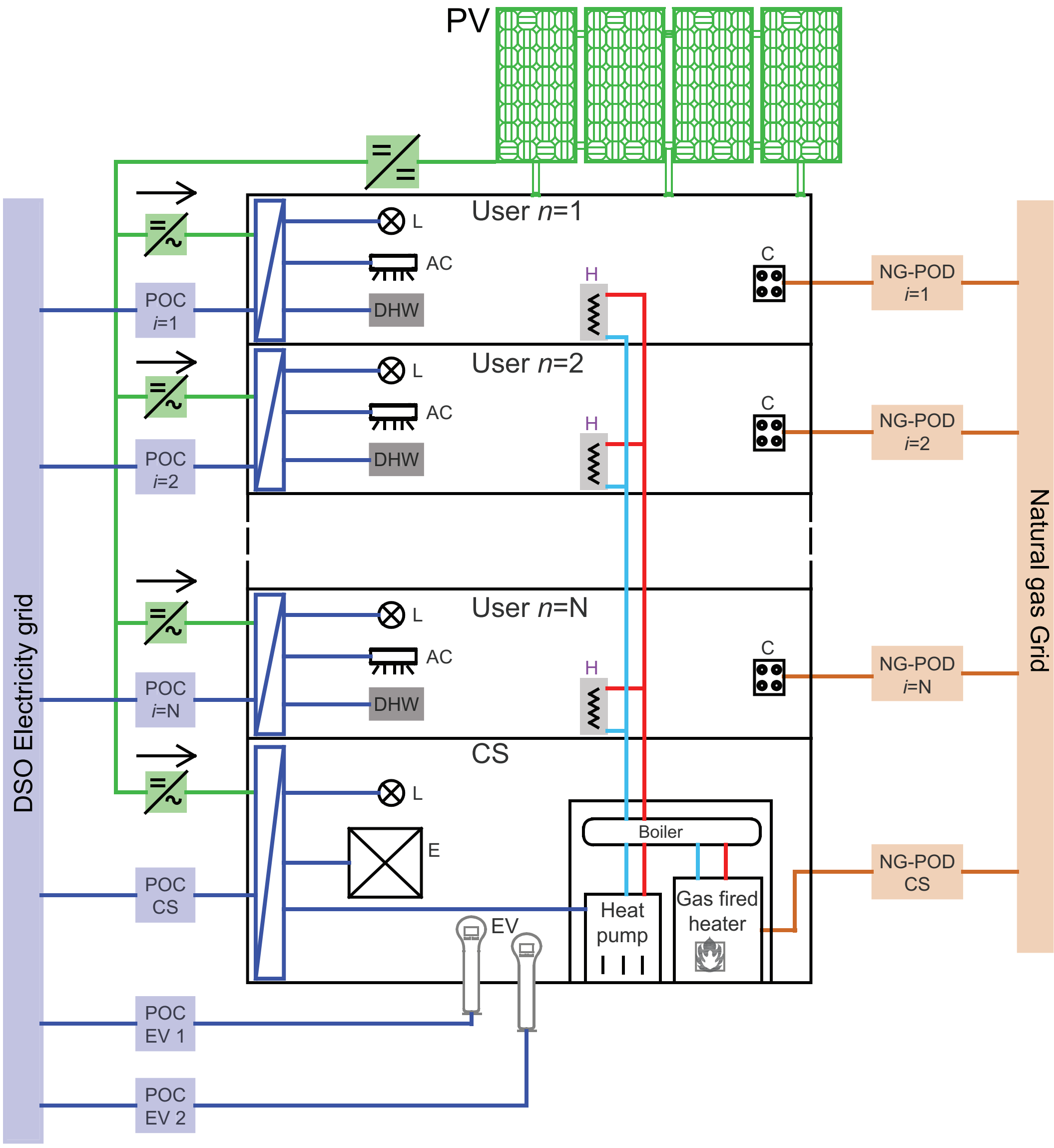


Figure 4.2. Proposed model for existing MUBs.

Figure 4.2 shows the energy architecture of the building in its entirety and also takes into account the connection points for electric vehicle charging stations (POC-EV1 and POC-EV2). The innovative part of the model is the implementation of a PV in *power-sharing* mode.

The dc PSL (see Fig. 4.1) allows the connection of the PV generator to several users and to the building CSs switchboard (e.g., elevators, stairs lights, auxiliaries, etc.). The switchboard constitutes the swing node of the system.

Each unit is powered by the PSL through its own dc/ac inverter characterised by a limited unidirectional power flow and controlled by a distributed management system that defines the amount of power available based on the system's current consumption. The sizing of the photovoltaic system is based on the heat production of the devices and the electricity consumption of the users. When the thermal demand is low, the excess power generated by the photovoltaic modules is shared among the users according to their needs or fed into the grid via the slak node.

4.2.4 MUBs' Model for New Buildings

The proposed model for new buildings and NZEB constructions is based on the exclusive use of electricity, without considering any kind of gas consumption and connection to the gas grid, as shown in Fig. 4.3. In the previous case, the hobs were gas-powered, whereas in this case they have been replaced by inductive hobs. The heating system, previously consisting of pre-existing natural gas boilers coupled with newly installed heat pumps, now becomes fully electric with the use of heat pumps alone. It would also be interesting to use geothermal heat pumps in which the relatively constant temperature of the earth could be exploited.

In this configuration, the building's CSs are connected to the main electrical panel, including charging stations for electric vehicles. In addition, the biggest boost is given to power-sharing configuration, as the PV system can be oversized to power the building's geothermal heat pumps and private units.

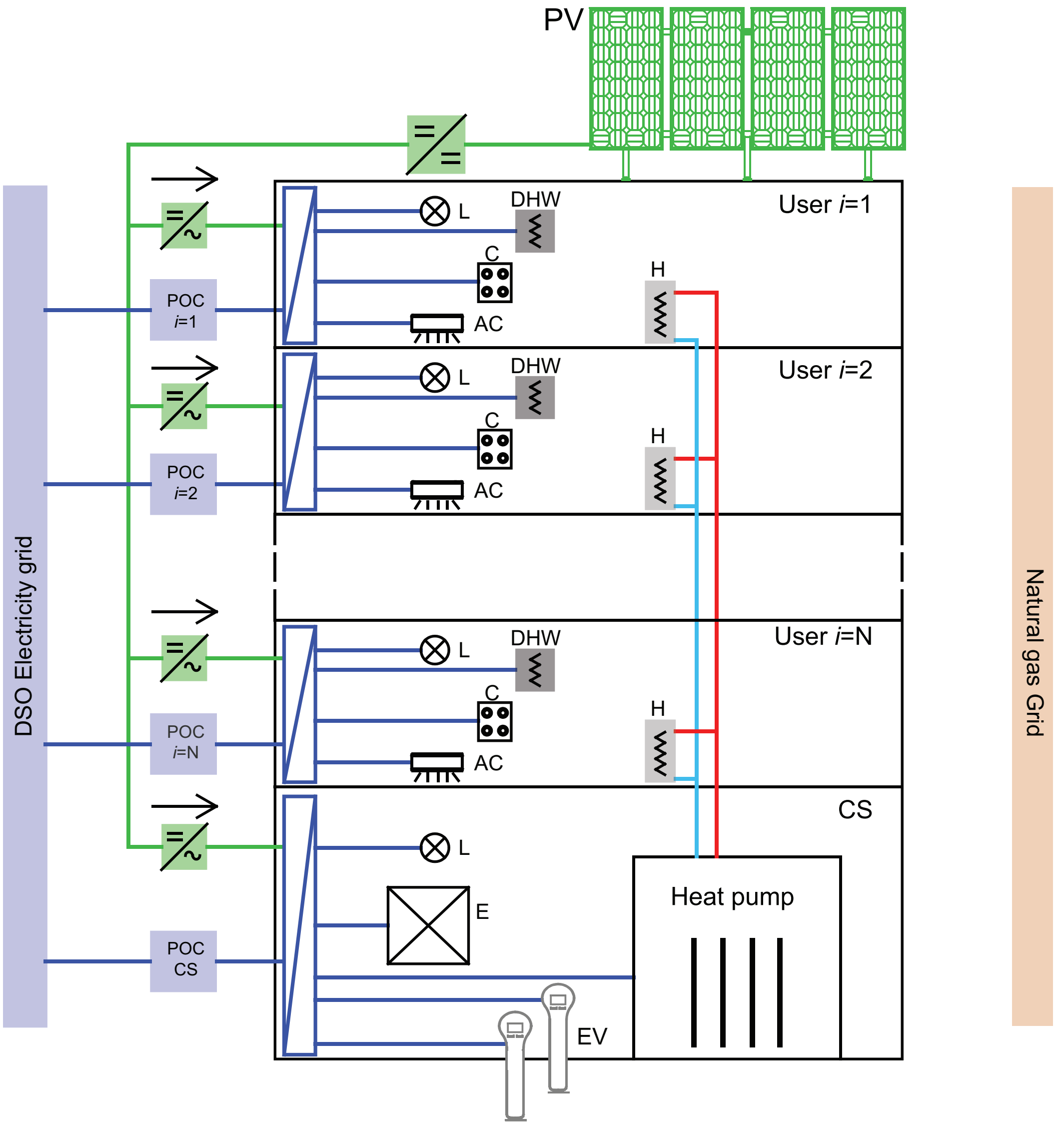


Figure 4.3. Proposed model for new MUBs.

4.2.5 Control Strategy

The power generated by the PV source is shared among the N users and the in excess power is fed into the power grid through the BU. The power P_{PV} produced by the common generators is split, at each t_k of the sampling-time of measured variables, according to the following rules:

- the P_{PV} power is divided among the users according to the nominal power of the inverter $P_{\mathrm{n},i}$ and, for each user i, the assigned power (AP_i) is compared with the actual

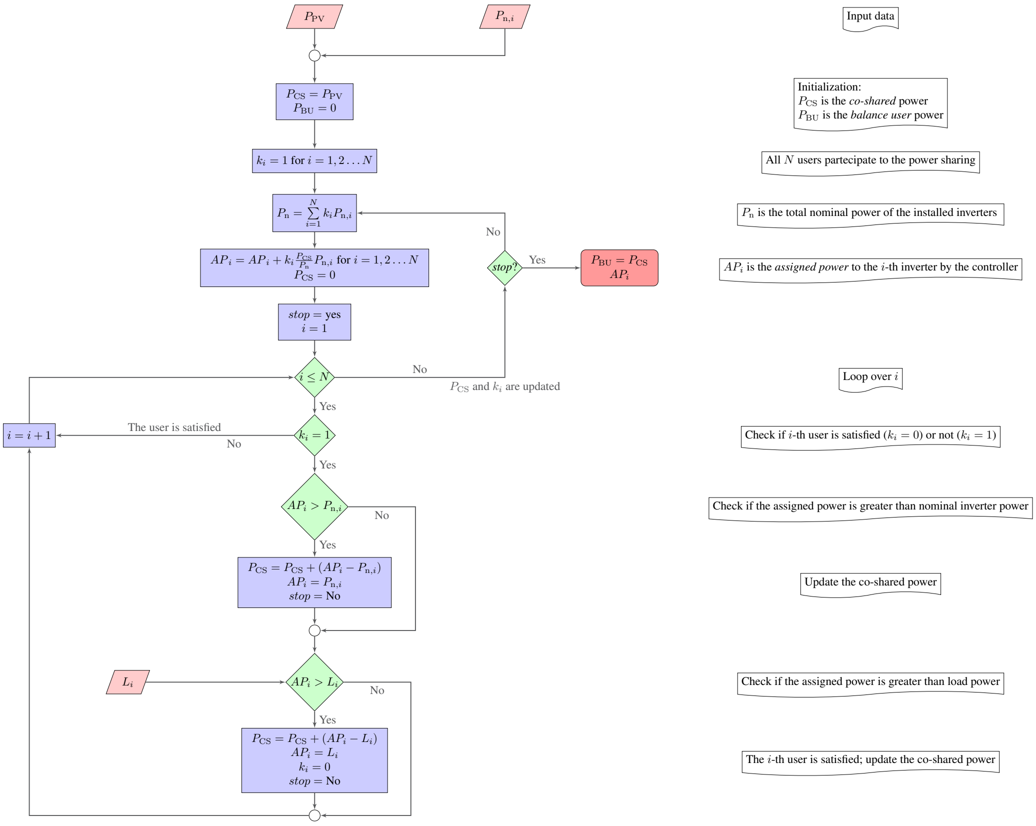


Figure 4.4. Flow chart of the control strategy.

load demand L_i;

- if the load demand L_i is completely satisfied by the dc-link ($AP_i >= L_i$), the power-sharing strategy is stopped for this user until a new control action is needed; the delta power ($AP_i - L_i$) will be at disposal of the other users;

- if there is a surplus of power with coming from the satisfied loads, this is assigned to users whose load demand L_i is *not yet* satisfied, always according to the nominal power of the inverters of the users that continue to participate to the power-sharing strategy;

- the power that is not assigned to the users at the end of the power-sharing control loop is reversed into the grid through the BU.

The control system has been implemented in a Matlab code in a vectorial manner and demonstrated to be computationally effective, reliable, and robust. Hence, the code doesn't require large computational resource and it can be easily implemented on commercial Programmable Logic Controllers.

The strategy can be achieved with a two-levels control system: general and local. The first level operates at the CPPS level (i.e., building level), while the second level works at the converter level. As mentioned above, the maximum power coming from the PV generator is transferred to the dc bus and constitutes the total available power P_{PV} at the PSL. This available power is monitored by the CPSS with a sampling rate of the order of one minute to perform the control strategy.

The controller consists of a main programmable logic controller with inputs and outputs. In this scheme, the constraints are the inverter nominal power of users $P_{\mathrm{n},i}$. The input data are:

- the load demand L_i of each user;
- the power generated by the PV source P_{PV}.

The outputs are:

- the power assigned to each inverter AP_i;
- the power sent to the balance user P_{BU}.

The flow-chart of the control system is reported in Fig. 4.4.

It is worth noting that, in real applications, a suitable communication protocol must be designed for exchanging data among devices in order to achieve an efficient and reliable control strategy. In [30], a low-cost communication system based on the IEC 61850 standard with a server-client TCP/IP protocol has been developed for small-scale grids. It represents a valid solution for collecting data related to the users power consumption, PV power production, and inverters configuration.

4.3 Matlab/Simulink Model

The main purpose of the proposed PSM model is to maintain the supply-demand balance through the implementation of energy-management schemes, taking into account the required

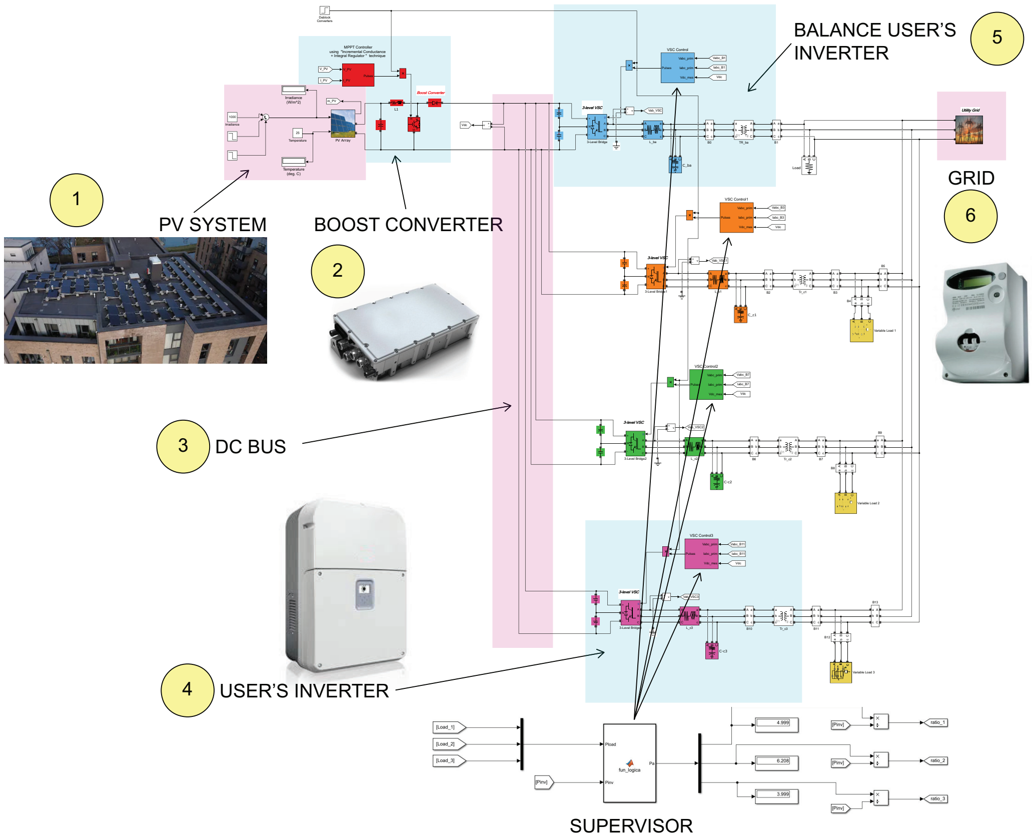


Figure 4.5. Matlab/Simulink model.

flexibility to chase the intermittency of renewable energy sources. Furthermore, such a scheme can play an active role in mitigating the financial feasibility and installation issues (e.g., the use of a rooftop terrace) of photovoltaic systems for small residential consumers [31].

In this section, a possible implementation of the PSM shown in Fig.4.1 is discussed using a dynamic Matlab/Simulink model. The model was developed to assess the feasibility of PSM and to show the real advantages it offers.

Users are equipped with individual Voltage Source Converters (VSCs) [32] and connected in parallel to a constant-voltage dc bus supplied by a PV source via a centralized dc/dc converter, on which the MPPT strategy is implemented [33]. The PSL architecture is completed with an inverter connected to the CSs of the building and functioning as a slack node of the power system.

The implemented Matlab/Simulink model is shown in Fig. 4.5 and consists of:

- a PV system installed on the rooftop of a construction. The PV array consists of 10 parallel strings composed of 5 Sunpower crystalline modules connected in series with nominal power of 305 Wp;

- a dc-dc step-up converter that boosts the PV array output voltage of the dc bus at 500 V. The converter is controlled by an incremental conductance algorithm to track the maximum power of the PV system under variable temperature or irradiation conditions;

- a dc bus connecting all the users. It is worth noting that the PSL architecture shown in this work can be extended to different dc bus solutions (e.g., bipolar dc bus, Ring dc-bus) depending on the system power ratings, the small-scale grid extension, the safety, and the fault protection constraints [34];

- four VSCs: the first operates as the balance node, while the second, the third, and the fourth supply power to variable three-phase loads that represent the consumers. Each consumer is also connected to the power grid through a 10 kW three-phase transformer. The VSCs maintain the dc bus voltage constant thanks to a voltage external control loop. Single phase users can also be considered together with their points of connection to the DSO and the relevant single-phase unidirectional inverter connected to the PSL.

Converters are controlled by a central aggregator which manages the energy sharing among the nodes while the MPP tracker maximizes the PV power output. The VSC of the i-th consumer handles its power output $P_{\mathrm{VSC},i}$ to feed the variable load of the final user $P_{\mathrm{l},i}$ by minimizing the power exchange with the grid $P_{\mathrm{g},i}$:

$$P_{\mathrm{l},i} - P_{\mathrm{VSC},i} = P_{\mathrm{g},i} \cong 0 \,. \tag{4.1}$$

If the power needed to satisfy all the consumers is smaller than the PV power output, the excess of power is injected into the power grid by the balance node.

4.4 Components of the Model

4.4.1 Step-Up/Boost Converter and MPPT Controller

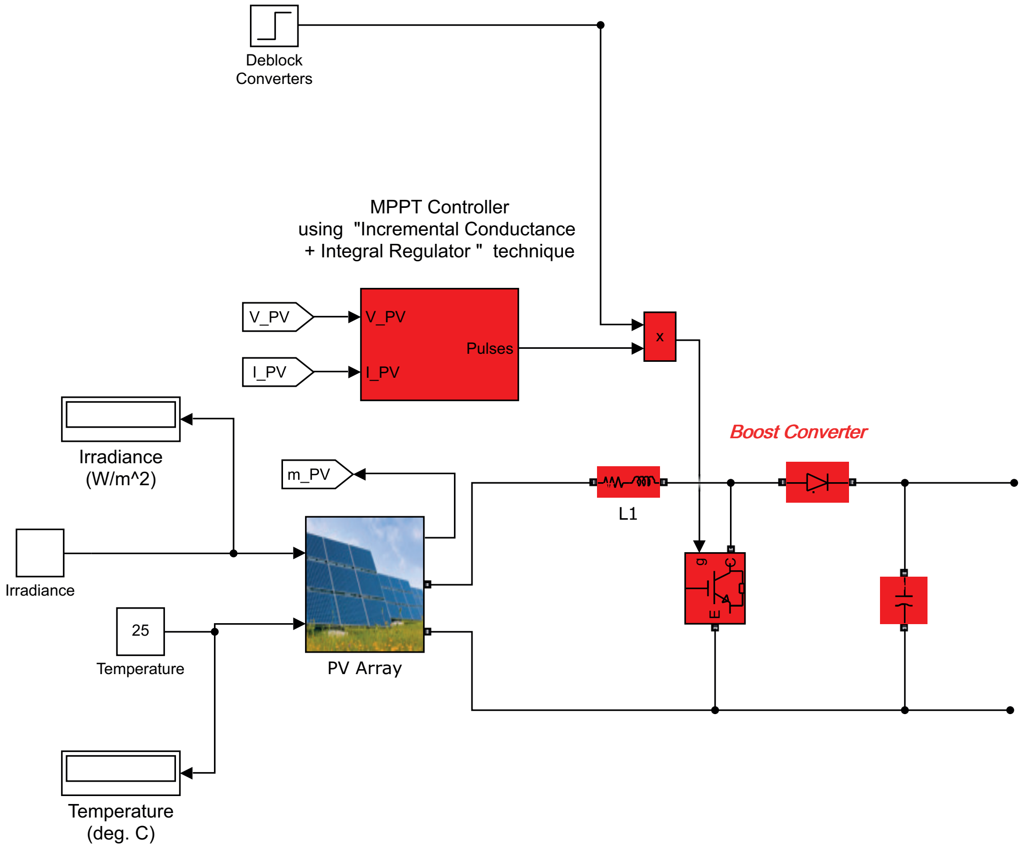


Figure 4.6. Electrical circuit of a boost converter

The step-up converter is a second-order dc/dc converter and allows the input voltage to be raised. Its electrical circuit, shown in Fig. 4.6, consists of a switch, an inductor, a diode and a capacitor. The switch can be either a Metal Oxide Semiconductor Field Effect Transistor (MOSFET) or an Insulated Gate Bipolar Transistor(IGBT). When the switch is closed, the diode is inversely polarised and the inductor is charged during this phase. The capacitor must have a high capacitance to supply everything downstream in the instant the switch is closed. When the switch is opened, the diode is directly polarised to ensure the continuity of the current through the inductor. Due to the presence of the diode, the output current will be very discontinuous, but the high capacitance of the capacitor is able to absorb the current harmonics of the diode itself. In the developed model, an IGBT with a switching frequency of 5 kHz was used as a switch.

The PV array efficiency is mainly affected by the efficiency of three components: (*i*) PV module; (*ii*) inverter; (*iii*) MPPT algorithm. The voltage-current characteristic of a PV array, as shown in Fig. 4.7, is non-linear and has a single maximum power point (MPP) if temperature and irradiance are the same for all modules (uniform conditions) [35]. MPPT algorithms are crucial for extracting maximum power from the PV system. These techniques are implemented in the boost converter by varying the duty-cycle D. The initial value of the duty- cycle in our model is 0.5.

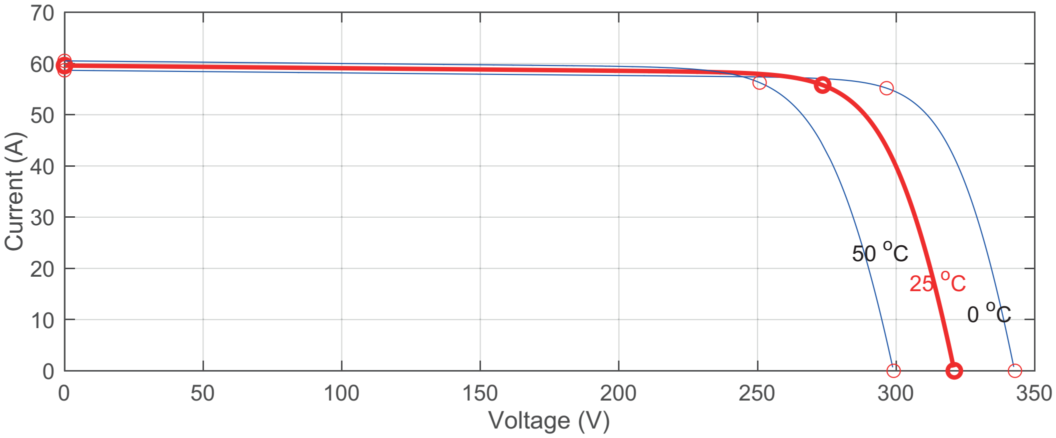


Figure 4.7. Voltage-Current characteristic of the PV array

In this analysis the algorithm used for the MPP tracker is the Incremental Conductance (IC). This technique can extract the maximum power from the PV array also in non-uniform working conditions.

The IC algorithm is based on the condition that the power-voltage characteristic has a zero slope at the maximum power point, as shown in Fig. 4.8. By differentiating the power $P = VI$ with respect to the voltage, we obtain:

$$\frac{\mathrm{d}P}{\mathrm{d}V} = \frac{\mathrm{d}(VI)}{\mathrm{d}V} = I + V\frac{\mathrm{d}I}{\mathrm{d}V} \cong I + V\frac{\Delta I}{\Delta V} \ . \tag{4.2}$$

When $\frac{\Delta I}{\Delta V} = -\frac{I}{V}$ the algorithm finds the MPP.

The IC algorithm is used together with an integral regulator (IR), as shown in Fig. 4.9, to minimize the error signal e and the time required to find the global maximum. The error

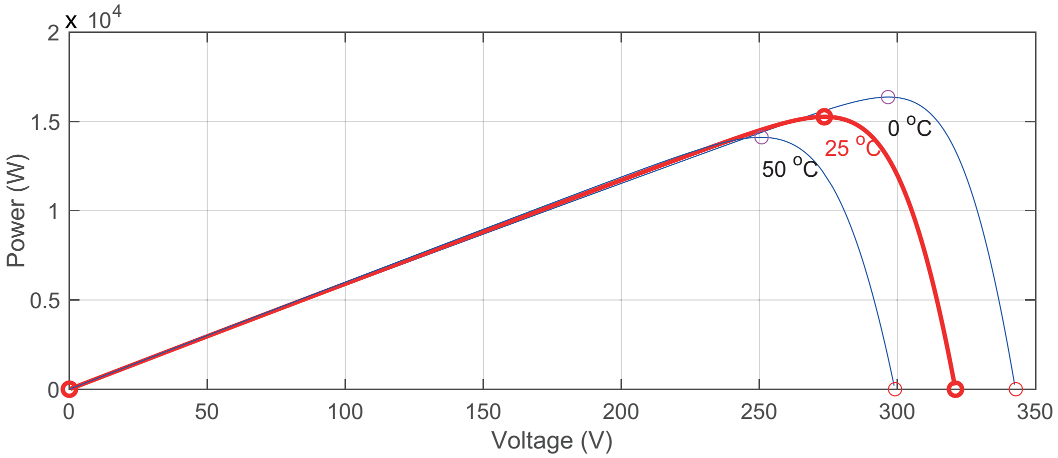


Figure 4.8. Power-Voltage characteristic of the PV array

is given by the sum of the instantaneous conductance $\frac{I}{V}$ and the incremental conductance $\frac{\mathrm{d}I}{\mathrm{d}V}$, i.e.,

$$e = \frac{I}{V} + \frac{\mathrm{d}I}{\mathrm{d}V} . \tag{4.3}$$

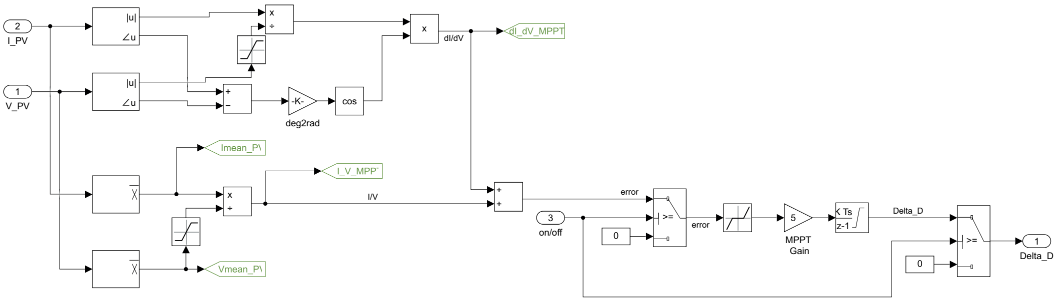


Figure 4.9. Incremental Conductance algorithm coupled with integral regulator and implemented in Matlab/Simulink

The integral regulator represents an extra-step between the MPPT algorithm and the PWM generator. The IR brings corrections to the duty-cycle, allowing greater control and adaptation to changing weather conditions that influence the MPP. This adaptive method increases system efficiency through three key factors:

- reduces the error between instantaneous and incremental conductance,
- reduces ripple and oscillation in the output suffered not only by the IC algorithm but by all hill-climbing algorithms;

- increases accuracy.

Table 4.1. Main data of the MPPT algorithm.

Block Name	**Sub-Block Name**	**Parameter Name**	**Parameter Value**
MPPT controller	PWM generator	f_c	5 kHz
	Duty cycle regulator $\delta D = K_p e + K_i \int e\,\mathrm{d}t$	K_p	5
		K_i	1
	Sampling time for MPPT	T_{MPPT}	200 μs

The instantaneous errors e are cumulated by the integral regulator which multiplies them by the integral gains and finally adds them to the controller output. In [36] guidelines are provided to select the optimal parameters of the IC with integral regulator. Moreover, a low-pass filter and a band-pass filter are added to the proposed MPPT algorithm in order to minimize the errors in the $\frac{I}{V}$ and in the $\frac{\Delta I}{\Delta V}$ calculations, respectively [37]. The filters help to reduce the noise in the PV voltage and PV current measurements.

The main data of the Matlab/Simulink MPPT model are reported in Table 4.1.

4.4.2 Voltage Source Converter

The voltage source converter (VSC) implemented in the model is shown in Fig. 4.10 . It is a three-level bridge converter using IGBTs with antiparallel diodes as switches.

The 500 V dc bus voltage is converted into a 260 Vrms ac voltage through the VSC. The technique used to independently control active and reactive grid currents is the vector current control [38] whose scheme is shown in Fig. 4.11. The control system of voltage and current exploits two loops: (*i*) the dc bus voltage is regulated to the 500 V nominal value by an external control loop and (*ii*) the active I_{d} and reactive I_{q} current components that feed the grid are managed through an internal control loop.

In this study, the VSC works with a unity power factor. The current component I_{d} allows for regulating the active power flow based on the load required by the end-user, whereas the reactive current component I_{q} is considered to be zero. A necessary feature of the power

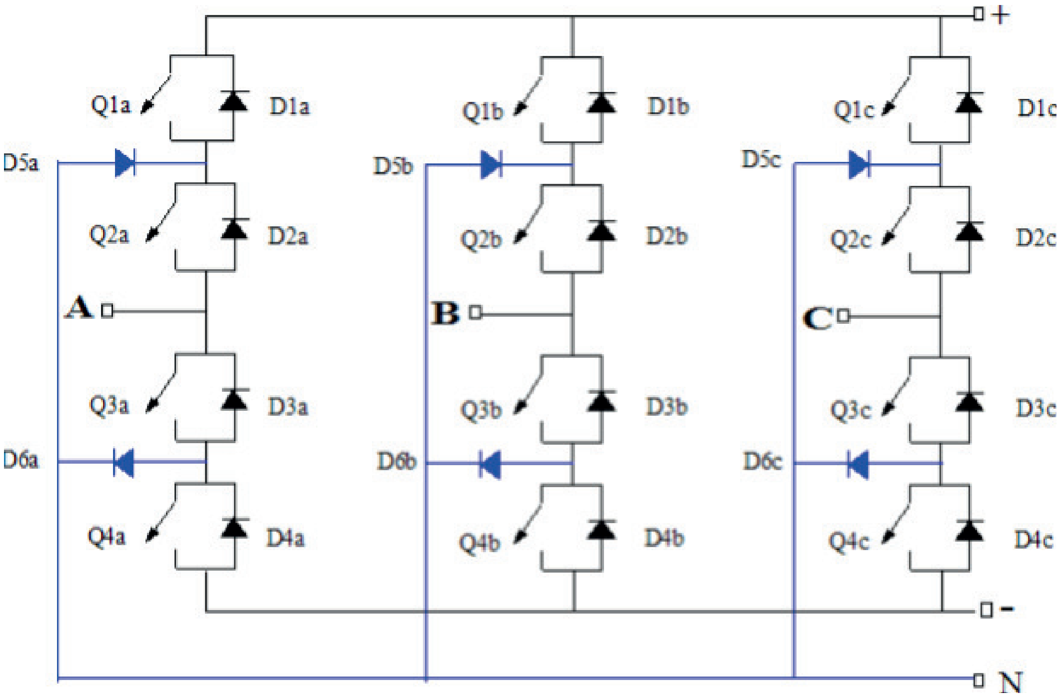


Figure 4.10. Electric circuit of the VSC

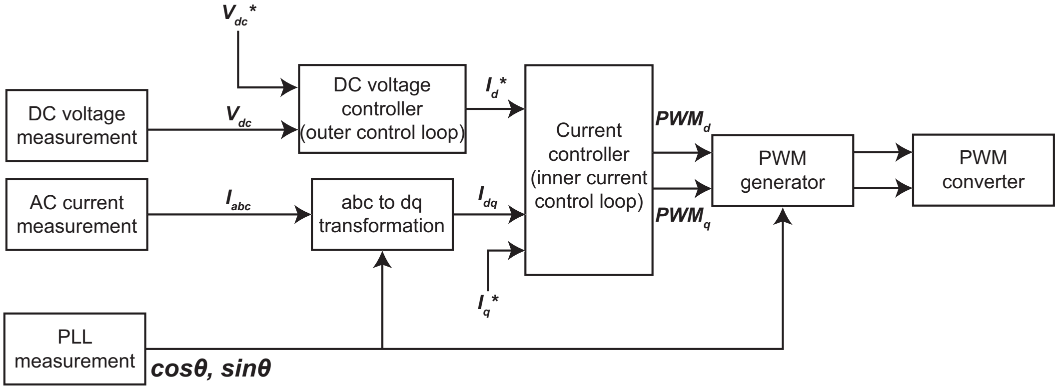


Figure 4.11. Vector current control applied to VSC

grid side converter control is the grid synchronization, obtained through a synchronization algorithm. This technique exploits a PLL [39] that can detect the phase angle of the grid voltage to obtain a unity power factor.

The sample time used by voltage and current controllers and by the Phase Locked Loop (PLL) synchronization system is 100 μs, while VSCs and pulse generators use a sample time of 1 μs. The active and reactive power flow can be separately managed by a Park transform that allows the synchronization with the power grid voltage through the transformation from a stationary reference frame abc to a rotating reference frame dq, as shown in Fig. 4.12. The first coordinate transformation step consists of representing the three-phase components $x_a(t)$, $x_b(t)$ and $x_c(t)$ as two vectors in the $\alpha\beta$ frame, using the Clarke transformation:

$$\begin{bmatrix} x_\alpha(t) \\ x_\beta(t) \end{bmatrix} = \begin{bmatrix} \sqrt{\frac{2}{3}} & -\frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{6}} \\ 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} x_a(t) \\ x_b(t) \\ x_c(t) \end{bmatrix} \tag{4.4}$$

Then, using Park's transformation, the relationship between the $\alpha\beta$ system and the dq frame is represented by the equation 4.5.

$$X_{dq} = X_{\alpha\beta} e^{-j\vartheta} \tag{4.5}$$

The vectors $x_\alpha(t)$ and $x_\beta(t)$ are rotating with the angular frequency $\omega(t)$ representing the angular frequency of the grid voltage in rad/s. If $\vartheta(t)$ is the angle defined by integrating $\omega(t)$, we obtain that the complete matrix of the Park transformation will be:

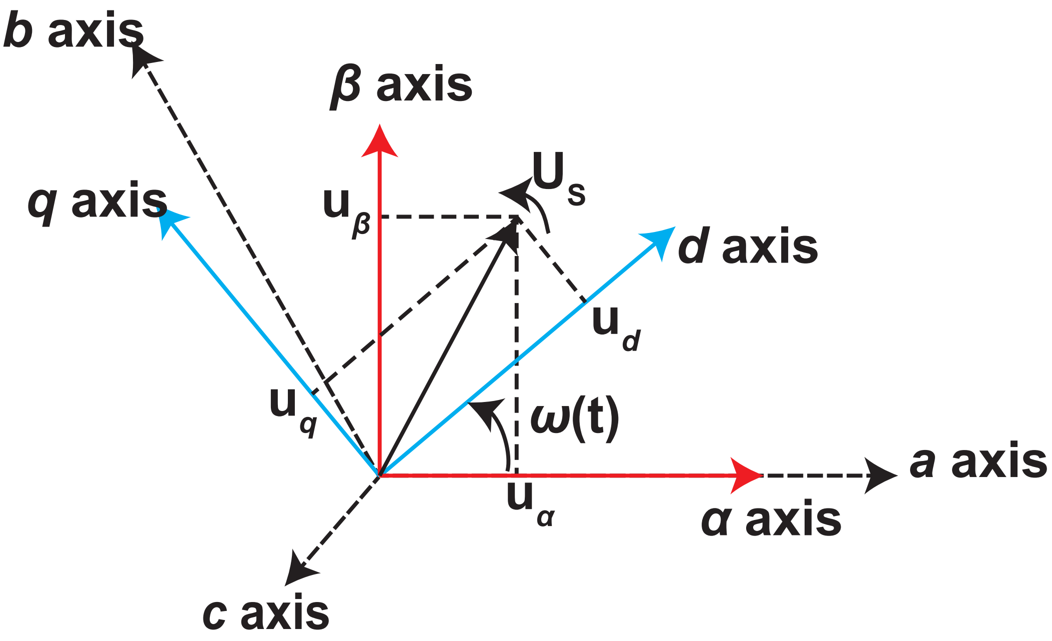


Figure 4.12. Representation of the three-phase and $\alpha\beta$ stationary reference systems and of the rotated frame dq

$$\begin{bmatrix} x_d(t) \\ x_q(t) \end{bmatrix} = \begin{bmatrix} \cos[\vartheta(t)] & \sin[\vartheta(t)] \\ -\sin[\vartheta(t)] & \cos[\vartheta(t)] \end{bmatrix} \begin{bmatrix} x_\alpha(t) \\ x_\beta(t) \end{bmatrix} \tag{4.6}$$

The vectors $x_d(t)$ and $x_q(t)$ represent the currents: the first one is the current that provides the required power to the dc bus while the second one is the current that defines the reactive power. The transformation provides an optimal control of the power flow. A correct transformation requires an accurate value of the angle ϑ in order to decouple the components for a separated power control. ϑ is given by:

$$\vartheta = \tan^{-1}\left(\frac{v_\beta}{v_\alpha}\right) \tag{4.7}$$

where v_β and v_α are the voltage components in the $\alpha\beta$ reference system.

The synchronization with the grid voltage implies that the q voltage component V_q is equal to zero, while the d voltage component V_d is equal to the grid voltage peak. Before using the Park transform, the grid voltage phase needs to be estimated. The tracked phase angle is the output of a PLL model which uses the three-phase voltages evaluated on the power grid side as inputs.

The currents $I_\mathrm{d,ref}$ and $I_\mathrm{q,ref}$ represent the reference current components while I_d and I_q are the grid current components. In the internal current control loop, shown in Fig. 4.13, a PI-regulator is present, whose input is the difference between the reference and measured components and whose output is the signal for the PWM.

The external voltage control loop, shown in Fig. 4.14, keeps the dc bus voltage constant. The dc bus voltage is compared with the reference bus voltage and the difference δ is the input of a Pi-regulator:

- if $\delta > 0$, I_d is increased to enhance the active power flow injected into the grid;
- if $\delta < 0$, I_d is reduced to decrease the active power flow injected into the grid.

The PI-regulator output is the reference current $I_\mathrm{d,ref}$. In the proposed architecture, all the converters are equipped with a voltage regulator that partecipates to maintain stable the

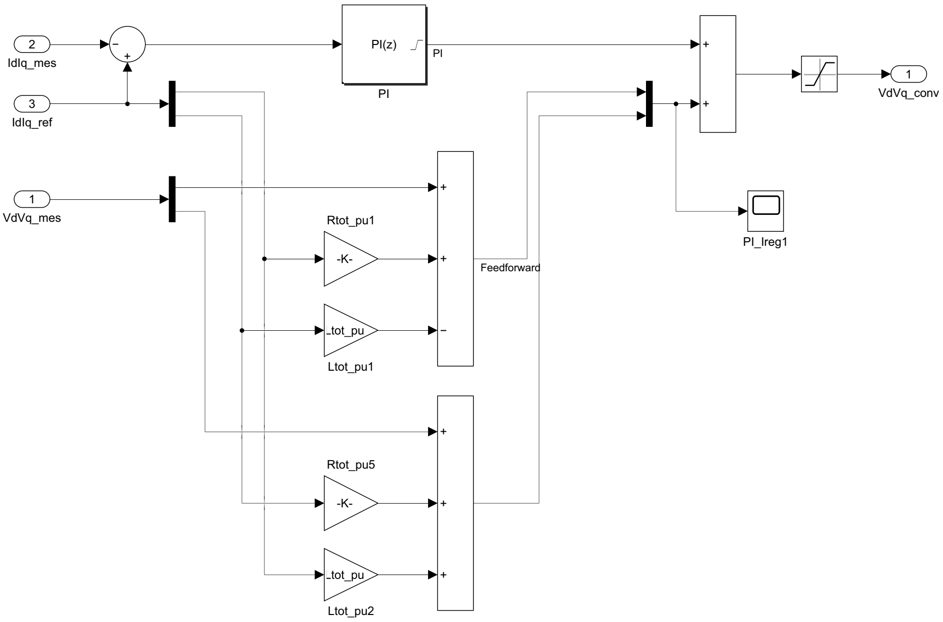


Figure 4.13. Internal control loop implemented in Matlab/Simulink for active and reactive current components

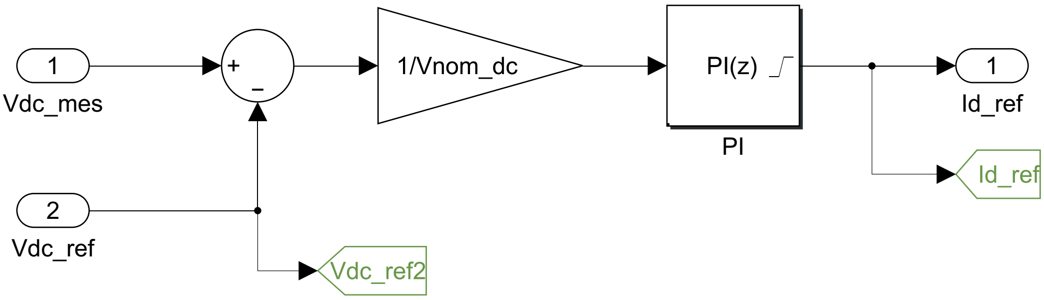


Figure 4.14. External control loop implemented in Matlab/Simulink to keep constant dc-link voltage

dc bus voltage. This design choice allows to increase the resiliency of the overall system to possible faults. The main data of the Matlab/Simulink VSC model are reported in Table 4.2.

4.5 Results and Discussion

To show the behavior of the proposed architecture, three consumers' nodes and one balance node are considered, as shown in Fig. 4.5.

First, we assess the behavior of the proposed control strategy for the energy sharing shown in Fig. 4.4. For the example shown in Fig. 4.15(a) we consider a PV system

Table 4.2. Main data of the VSC model.

Block Name	Sub-Block Name	Parameter Name	Parameter Value
VSC control	Voltage regulator	K_p	7
		K_i	800
	Current regulator	K_p	0.3
		K_i	20
	Choke impedance	R	2 mΩ
		L	250 μH
Output filters	Series connected	R	1.8850 mΩ
		L	250 μH
	Parallel connected	P	100 W
		Q	10 kvar

with a delivering power output equal to 8 kW, which feeds three consumers' loads (User-1, User-2, and User-3) by means of inverters with a rated power of 7.5 kW, 5 kW, and 2.5 kW, respectively. We assume that the users power consumption ranges between 0 and 4 kW for User-1 (black line in Fig. 4.21), while is fixed to 4 kW and 2 kW for User-2 and User-3, respectively.

Initially, when the energy demand of User-1 equals 1 kW, all the users energy demands are satisfied (since their summation is equal to 7 kW) and 1 kW of excess power is supplied to the slack node. When the demand of User-1 increases to 2 kW, there is no excess power for the balance node. Next, when the demand of User-1 further increases to 3 kW, the total demand is equal to 9 kW so that the PV production is no longer sufficient to satisfy all the loads.

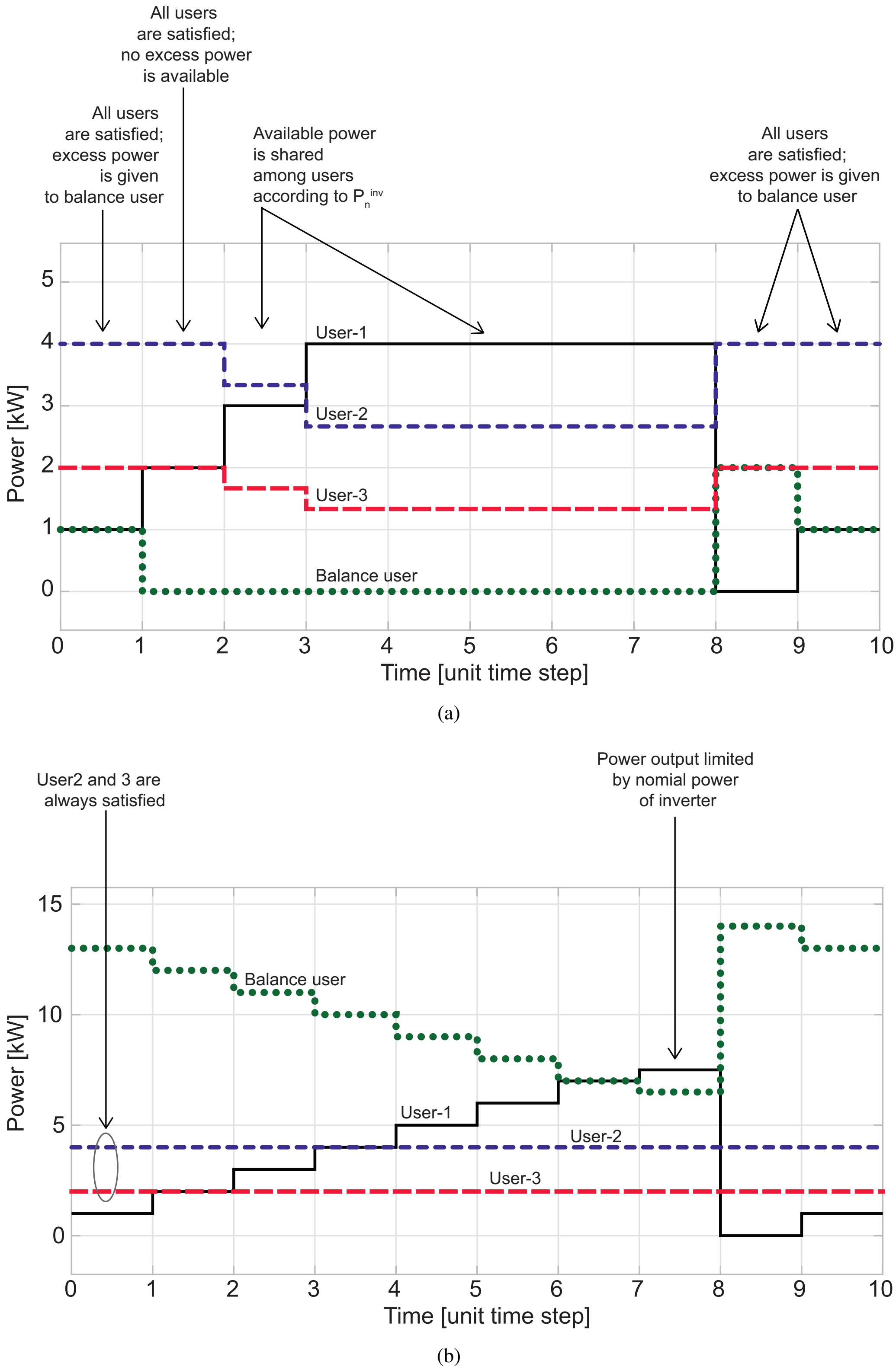


Figure 4.15. Behavior of the control strategy in two scenarios (nominal power of inverters: User-1 7.5 kW; User-2 5 kW; User-3 2.5 kW): (a) PV output equal to 8 kW; (b) PV output equal to 20 kW.

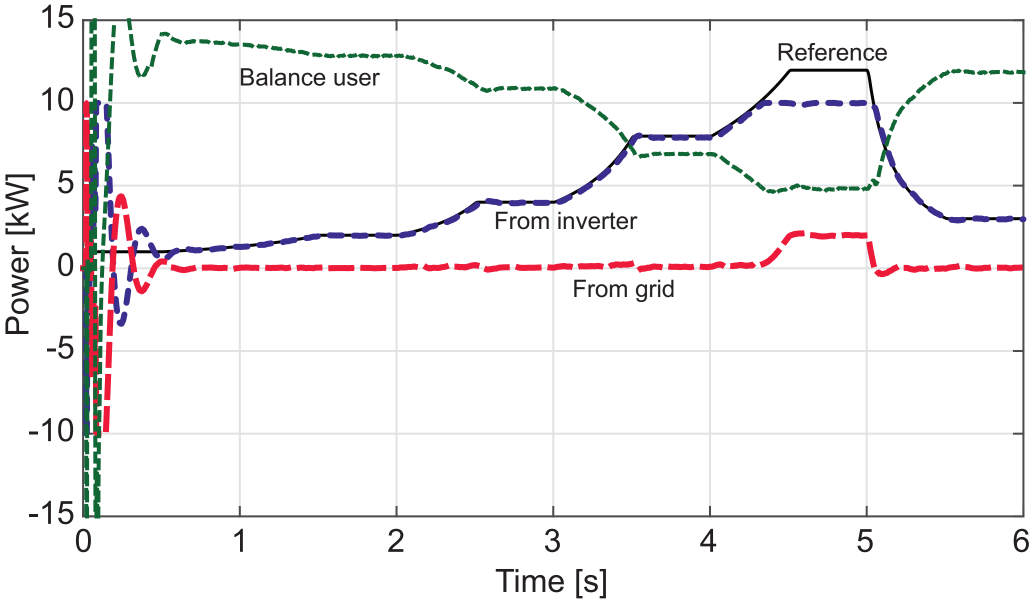
Hence, the 8 kW power output of the PV field is divided by the PSM control strategy among the users by considering the following steps:

- according to the rated power of the inverters, User-1 has 4 kW (i.e., $\frac{8}{15} \times 7.5$), User-2 has 2.66 kW (i.e., $\frac{8}{15} \times 5$), and User-3 has 1.33 kW (i.e., $\frac{8}{15} \times 2.5$);
- since the assigned power to User 1 (4 kW) is greater than its power demand (3kW), the exceeding power (1kW) is shared between User-2 and User-3 according to the rated power of their inverters: 0.66 kW more for User-2 (i.e., $\frac{1}{7.5} \times 5$) and 0.33 kW for User-3 (i.e., $\frac{1}{7.5} \times 2.5$);
- the PV power is then assigned to the users as follows: 3 kW to User-1, 3.33 kW to User-2 and 1.66 kW to User-3.

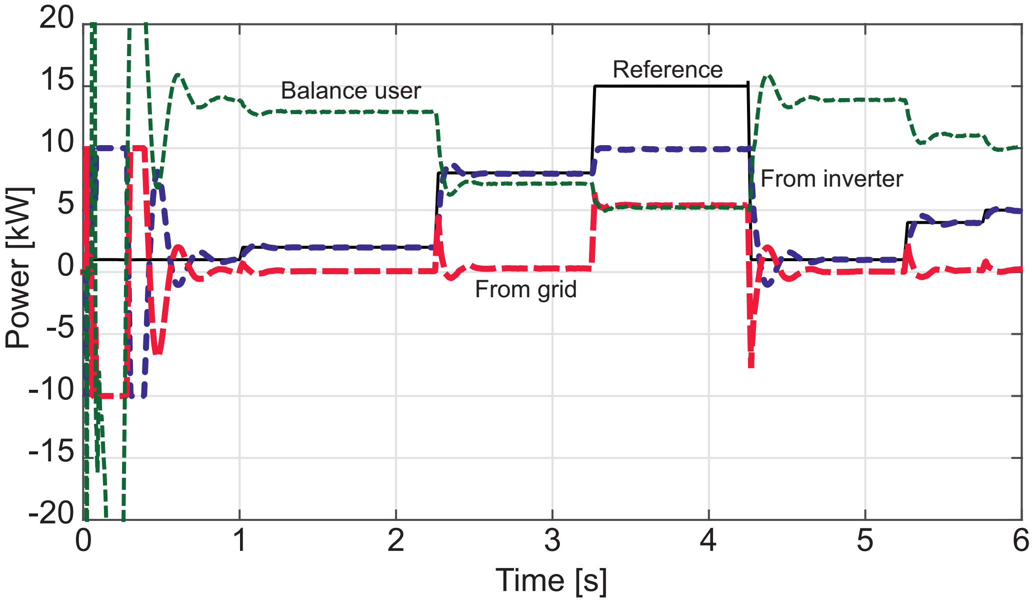
With this reasoning in mind, it is straightforward to see that when the energy demand of User-1 increases to 4 kW, the energy sharing is 4 kW to User-1, 2.66 kW to User-2, and 1.33 kW to User-3. Finally, we can observe that when the energy demands of User-1, User-2, and User-3 are all satisfied, the excess power is again supplied to the balance node.

In Fig. 4.15(b), we investigate more deeply the control strategy, assuming a power output of the PV array equal to 20 kW and a more variable load of User-1. We observe again that all the loads demands are satisfied except when the energy demand of User-1 equals 8 kW. In this case, since the load demand is greater than the nominal power of the inverter (which is 7.5 kW), only 7.5 kW is delivered to User-1 and the remaining power is fed to the balance node.

In Figs. 4.16, we test the dynamic response of a user node in the Matlab/Simulink model: for the sake of clarity and simplicity, only one user is considered in addition to the balance user. In Fig. 4.16(a), soft linear variations of the reference load profile are considered, in the scenario of a PV output equal to 15.25 kWp (10 strings) and a consumer's inverter nominal power equal to 10 kW. After an initial transient, the consumer inverter output follows the consumption of the load to minimize the power exchange with the power grid. Power is required from the grid only when the load demand is higher than the inverter rated power, in



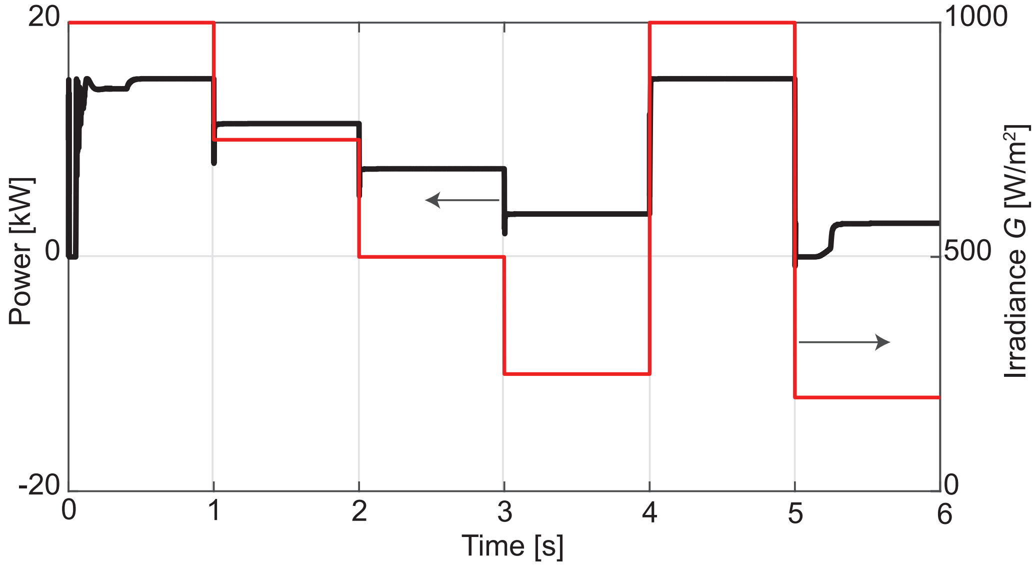
(a)



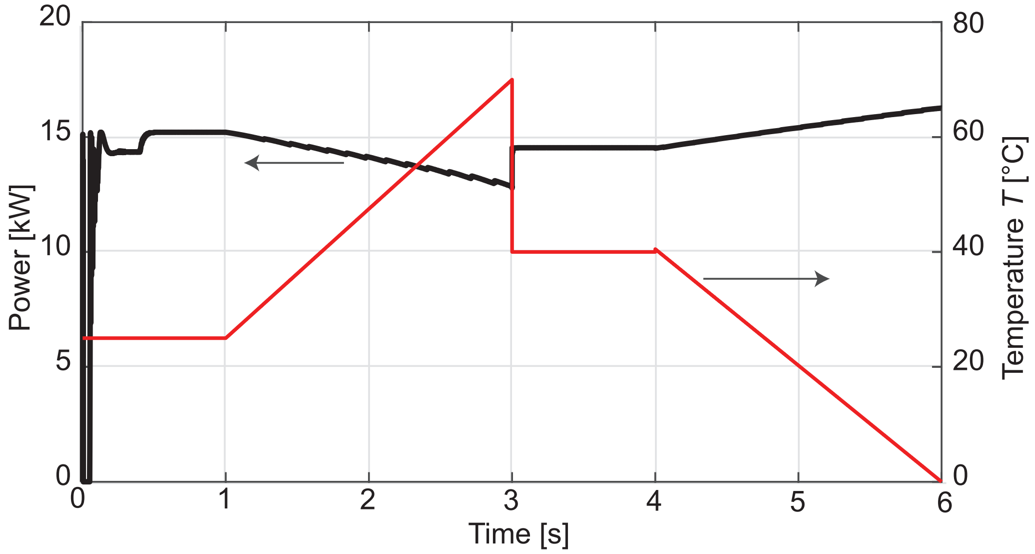
(b)

Figure 4.16. Dynamic behavior of the Matlab/Simulink model with one consumer node and the balance node under a variable load profile with soft (a) and sharp (b) variations.

which case it cannot obviously satisfy the load demand. In this proposed architecture, the balance node only intervenes to provide the excess power flow to the grid. In Fig. 4.16(b), the system is stressed by sharp variations of the load profile. We observe a good stability of the control system of the inverter: the system reaches the steady-state under bounded input applied to it and is able to get the desired response without any intolerable variation, i.e., it is able to follow the energy demand of the load in the range of its rated power. The power grid exchanges energy only during the transitions, for short time intervals and when the energy demand of the load exceeds the rated power of the inverter.



(a)



(b)

Figure 4.17. Time trend of the power output (black line) of the boost converter controlled by the MPPT, under variable irradiance G (a) (red line) (T = 25 °C) and temperature T (b) (red line) (G = 1000 W/m^2).

The system dynamic response is tested also in the presence of irradiance and temperature variations. In particular, in Fig. 4.17(a), the PV system is assumed working at 25 ° C; the irradiance is reduced by steps of 250 $\mathrm{W/m^2}$ from 1000 $\mathrm{W/m^2}$ to 250 $\mathrm{W/m^2}$ and, finally, increased abruptly back to 1000 $\mathrm{W/m^2}$ and decreased to 200 $\mathrm{W/m^2}$. Consequently, the PV array output power decreases from 15.25 kW to 11.38 kW, next to 7.22 kW and then to 3.66 kW. Correspondingly to the abrupt irradiance increasing, it rises up back to 15.25 kW and, finally, falls down to 2.83 kW. The response of the system is excellent: the MPPT is able to follow the irradiance variations maintaining stability and accuracy. The effect of the MPPT is visible in the small spikes of the PV power output and in the ringing effect when the irradiance increases abruptly from 250 $\mathrm{W/m^2}$ to 1000 $\mathrm{W/m^2}$. In Fig. 4.17(b), the MPPT is tested under temperature variations as well; the irradiance is assumed equal to 1000 $\mathrm{W/m^2}$. Again, it is possible to observe the ability of the MPPT to maximize the PV power output,in response to the effects of the temperature variations. In general, it is worth noting the effectiveness of the incremental-conductance method.

Postponing an accurate resilience assessment of the proposed PSM to subsequent studies, we observe that using the general resilience time-dependent quantification proposed in [40] as equation (1) and recalled in the more recent paper [41], the average residence of the system (intended as adaptability and recovering ability of the system) against abrupt irradiance and temperature variations, or even outage of an end-user inverter, is above 88%. The main vulnerability of the PSM lays in the fact the system is unable to cope with the boost converter or the BU inverter outage, since they are fundamental components. It should be observed that when the supervisor is down, all the generated energy is fed into the grid through the BU node, and no energy is delivered to the end-users, since the priority is to avoid that any end-user may appear as active to the DSO. Improved self-healing schemes with protection coordination studies will be investigated in further research.

Finally, in Fig. 4.18, the behavior of the full Matlab/Simulink model is reported with three consumers' nodes and one balance node. In this scenario, we assume a nominal power for the three users' inverters equal to 10 kW. Under a sharing strategy, each user has an initial available power of 5.08 kW. When a user has a lower power demand, the excess power will always be shared among the remaining two users. The energy demand is assumed variable for User-1 (dashed black line) and fixed for User-2 (8 kW, dashed blue line) and for User-3 (4 kW, dashed red line). In Fig. 4.18, we have also reported the time trend of the power requested by the users and the effective delivered power (continuous lines) calculated through the Matlab/Simulink model (the efficiency of the VSC is 0.98%). The main numerical results are reported in Table 4.3; for the sake of clarity,figures have been rounded without considering the efficiency of the inverter stage. The results confirm the robustness of the proposed architecture and the effectiveness of the control strategy that shares the energy produced by the common PV array among the consumers,based upon their instantaneous load requirements and the nominal power of the installed inverters.

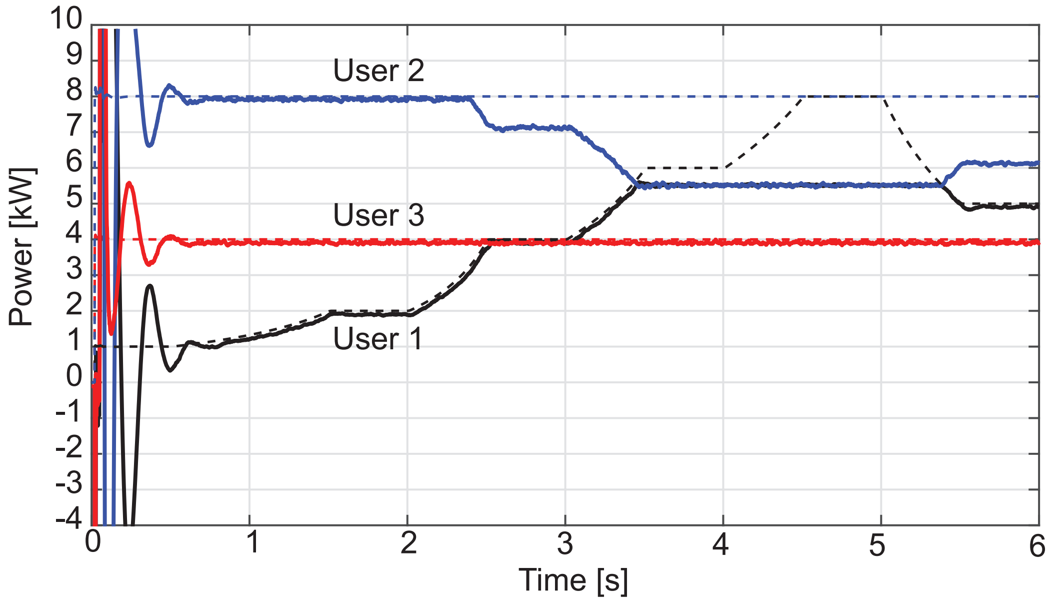


Figure 4.18. Dynamic behavior of the Matlab/Simulink model controlled by the proposed democratic power sharing control strategy with three consumers' nodes (User-1, User-2 and User-3) plus a balance node under a variable load of User-1 (dashed line: load power demanded by the user; solid line: effective power delivered by the common generator to the user).

The main numerical results are reported in Table 4.3; for the sake of clarity,figures have been rounded without considering the efficiency of the inverter stage. The results confirm the robustness of the proposed architecture and the effectiveness of the control strategy that shares the energy produced by the common PV array among the consumers,based upon their instantaneous load requirements and the nominal power of the installed inverters.

Table 4.3. Summary of the results in Fig. 4.18.

Time [s]	**Requested power** [kW]				**Delivered power** [kW]			
	U-1	U-2	U-3	**Total**	U-1	U-2	U-3	**Total**
1	1	8	4	**13**	1	8	4	**13**
2	2	8	4	**14**	2	8	4	**14**
3	4	8	4	**16**	4	7.25	4	**15.25**
4	6	8	4	**18**	5.625	5.625	4	**15.25**
5	8	8	4	**20**	5.625	5.625	4	**15.25**
6	5	8	4	**17**	5	6.25	4	**15.25**

Comments:
1: all Users' load demand satisfied
2: all Users' load demand satisfied
3: surplus power of User-1 and User-3 given to User-2
4: surplus power of User-3 shared between User-1 and User-2
5: surplus power of User-3 shared between User-1 and User-2
6: surplus power of User-1 and User-3 given to User-2

4.6 Economic Considerations

The goal of this work is to present a novel PSM and to assess its robustness and performance as a whole dynamic system. Nevertheless, economic considerations are deemed necessary. Table 4.4 reports the end-user costs of the most common PV plants in the U.S.. The cost accounts for all system hardware (storage not included) and project-development costs. The scaling up from single residential PV systems to commercial PV systems reduces the End-user PV cost of more than 30%, whereas more than 20% of cost saving may be obtained by scaling up a battery energy storage from 3 kWh to 18 kWh, as shown in Table 4.5. The cost of the common power-sharing system (including PSL and control systems) is estimated at approximately 25% of the final installation costs. These figures show how the cost savings largely compensate the cost of using a more complex power-sharing architecture, like the one proposed in this work.

To better grasp the economic benefits behind the proposed PSM, we study the energy community with the three users, named User-1, -2 and -3 having the load profiles derived from measured data over the two years 2018 and 2019. The users live in a building with a common PV field on the roof with a rated power of 22 kWp. In this analysis we neglect the

Table 4.4. End-user PV costs taken from [42]. The costs in the brackets include the inverter costs.

Sector	**Description**	**PV size**	**Cost [\$/W]**
Residential	rooftop-mounting	3-10 kW	2.70 (3.11)
Commercial	rooftop-mounted, ballasted racking	10 kW - 2 MW	1.83 (2.10)
Utility-Scale	ground-mounted, fixed-tilt	> 2 MW	1.06 (1.44)

Table 4.5. Cost of PV battery energy storage taken from [43]

Storage capacity	**Battery**	**Battery + inverter/charger**
3 kWh	1140 \$/kWh	1920 \$/kWh
8 kWh	1060 \$/kWh	1470 \$/kWh
18 kWh	870 \$/kWh	1159 \$/kWh

energy costs for the common services.

In the *basic scenario* (denoted as BS, see inset in Fig. 4.19), the PV is connected to the grid through the POC of the common services (POC-CS) and the three users have their own separate POCs (POC-1, POC-2, POC-3), with rated power $P_{\mathrm{n},i}$ equal to 3 kW, 4.5 kW and 6 kW, respectively.

Without the adoption of the PSM, all the energy (E_{PV}) produced by the PV generator would be fed into the grid through the common service (CS) and sold at the hourly single national price c_2 with a total revenue of R^{BS} for the energy community:

$$\mathrm{CS} = \begin{cases} E_{\mathrm{sold}}^{\mathrm{BS}} = E_{\mathrm{PV}} & \text{Energy sold at balance node} \\ R^{\mathrm{BS}} = c_2\,(h)\,E_{\mathrm{PV}}\,(h) & \text{Revenue for selling PV energy} \end{cases} \tag{4.8}$$

where h is the hour index over the year.

The users purchase the energy E_i^{BS} by the providers with a fixed tariff equal to c_1 = 0.159 €/kWh, given by the flat energy tariff (0,069 €/kWh), metering & transmission costs (

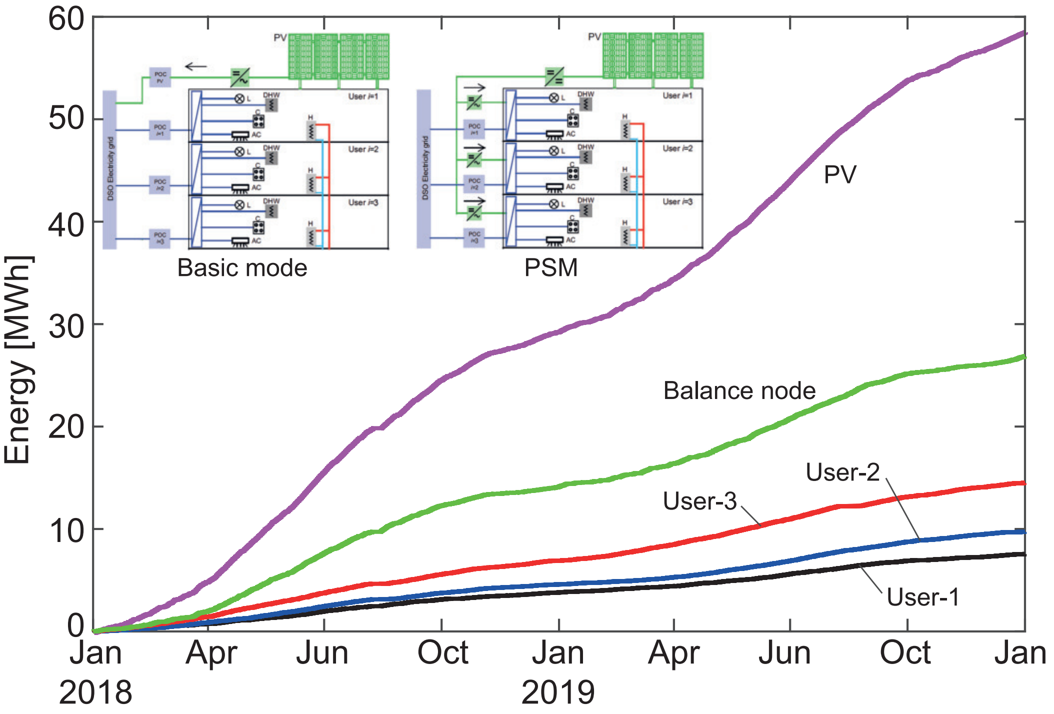


Figure 4.19. Time trend of the cumulative energy produced by the PV generator, shared among the three users and fed into the grid through the balance node.

0,00861 €/kWh), general system costs (0,054343 €/kWh), taxes (0,0125 €/kWh), and VAT (10%). Thereby, the total bill (B_i^{BS}), the revenue (R_i^{BS}) and the effective energy expense (E_i^{BS}) for the single user are given by:

$$\mathrm{User}_i^{\mathrm{BS}} = \begin{cases} B_i^{\mathrm{BS}} = c_1 E_i^{\mathrm{BS}} & \text{User energy bill} \\ R_i^{\mathrm{BS}} = \frac{P_{\mathrm{n},i}}{P_{\mathrm{n}}} R^{\mathrm{BS}} & \text{Revenue for selling PV energy} \\ E_i^{\mathrm{BS}} = B_i^{\mathrm{BS}} - R_i^{\mathrm{BS}} & \text{Effective energy expense} \end{cases} \tag{4.9}$$

In the *power sharing scenario* (denoted as PSM), each user is connected to the PV generator system through the dc-link with inverter having nominal power $P_{\mathrm{n},i}$ equal to the rated power of the POCs. The POC-CS acts as balance node, i.e., POC-CS=POC-BU. The PSM shares energy among the users who receive trough their own inverter the amount of renewable energy $E_{\mathrm{sh},i}$; the in excess energy is fed into the grid through the balance node and is sold at the hourly price c_2:

$$\text{BU} = \begin{cases} E_{\text{sold}}^{\text{PSM}} = E_{\text{PV}} - \sum_i E_{\text{sh},i} & \text{Energy sold at balance node} \\ R^{\text{PSM}} = c_2\,(h)\,E_{\text{sold}}^{\text{PSM}}\,(h) & \text{Revenue for selling PV energy} \end{cases} \tag{4.10}$$

The total bill (B_i^{PSM}), the revenue (R_i^{PSM}) and the effective energy expense (E_i^{PSM}) for each user are computed as before. With resect to the basic scenario the user asks for a reduced amount of energy to the provider that is paid with a reduced bill B_i^{PSM}.

$$\text{User}_i^{\text{PSM}} = \begin{cases} E_i^{\text{PSM}} = E_i^{\text{BS}} - E_{\text{sh},i} & \text{Reduced purchased energy} \\ B_i^{\text{PSM}} = c_1 E_i^{\text{PSM}} & \text{User energy bill} \\ R_i^{\text{PSM}} = \frac{P_{\text{n},i}}{P_{\text{n}}} R^{\text{PSM}} & \text{Revenue for selling PV energy} \\ E_i^{\text{PSM}} = B_i^{\text{PSM}} - R_i^{\text{PSM}} & \text{Effective energy expense} \end{cases} \tag{4.11}$$

To prove the benefit of the PSM architecture, the previous equations are used to calculate the savings for each user, computed as the difference between the effective energy cost in the two scenarios, i.e., $S_i = E_i^{\text{BS}} - E_i^{\text{PSM}}$ and $S_i^{\%} = \frac{S_i}{E_i^{\text{BS}}} 100$ for a real case.

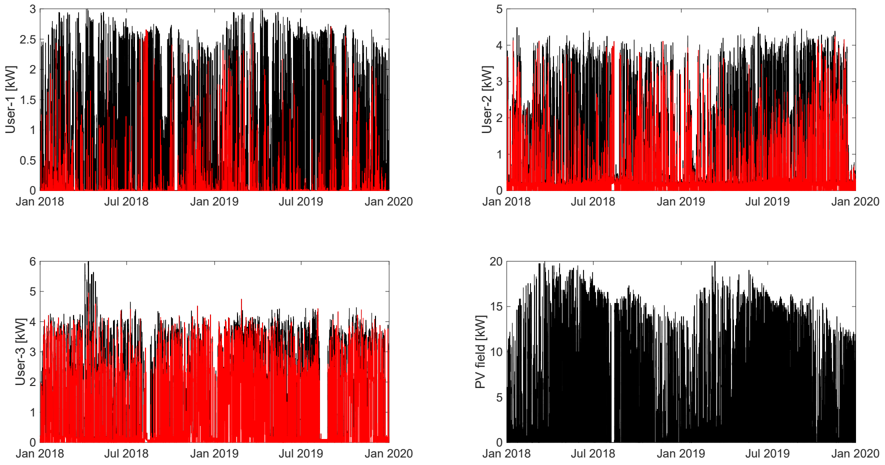


Figure 4.20. Time trend of the measured load consumptions of three users and of the generation a common PV field.

The measured time trend of the three users' loads and the PV output are reported in Fig. 4.20 (black line); the load consumption of the three users after the application of the PSM is reported as well (red lines). In Fig. 4.19, we have shown the cumulative time trend of the energies shared among the three users, the in excess energy fed into the grid trough the balance node, and the energy produced by the common PV generator. Tab. 4.6 summarizes the most relevant results: the last two columns show, in absolute and percentage values, the savings for each user, computed as the difference between the balances in the two scenarios, i.e., $S_i = BA_i^{\mathrm{BS}} - BA_i^{\mathrm{PSM}}$ and $S_i^{\%} = \frac{S_i}{BA_i^{\mathrm{BS}}} 100$.

Table 4.6. Energy and economic savings with PSM

			Basic scenario					Power sharing scenario					Savings	
User	POC $P_{\mathrm{n,i}}$ [kW]	Energy produced E_{PV} [MWh]	Energy purcased E_i^{BS} [MWh]	Bill B_i^{BS} [€]	Energy sold $E_{\mathrm{sold}}^{\mathrm{BS}}$ [MWh]	Revenues R_i^{BS} [€]	Balance BA_i^{BS} [€]	Energy purcased E_i^{PSM} [MWh]	Bill B_i^{PSM} [€]	Energy sold $E_{\mathrm{sold}}^{\mathrm{PSM}}$ [MWh]	Total revenue R_i^{PSM} [€]	Balance BA_i^{PSM} [€]	S_i **[€]**	$S_i^{\%}$ **[%]**
U_1	3		8.57	1362		726	636	1.01	161		325	-164	**799**	**125.5**
U_2	4.5		14.88	2364		1089	1275	5.16	820		486	334	**942**	**73.8**
U_3	6		35.08	5575		1452	4123	20.58	3270		649	2621	**1501**	**36.4**
CS/BU	22	58.64			58.64	3267				26.85	1460			

4.6.1 Economic Analysis for the Italian Energy Market

In this section we present the significant impact that the proposed PSM can have in enabling access to new economies and share benefits among participants to the EC. The effectiveness of the PSM is tested on real-world data provided by Byom through “Home EnergIA”, Engineering non-intrusive load monitoring (NILM) smart meter project. The obtained results confirm the high performance of the proposed PSM which allows a democratic sharing of the energy produced by the common renewable generators, under the proposition that “democracy encourages peaceful interaction among citizens”. We investigated the economic advantages of the PSM for a system configuration consisting of a common photovoltaic RES, a balance node and three users. The common PV source has a rated power output of 10 kWp. Each end-user is equipped with:

- a POC whose rated power is 3, 4.5 and 6 kW, respectively,
- an unidirectional inverter with a nominal power of 3, 4.5 and 6 kW, respectively (equal to the POC).

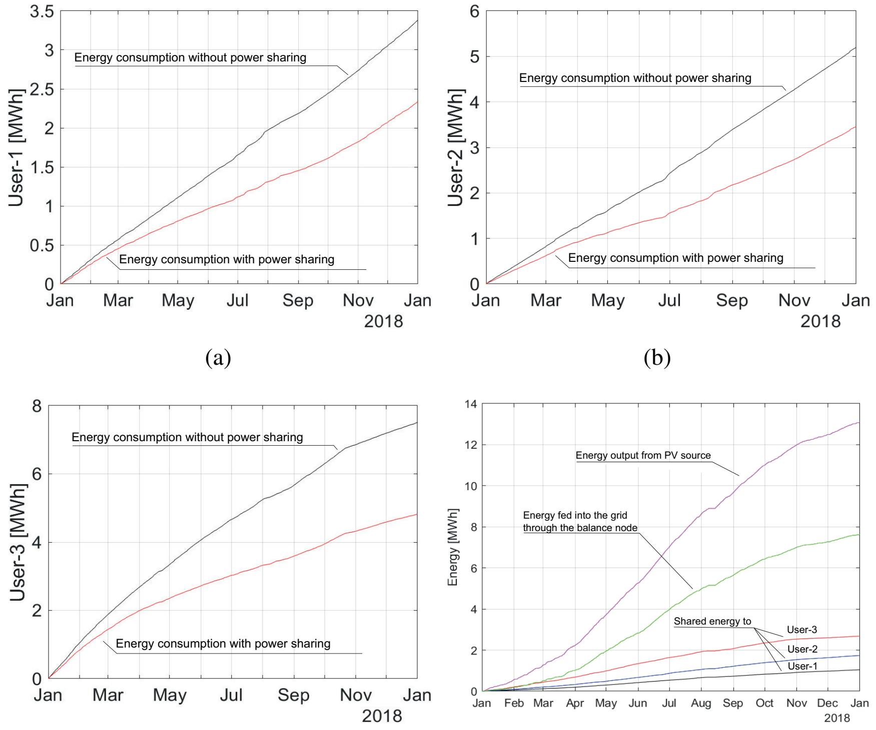
The balance node, equipped with a bi-directional inverter, feeds the CSs and represents the only active user of the system.

All the data, i.e., PV production and energy consumptions, have been measured and provided by Byom on quarter hour time slots.

Figs. 4.21 show the cumulative energy consumption of the three users before and after the application of the proposed PSM during the year 2018. In particular, Fig. 4.21(d) shows the PV production, the energies shared with the three users (which result form the difference between the energy consumption before and after the application of the PSM), and, finelly, the energy fed into the grid through the balance node of the CSs.

The economic analysis has been carried out considering three different regulated tariff:

- single national price (SNP) plus spread (set to 3%);
- two-tier time-of-use tariff (T2) regulated in the safeguard service;
- free market fixed tariff (T1).



(a) (b)

(c) (d)

Figure 4.21. Comparison of the energy consumption with and without power sharing by the three users (a),(b) and (c), and energy produced by PV and fed into the grid through the balance node (d).

Table 4.7 shows the consumers' total expense for electricity only, which is approximately 45% of the final cost (it is necessary to add transmission, distribution and metering tariffs, network charges and taxes).

Table 4.7. Economic analysis

User	Type of Market	Cost without sharing [€]	Cost with sharing [€]
U-1	SNP+Spread	222.72	154.09
	T2	310.36	213.71
	T1	311.77	218.24
U-2	SNP+Spread	343.85	229.64
	T2	479.88	317.78
	T1	479.73	323.69
U-3	SNP+Spread	484.72	312.66
	T2	673.19	429.30
	T1	671.35	436.53

Chapter 5

Operation and Maintenance Practices in Energy Communities PV Plants

5.1 Introduction

In the recent years, the PV industry has undergone a large growth, mainly due to government financial incentives, e.g., feed-in tariff, net metering, investments subsidies and solar renewable energy certificates [44, 45], justified by climate change threats and environmental impacts [46]. This growth has allowed high market penetration levels [47] and lower costs for both PV arrays and the balance-of- system (BOS). This has also allowed the break-even point, where the levelized cost of energy (LCOE) [48] generated by PV sources is lower than the cost of electricity produced by conventional power plants [49]. Today, the PV market has reached the grid-parity in several countries [50] and investors are beginning to invest even in the absence of government incentives, leveraging several financial options, such as leasing and/or Power Purchase Agreements (PPA).

In this context, PV stakeholders, operators and asset managers shifted their focus from the engineering, procurement and construction (EPC) of utility-scale grid-connected PV plants to tailoring monitoring and best operation and maintenance (O&M) practices [51]. It is widely acknowledged that high-quality O&M services ensure that PV systems will maintain high levels of technical and, consequently, economic performance over their lifetime; a high

(a) Zimmermann tilted-fixed systems (b) Convert flat uniaxial tracking systems (c) Solfocus biaxial tracking systems with high-concentration photovoltaics

Figure 5.1. Construction methods of the PV plant portfolio where reports and measurements have been performed.

quality service package mitigates potential risks, improve long-term reliability, LCOE and PPA prices, and positively impact the return on investment (ROI). In the past, very favorable feed-in tariffs have compromised the perception of the true risk of the PV investment, made worst by the use of ineffective performance metrics. These factors have caused the value of professional and high-quality service provisions to be underestimated. Today, the young PV industry is evolving into the services segment and is passing the grid-parity worldwide [52].

In general, the availability of a PV system is dependent upon the reliability of the PV system [53]. While availability is generally defined as the uptime divided by the total time (uptime plus downtime), uptime is dependent on the various components working together in a system. Thus, the uptime is strictly connected to the long-term equipment reliability, especially that of the essential components. Reliability is commonly defined as the probability that an equipment will perform its intended functions satisfactorily without failure and within specified performance limits, for a specified length of time, operating under specified environmental and operating conditions.

PV systems reliability can be increased with proper monitoring techniques that can provide modern diagnosis and prognosis tools [54, 55]. The first source of data comes from real-time monitoring: this can be implemented in many cases exploiting cheap and effective communications protocols like ZigBee [56]. In other cases, for reducing the investment cost related to additional sensors, the performance analysis of the PV plant is performed by an architecture that, instead of measuring the irradiation and module temperature by means of pyranometers and thermometers, it uses their theoretical values calculated from the PV-module characteristics and measured dc voltage and current of a PV inverter [57].

The reliability of PV systems is challenged by their continuous exposure to weather: the lifetime expectancy of PV equipment will depend on design, environment and conditions under which they are operated [15, 16, 58]. The effects of environmental condition, that can be in many cases extreme, are nowadays well studied both using measurement data and artificial aging of the modules [59, 60].

Currently, guidelines or technical standards that include PV systems-specific data for reliability assessments have been only recently proposed, which has caused non-standardized fault analyses. Currently, PV experts around the world have jointly worked to establish widely accepted standards under the "IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications" (IECRE) system (e.g., IECRE OD-404 "PV Plant operational status Assessment")[1]. These differences in practices have somehow compromised the understanding of PV systems reliability at industry level, especially in large asset management cases. Several monitoring techniques, operational diagnostics and defectoscopy methods have been proposed in literature. In [61], four basic classic detection methods are presented for the assessment of the PV system's operational performance: electroluminescence, infrared thermography (IRT), flash test, and current-voltage ($I - V$) characteristics measurements. The authors also discuss effective field methods, based on insulation resistivity measurement, which can adequately detect Potential Induced Degradation (PID)of the PV modules, to identify their performance degradation as a consequence of the high-voltage stress. In [62], a specific array fault diagnosis method is proposed based on fuzzy C-mean (FCM) and fuzzy membership algorithms. In [63], unmanned aerial vehicles (UAVs) with infrared cameras are proposed for a continuous surveillance/monitoring of PV systems. These methods are effective for the identification of macroscopic defects, e.g., cracked PV cells with broken contacts. In [64] an algorithmic solution is proposed for the rapid detection of multiple visible defects in photovoltaic modules images obtained with unmanned aerial vehicle. In [65], the authors propose a real time

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[1] The interested reader can visit: https://blog.iec.ch/2018/10/global-iecre-certification-and-future-rating-system-instils-confidence-in-solar-pv-industry/

inspection of the solar garden based on the use of a drone equipped with two cameras, a thermal and a Charge-Coupled Device CCD.

The use of UVAs combined to the grows in the digitalization of the O&M sector, is opening new frontiers in the design of optimized maintenance plans [66] and integrated management of different type information (SCADA systems, images, laboratory tests) in a single tools [67]. The following sections outlines monitoring techniques that are suitable for a general standardization and can be used as a common basis for reliability assessments and effective O&M. By discussing the most widespread issues, major failures and unexpected events that can occur in PV systems, the authors identify novel remote monitoring techniques to improve both failures reporting and corrective action systems (FRCAS).

5.2 Description of the PV Plant Portfolio Examined

The monitoring techniques herein described are based on a large data set of reports and measurements from more than eighty large-scale PV plants built with different technologies. The construction methods are mainly three: fixed tilted type (most widely applied), flat uniaxial tracking mode, and biaxial tracking mode, often using High-Concentration Photovoltaics (HCPV). The three systems are shown in Fig. 5.1. The fundamental difference between different constriction methods lies in their power generation capacity, as well as in the initial Capital Expenditure (CAPEX) and Operation Expenditure (OPEX). According to well established studies [68], based on the optimum tilt angle fixed installations (the average tilt angle in Italy is ranging between 25°and 30°), the power generation of horizontal uniaxial tracking is greater by 25% and that of biaxial HCPV tracking by 50-75% [69]. Anyway, according to operation and maintenance reports, tilt angle regulating systems may fail, and cause generating capacity lower than expected. This problem can be very severe in biaxial tracking systems, especially when installed in windy regions, mostly due to failure of the hydraulic rams.

5.3 Survey of Failures and Unexpected Events

5.3.1 Geological Instability Issues

The installation surface of large-scale PV plant may be subject to geological instability, due to severe weather events, e.g., rain or snow, or earthquakes. The ground mounted solar racking system may slide, causing a low Performance Ratio (PR) of the PV system. According to Std. IEC 61724, the PR is defined as the ratio of the measured output energy delivered into the grid E_{grid} during a specific period of time to the expected output for the same period of time based on the system name-plate rating P_{nom}, i.e.:

$$\frac{E_{\text{grid}}}{P_{\text{nom}} G_{\text{inc}}} \, , \tag{5.1}$$

where G_{inc} is the irradiation on the PV array plane.

The accidental sliding of the solar racking system due to soil movements may cause partial shadings of the PV modules during the day, resulting in power loss. The problem becomes worse when the compromised support structures must be replaced to prevent damage and breakage of the modules; this circumstance may lead to the shutdown of the entire array sub-field.

Figs. 5.2 shows relevant earth sliding events that were observed: in Fig. 5.2(a) a slope sliding has caused the skidding and overturning of the solar racking systems; in Fig. 5.2(b) a landslide near the main electrical cable duct bank has damaged the DC array cables and caused a plant shut-down for more than 50 days; in Fig. 5.2(c) a landslide has determined the rotation of the MV/LV substation, resulting in the tear of the service-entrance MV cables and, consequently, the unavailability of the system for a period longer than one week.

A variety of solutions is available to prevent the above problems, as shown in Figs. 5.3, including the installation of draining trenches with geocomposite materials, diversion ditch with anti-erosion three-dimensional geomat, ducts made of concrete and HDPE pipes, stakewall or paling. The above solutions may require deeper foundations for the solar racking systems so that to avoid interceptions with the underground drainage system.

(a) Sliding of tilted-fixed racking systems (b) Landslide with tearing of DC cables (c) Sliding of a power substation

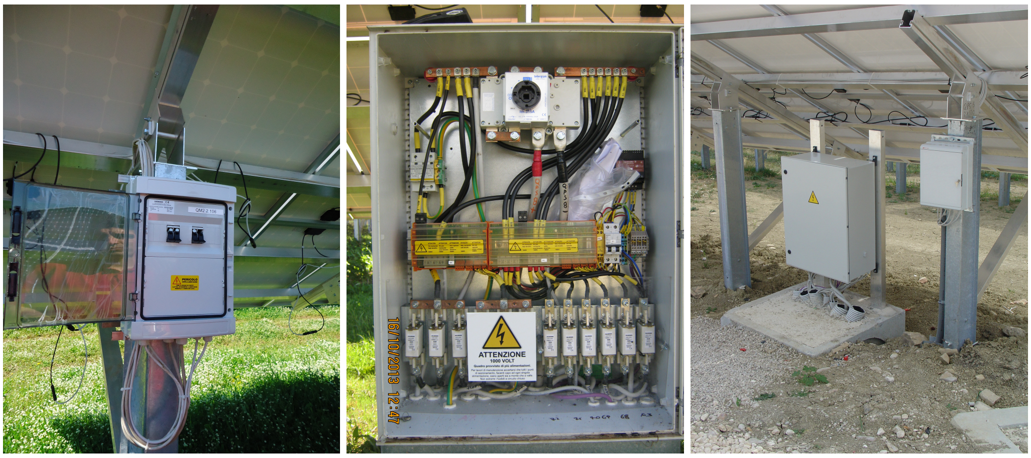
Figure 5.2. Observed slope sliding phenomena.

(a) Concrete stakewalls and boxes (b) Ditch (c) Draining trenches

Figure 5.3. Solutions for slope sliding problems.

5.3.2 String Fuses

According to recommended installation practices [70], PV strings are electrically connected in parallel at combiner boxes, where an overcurrent protection device is required for each string [71]. When the scale of the PV plant is large, string cables can be more than 100 m long, and combiner boxes may be equipped with costly String Monitoring Units (SMUs). To reduce the length of string cables and the number of combiner boxes, an installation practice consists of connecting in parallel only two or three strings at the time via an intermediate combiner box (first parallel level), with no SMU and with fuses on each string. The output circuit conductors will then be connected in parallel at a monitored combiner box (second parallel level). This practice allows a greater DC power combined into the main string combiner boxes, whose output is connected to the inverter input terminals. This layout



(a) First intermediate un-monitored combiner box (b) Main combiner box equipped with String Monitoring Unit (c) Intermediate and main boxes

Figure 5.4. Intermediate and main combiner boxes.

achieves a comprehensive, cost-effective and highly modular solution and has been adopted in several PV plants.

In periods of the year with high irradiation and not excessive temperatures (e.g., March and April), PV plants with this layout have however showed a widespread problem: the frequent unexpected operation of fuses within the main combiner boxes. The tripping of fuses may cause the disconnection of a large number of healthy strings, resulting in a poor PR. The problem is obviously made worst by the fact that a protective device in the main combiner box protects against overcurrents two or three strings at the time. In order to seek a cost-effective solution, the main combiner boxes have been equipped with 10×38mm 1000 V PV fuse links rated 30 A, installed into modular fuse holders rated 32 A. The rating choice has been based on the short-circuit current I_{sc} of the modules under standard test conditions (STC), which is 8.4 A, adopting a very low safety factor k (equal to $30/25.2 = 1.19$). In particular weather conditions, the output current from strings in parallel may exceed the rated current of the fuses over a period of time sufficient to cause their operation. Additionally, the fuse operation may also occur under sudden weather changes (e.g., from overcast to clear sky), which may produce short-durations overcurrents; if such overcurrents occur frequently, the fuse may experience a thermal stress that may cause its undue operation.

The Italian Std. CEI 82-25 does not provide any requirement for the sizing of PV fuses.

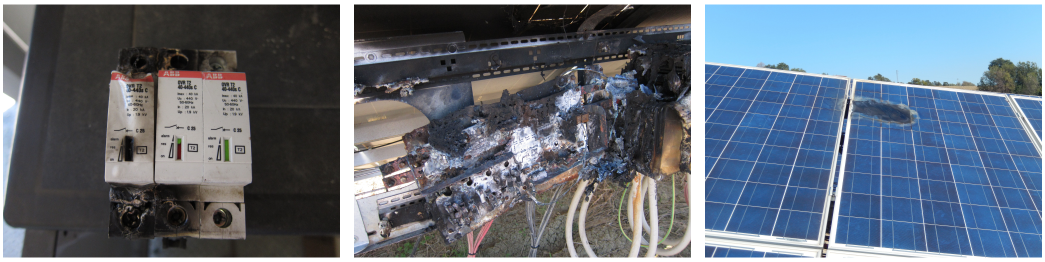
The solution is in the IEEE Std. 1374 that prescribes the application of two safety factors for the correct sizing of overcurrent devices:

- according to NEC Section 690-8, that requires that overcurrent devices be sized so that they shall not be operated continuously at more than 80% of their rated current, a first derating factor annotated as 125% E (E stands for equipment limitations) must be applied;
- according to UL 1703-1993, an additional multiplicative factor of 125% N (N stands for normal operation) must be used to account for normal and expected operating conditions that occur on warm sunny days around solar noon when the module short-circuit current can be well above the rated STC value. Thus, a total safety factor of $1.25 \times 1.25 = 1.56$ is recommended to be applied to properly size the overcurrent protective device.

Thus, the solution is to upgrade the fuse rating from 30 A to 50 A. The major drawback of this upgrade is that 50 A fuses may only be available of the blade type, which requires the redesign of the string combiner box [see Fig. 5.4(b)]. When free space is available in existing combiner boxes, new fuses can be installed; otherwise, additional string combiner boxes may be installed.

5.3.3 Overvoltages

One of the major causes of failure of electronic devices in PV systems are the external overvoltages. Lightning strikes can release a very high power that can cause damage on PV plants located even kilometers away from the point of impact, due to radiated couplings (the frequency content of the lightning electromagnetic pulse can reach several MHz) [72, 73]. It is common practice to design the grounding system of PV plants at power frequency, to obtain a sufficiently low grounding resistance R_g that ensures an effective protective grounding. However, in the presence of the lightning current, the impedance of the ground-electrode would exhibit an impulse behavior, based upon many factors, such as the characteristics of the soil, the peak and waveform of the impulse current and the geometry



(a) SPD failure (b) Combiner box failure (c) Fire damage on PV modules

Figure 5.5. Failure and fire effects due to overevoltages.

of the grounding-electrode. The peak of the transient Ground Potential Rise (GPR) can be so high to break-down components insulation, and destroy surge protective devices.

Transient Overvoltages (TOVs) may cause serious failures as well. In recent years in Europe, Distribution System Operators (DSOs) may adopt high-impedance and resonant grounding, with a remarkable trend toward the latter [74]. However, significant portions of the existing MV distribution system in Italy are still operated with ungrounded neutral, especially in rural areas where large-scale PV systems may be located. The earth-fault factor factor that is used for insulation coordination and sizing of Metal Oxide Surge Arresters (MOSA) or Surge Protective Devices (SPDs), is equal to 1.73 p.u., even though, practice has shown that this factor is too optimistic. Large MV networks with underground lines can be subject to ground-faults TOVs well in excess of 2.0 p.u. [75, 76].

Lightning strikes may cause, directly and indirectly, severe damages [77]. In some instances, telecommunication systems, video-alarm and surveillance apparatus can be out of service, because of the damages occurred on active components, e.g., the central alarm card, 16-channels encoder, infrared cameras, processing boards of the microphone perimeter system, UPS, the entry gate infrared barrier. In other cases, damages were observed on the mechanical structures and the electronic circuits of the inverter cabinets, e.g., DC block capacitors, IGBT, control panels, conductors in the DC block, protection and signaling fuses on the DC inputs, choppers (voltage limiters), ethernet cards, production meters, radiation sensors, etc. The repair or replacement of damaged components imply substantial cost, as well as loss of solar energy revenue.

In some cases, as shown in Figs. 5.5, the failure of the modular multipole SPDs installed within the main combiner boxes has been reported by O&M staff [see Fig. 5.5(a)]; these SPDs are usually Type II as per Std. EN 50539-11. The breakdown of SPD may originate a ground-fault that can cause fire or burns. The consequent ground-fault currents, whose magnitude depends on how the DC side of the plant is operated (i.e., with the negative pole ungrounded or grounded), may be interrupted by the operation of overcurrent protective devices installed on the DC side of inverter. However, during the clearing time, electrical shock hazard is present, and fires may be caused, with damages to equipment and modules [see Figs. 5.5(b) and 5.5(c)].

To avoid this problem, a coordinated system that includes a Lightning Protection System (LPS) and a set of surge arresters should be installed. However, in large-scale PV plants, only modular Type 2 SPD may be installed in combiner boxes, and no lightning protection system is adopted, since the PV plant is considered protected according to Std. EN 62305-2. In fact, only the risk R4 of economic loss is normally considered in the risk assessment to evaluate whether or not lightning protection of a PV installations is needed. The risk R1 of loss of human life (including permanent injury) is much below the threshold of the tolerable limit; this is based on the fact that persons are infrequently present at PV installations. In addition, the risks R2 and R3, respectively of the interruption of public service and loss of cultural heritage, are not present. Thus, the lack of an LPS, uniquely based on economic factors, has often made PV systems vulnerable to direct lightning strikes and/or to lightning flashes striking nearby. Based on the above, the proper protective solution of PV systems should include an LPS with air-termination rods, and a coordinated SPD system choses according to Std. EN 62305-2, including Type 1 SPD at the main electric supply, Type 2 SPD for the electrical equipment and Type 3 SPD for sensitive electronic apparatus.

5.3.4 Substation Over Temperature and Inverter Failures

At the beginning of the PV era, the thermal problem of the PV substation, which may host the inverter, had been underestimated. The air circulation and filtering system in the PV substation, together with the thermal insulation, had not been properly optimized. Therefore, PV substations installed in harsh environments for temperature and humidity (e.g.,

(a) Infrared imaging of a PV station (b) Fire incident on a PV inverter (c) Fire incident in a PV DC/AC station

Figure 5.6. Over temperatures and fire incidents.

Southern Italy near the sea) were unable to operate with the desired service continuity. The temperature control inside prefabricated station made in vibrated reinforced concrete mainly relied on wall mounted axial fans or roof mounted centrifugal fans, which could ventilate PV inverters through their air intake vent openings at the bottom and exhaust air openings at top. Initially, inverters were not equipped with forced air systems to allow the exhaust of hot air into the substation. An insufficient cooling capability within the PV station can cause over-temperatures, especially over summer months, which is detrimental to utility-interactive inverters.

Fig. 5.6(a) shows an infrared imaging inspection of a PV station installed in Southern Italy, where temperatures of 50°have been recorded in summer months. The over-temperature, together with a possible under-sized PV inverters, with respect to the DC power of field, can cause an overheating of the inverter that may only be partially reduced by on-board systems. O&M staff reported failures of inverters due to DC arc flash and consequent fires (see Fig. 5.6(b)), which may catastrophically affect the whole station [see Fig. 5.6(c)].

5.3.5 Low DC Insulation

A typical problem of PV plants may be the low value of the DC insulation-to-ground resistance R_{INS} of the PV arrays that are operated with the negative pole ungrounded. The data collected over a time span of 8 years clearly show that R_{INS} of PV plants decreases through the years [78]. This causes issues with the insulation monitors at the PV inverters

(a) Old MC3 connector.

(b) MC3 connector with worst degradation.

(c) Insulation measurements on string cable connections.

Figure 5.7. Low DC insulation problems.

when the leakage current is greater than the threshold of the monitoring relay.

The total leakage current is due to contributions from all system components (e.g., PV modules, DC cables and inverter). According to DIN EN 61646, the R_{INS} must be greater than 40 $\text{M}\Omega/m^2$. According to DIN VDE 0126-1-1, that is focused on transformerless inverters (i.e., without galvanic isolation), the R_{INS} must be greater than 1 $k\Omega/V$ with a minimum value of 500 kΩ.

The magnitude of the insulation resistance R_{INS} depends on a variety of factors, including the size of the system, the amount of conductive surface, the presence of conductive media (e.g., moisture, rain, humidity), and damage to the integrity of circuits. In large-scale PV systems, we have observed that the insulation has been mainly affected by:

- spring water infiltrations, which caused the electrical cables installed in buried ducts to be immersed in water;
- degradation of the insulating material of old multi-contact connectors (e.g., MC3), which PV panels may be equipped with (Figs. 5.7).

A possible solution to prevent water infiltrations mat be the installation of a coordinated network of concrete raceways and gutters to drain the water out. An MC connector consists of two rubber shielded jacks and sockets which would push-mate. The MC3 type connectors have no locking system. The new MC4 type connectors, widely used nowadays, are provided with positive locking and input protection. This connector type ensures a better contact between poles and a better insulation level of the cable couplers. It should be noted that a loose connector or an intermittent connection, due to the decay of the connections, are possible sources of arc fault failure in PV systems. The replacement of old MC3 connectors with new MC4 type connectors may however, cause issues for the solar panels warranty.

5.3.6 MV/LV Transformer Failures

Utility-scale PV plants are usually connected to the MV distribution network by means of MV/LV of transformers [79]. In general, Cast-Resin Dry Type Transformers (CRT) are more frequently installed. Reasons for using dry transformers include: (*i*) higher safety for operators and property; (*ii*) maintenance and pollution-free solution that is environmentally friendly and requires less side clearance; (*iii*) less labor-intensive installation, with reduced cost for concrete work and fire protection systems, due to the non-existent fire hazard; (*iv*) excellent capacity to support overloads and withstand short circuit currents. However, dry-type transformers are very sensitive to winding failures, which may cause outages.

In several PV fields, which were investigated, environmental stresses, severe climate conditions, together with overvoltages, and high thermal stress during operation, caused clear signs of deterioration of the dry insulation (Figs. 5.8). Options to address this issue include: do nothing and wait for the tripping of the overcorrect protections (dangerous choice), do weekly visual inspections, install online condition monitoring equipment, replace the unit. Asset management must decide the best course of actions in coordination with the whole PV plants portfolio.

5.3.7 Modules Failures

A good deal of literature and technical reports describe the common failures of PV modules and their effects on PV plant efficiency [80]. They can be broadly divided into main categories: (*i*) infant failures, that occur at the beginning of the operating life of PV modules, usually within the first two years; (*ii*) midlife failures, that appear in PV modules that have been in the field for six to eight years; (*iii*) wear-out failures, that determine the maximum operating life of a PV module, which ends when the power drops below 70% -80% of the initial rated power.

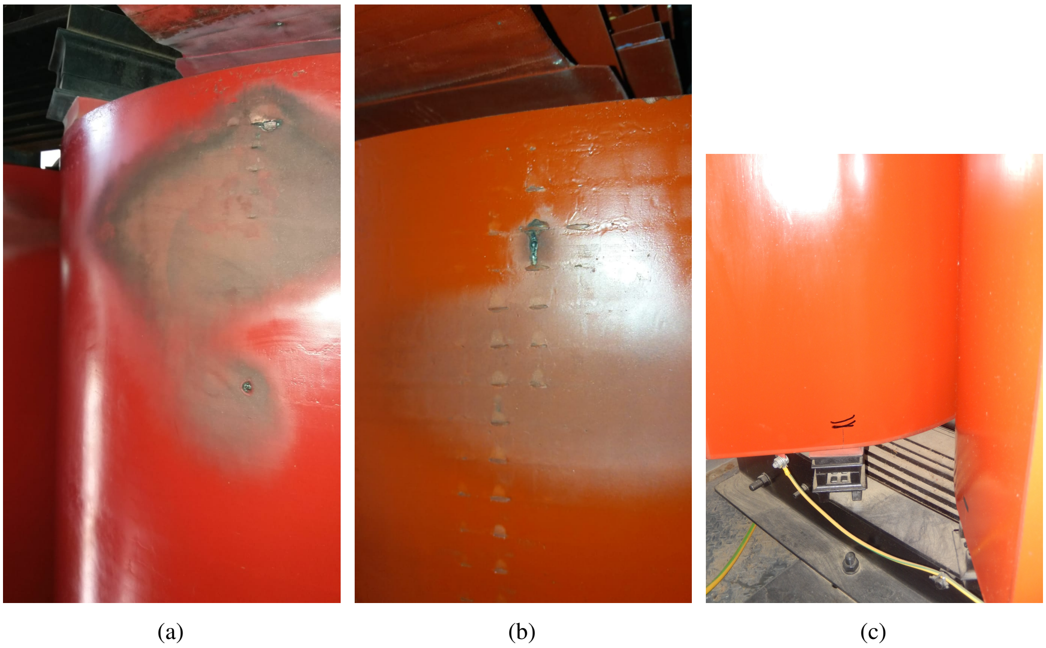

(a) (b) (c)

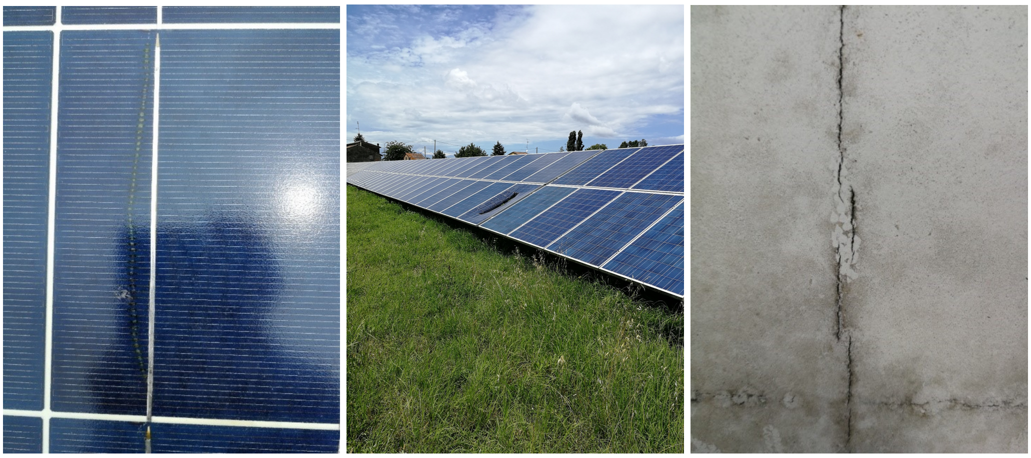
Figure 5.8. Deterioration of dry-transformers.

According to common industrial practice, in this work, we have not considered the light-induced power degradation (LID), which occurs in the very first hours of exposition to the sun, as well as common damages occurring during installation (e.g., glass cracking of frameless PV modules caused by the clamps or cells breakage due to vibrations and shocks). These damages may be difficult to detected: for instance, a cell cracking that is not visible through visual inspection [see Fig. 5.9(a)] can only be detected through electroluminescence image or infrared lock-in thermography.

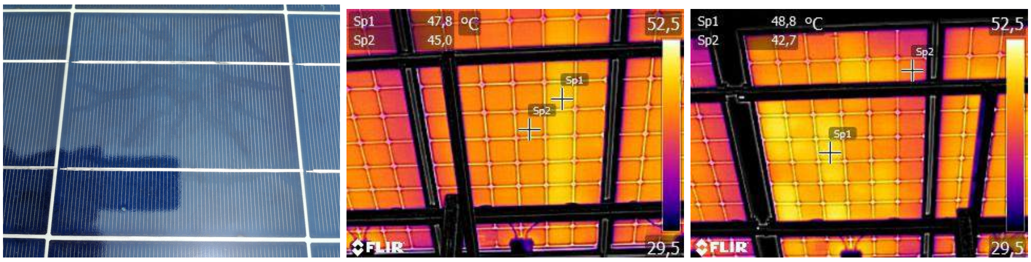
The most common PV module failures are herein briefly reported.

Environmental stresses and severe climate conditions, e.g., temperature, rain, humidity, condensation, etc., can lead to cracking, front side yellowing and bubbling of the tempered glass [Fig. 5.9(b)] and cracking and rapidly thickness reduction of the back sheet [Fig. [Fig. 5.9(c)], especially if PET-based. Therefore, modules with long-term proven materials must be used.

Snail Trail is a grey/black discoloration of the metallization silver paste used in the solar cell manufacturing process for the gridlines on the cells, which usually occurs after a couple of years of operation [Fig. 5.9(d)]. The discoloration occurs at the edge of the solar cell



(a) Cell cracking (b) Front tempered glass damage (c) Back-sheet damage



(d) Snail-trail (e) Bracken by-pass diode under thermography (f) Hot-spot under thermography

(g) Visible effects of hot-spots (h) TCO corrosion on a CdTe thin-film (i) Welding oxidation

Figure 5.9. PV modules failure.

and usually along not visible cell cracks. The discoloration speed depends on the season and the environmental conditions: during summer and in hot climates, snail trail seems to occur faster. Usually, snail trail leads to high leakage currents and it does not produce any measurable power loss of the PV module. However, snail trail may cause cracks in the solar cell, which are clearly visible and reduce the PV module efficiency. It has been observed that the right choice of the EVA and the back sheet material play an important role on the snail trail occurrence.

Hot spots are places on the module that are overloaded and therefore become warm. Ill-soldered connections, reverse-biased cells under partial shading, broken by-pass diode [Fig. 5.9(e)] and mismatch effects, may lead to a concentration of generated power in some parts of the module and cause hot spots [Fig. 5.9(f)]. This phenomenon shorten the lifetime of the system and cause energy-yield loss and, ultimately, can lead to short-circuits with visible effects [Fig. 5.9(g)]. Hot spots have been identified in a large number of solar parks. Affected PV modules must be replaced, adding significant OPEX to the business plan.

Potential Induced Degradation (PID) [81, 82] arises when a voltage difference occurs between the solar cells and the ground. In large-scale power plants, where strings are usually long and characterized by an open circuit voltage V_{OC} up to 1 kV, a high voltage difference V_{SM} between solar cells and the module frame, which is grounded for safety reasons, may be induced in modules at either end of a module string. The electric potential difference may cause leakage currents to flow from the frame to the solar cells (or vice versa) mainly along the surface of the front glass and through the bulk of front glass and the encapsulant. When the polarity of V_{SM} is negative, i.e., on modules located at the negative pole of the string, the leakage current drives alkaline metal ion (mostly Na^{+}) to drift into the solar cells and with the result to reduce the shunt resistance. This is the PID-shunting phenomenon, the most commonly observed type of PID, usually in conventional p-type silicon PV modules. It may result in significant shunting of the cells (both ohmic and non-linear), which degrades their efficiency, and may lead to a loss of performance up to 10%. The problem is enhanced under environmental stress and may become more severe in the near future. In fact, the PV industry is trending towards 1.5 kV rated voltage systems for overall cost reductions. To prevent PID phenomenon, solar cells should not be at negative potential with respect to their metal frames. Grounding the negative pole of the PV array resolves this problem, even though high common mode currents may be injected into the ground [83]. Alternatively, a PV Offset Box (e.g., APID) can be used for transformerless inverters that cannot be grounded.

When the leakage current phenomenon occurs on thin film modules (e.g., CdTe), usually at operating temperatures as high as 70 °C, the migration of sodium ions from the glass into the transparent conductive oxides (TCO) may destroy the TCO layer in a couple of years [Fig. 5.9(h)]. The damages due to this phenomenon, referred to as *TCO corrosion* [84, 85], cannot be repaired; the TCO corrosion can be suppressed by using frameless modules and using sodium-free glass. In the past, it was thought that by just grounding the negative pole of the array could completely avoid corrosion. Today, the state-of-the-art is to introduce galvanic insulation through a transformer, ground the negative pole and mount the modules with back rails. However, studies have shown that the corrosion can occur also for positive potentials [86].

Internal corrosion and *delamination* occur when moisture penetrates into panels. The components of modules (i.e., the glass layer, the solar cells and the back sheet) are laminated under vacuum to obtain air- and water-tight modules. However, if the lamination process is not performed properly, or was of a too short duration, the delamination during operation, i.e., the detachment of the laminated components, may occur. Delamination can cause moisture to ingress into the module and lead to corrosion, which manifest itself as darker spots on the panel. Penetration of humidity and moisture can lead to rusting on the metal conducting part of the module, e.g., oxidation of the connections [Fig. 5.9(e)]. For the above issue, there is no available solution, and PV modules must be replaced, which may add significant OPEX.

5.4 Failure Rates, Production Losses and Expenses

The solar PV systems that have been analyzed are 84 plants placed in the Central and Southern part of Italy, whose rate power ranges from 996 kWp to 3.6 MWp. The systems have been installed between 2007 and 2010 with different technologies:

- as to PV modules, 70 systems are made of polycrystalline solar panels (e.g., Solarfun, Trina Solar, Yingli Solar), 12 of thin film cadmium telluride (CdTe) First Solar photovoltaic panels, and 2 of Solfocus High-Concentration PV modules;
- as to supporting structures, 73 plants are fixed tilted type (azimuth $\alpha_\mathrm{t} = 0$, tilt $\gamma_\mathrm{t} = 20 \div 30°$), 7 have uniaxial tracking systems (mainly Convert Valmont type) and 4 have bi-axial tracking systems.

All the plants have been satisfactorily commissioned prior to being energized, and have had the scheduled maintenance and testing over their lifetime; this to ensure the highest levels of safety, quality and performance of the PV installations. The standard maintenance plan has included inspecting system and wiring components, structural attachments and weathersealing, cleaning and removing moisture and debris around arrays, grass-cutting, conducting electrical tests, replacing or repairing damaged or failed system components.

In table 5.1 we summarize the major data regarding system problems and failures occurred and cost of repairs. As to the economic impact, information about the reduced revenue due to downtime of the PV systems is not available, as the authors have worked as an external engineering firm for the O&M operators, and not directly with the stakeholders.

5.5 Main Techniques in PV Monitoring

Monitoring is a key aspect for the operation of PV plants: an average of 44% of the OPEX is dedicated to O&M, mainly due to personnel, external services, materials and other costs (Figure 5.10).

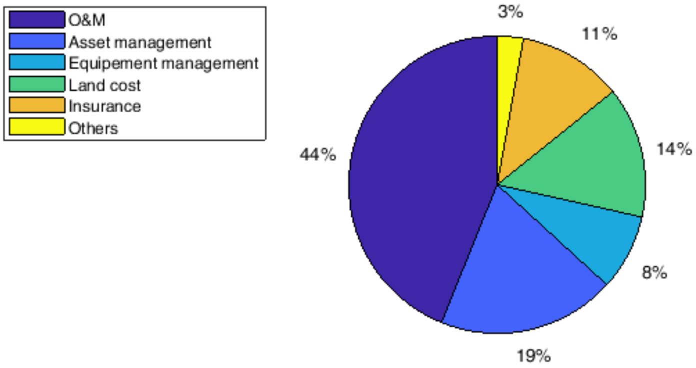


Figure 5.10. OPEX break down for PV plant management.

The most common techniques for reducing O&M costs are based on digitalization of the information processing and access, and on the robotization of the inspection and maintenance operations/activities.

From a general point of view, failures or PV systems are mainly concentrated in the inverters and PV modules. An analysis conducted on a large set of PV plants has indicated that the 52% of the production lost was due to inverters failures and the 31% due to PV modules failures and defects (see Figure 5.11).

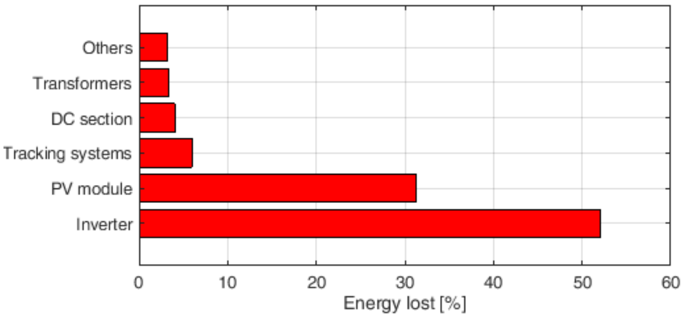


Figure 5.11. Lost of production associated to failures of each component.

Monitoring the inverters is a very common activity and may be easily automatized and performed in real time thanks to their communication technologies [87]. On the other hand, PV modules are generally not connected to communication systems, whose implementation by retrofitting existing PV power plants would be cost-prohibitive [88].

Monitoring of PV modules is a very critical aspect, especially in large-scale or rooftop PV plants. Several studies [89, 90]have indicated that most of the damages of PV modules can be detected and analyzed by mean of a combination of thermographic (infrared, IR) and visual images. This type of inspection does not affect the production of the plant because it does not require the disconnection of the modules. The most traditional inspection of PV plants is performed by an operator equipped with a thermal imager, who inspect parts of the PV plant. Some defective modules may be further analyzed in laboratories or in the field with more accurate tests [91].

The problem with this type of inspection is the significant time that is required. In fact, for ground plants the manual inspection may take up to 8h/MW, depending on the percentage of sampled modules. This time can be more than doubled for rooftop systems, according to the specific installation [92]. The required time is a critical aspect because for obtaining reliable results from the thermographic images a high level of solar irradiation is required.

Problems of the manual inspection may be resolved with Unmanned Aerial Vehicles (UAVs) [93]. In this case, the inspection process is performed by drones equipped with cameras. This can reduce the inspection time to 1h/MW: this time is highly affected by the required resolution of the images and by the battery-changing time for the UAV and downloading the images [92].

Thanks to a shorter required time, UAV-based inspections may allow to sample all the modules of the plant and it is easily applied also to rooftop PV systems. UAV-based inspections also allow automated periodic inspection of very large-scale plants in countries were local laws permit the unmanned flight of drones. However, the authors believe that to properly exploit the information acquired by UAVs, a digital infrastructure is required for mapping, processing and easily accessing the information.

5.6 Plant Digitalization with Defect Layer

Plant digitalization is a new important trend especially for large energy companies and utilities whose portfolio consists of several industry-scale plants. The digitalization allows data management, easy information access, data modelling and forecasting. This process involves several stakeholders, being the owner and the O&M company the most important, but also insurance companies may have an interest in obtaining an overview of the plant status.

The plant digitalization can be done using a multi-layer approach, with an indexed database and a smart visualization tool capable to gather information at different level and from different sources [67], as shown in Figure 5.12.

Data can be acquired from different sources: from SCADA systems it is possible to monitor the inverter production in real time. From the data it is possible to diagnose faults and identify some significant KPIs for the power plants. This type of information is aggregated, and it is not possible to detect the specific position of the defects. UAV inspection, on the other hand, can be performed one or twice a year: it provides data from which the modules status can be analyzed. Once the defective modules are identified, it is possible to inspect them manually, if required, or replace them for recovering the production level of the PV plant.

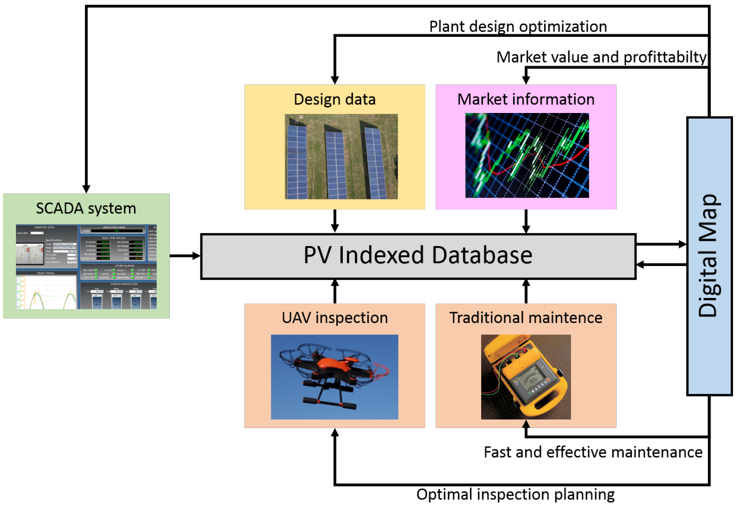


Figure 5.12. Overview of digitalization in PV inspection.

From the images gathered from the UAV, it is possible to obtain the IR and visible images associated to each PV module (Figure 5.13).The analysis of these images can be used to identify the three main type of defects: hot spots (orange frame of the modules in the Figure), broken bypass diode (red in the Figure 5.13) and disconnected modules.

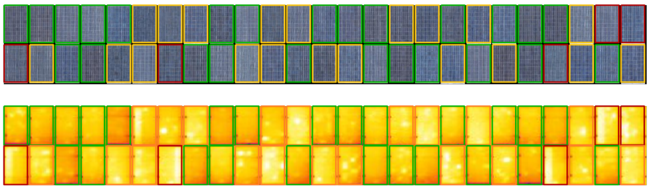


Figure 5.13. Example of row of PV modules: visible and IR images with coloured frames according to the defectiveness status.

Table 5.1. Summary of failure rates

	Expectation	Standard deviation
Geological instability issues		
Number of affected plants:	7	
Type of plants:	fixed modules	
Plant nominal power:	1032.1 kWp	49.3 kWp
PR reduction:	13,5%	8,3%
Downtime/failure:	5 months	2 months
Repair costs:	152.8 k€	74.0 k€
String fuses		
Number of affected plants:	16	
Type of plants:	fixed modules - uniaxial tracking	
Plant nominal power:	1515.4 kWp	336.9 kWp
PR reduction:	2,1%	1,4%
Downtime/failure:	2 months	1 months
Repair costs:	93.2 k€	65.4 k€
Overvoltages		
Number of affected plants:	4	
Type of plants:	fixed modules	
Plant nominal power:	1032.1 kWp	159.7 kWp
PR reduction:	20,1%	5,6%
Downtime/failure:	3 months	1.5 months
Repair costs:	234.2 k€	82.0 k€
Substation over temperature and inverter failures		
Number of affected plants:	5	
Type of plants:	fixed modules - tracking	
Plant nominal power:	1570.2 kWp	1230.00 kWp
PR reduction:	40.0%	9.3%
Downtime/failure:	8 months	3 months
Repair costs:	225.5 k€	75.0 k€
Low DC insulation		
Number of affected plants:	3	
Type of plants:	fixed modules - tracking	
Plant nominal power:	1584.0 kWp	487.1 kWp
PR reduction:	6,5%	3,3%
Downtime/failure:	10 months	2 months
Repair costs:	250.4 k€	25.00 k€
MV/LV transformer failures		
Number of affected plants:	2	
Type of plants:	fixed modules	
Plant nominal power:	3288.0 kWp	441.2 kWp
PR reduction:	-	-
Downtime/failure:	2 days	-
Repair costs:	25.0 k€	-
Modules failures		
Number of affected plants:	11	
Type of plants:	fixed modules - uniaxial tracking	
Plant nominal power:	1337.0 kWp	575.3 kWp
PR reduction:	14,5%	8,5%
Downtime/failure:	10 months	5 months
Repair costs:	374.8 k€	290.5 k€

Chapter 6

Floating PV: an Alternative Pathway for Rural Energy Communities

6.1 Introduction

Energy communities can be realised not only in cities, but also in peripheral areas near waterways or reservoirs. In such areas, the installation of photovoltaic systems is problematic due to natural constraints or because the land is often used for agricultural purposes. A good alternative to overcome these problems is represented by floating photovoltaic systems. Floating photovoltaic systems (FPV) are intended for any PV system installed on water, usually artificial bodies, such as irrigation ponds, lakes, water treatments ponds, hydroelectric dams, reservoirs, and coastal lagoons [94]. These systems have been induced due to the high cost or limited availability of land in some countries, such as Japan, Singapore, and the Republic of Korea. Nowadays, the use of bodies for the construction of photovoltaic systems is spreading more and more. This technology introduces some additional advantages, such as allowing the installation of large photovoltaic systems near the load centers, thus reducing the cost of transmission infrastructures [95].

The technological applications of FPV are pretty recent, so it is not yet able to compete in terms of costs with the traditional terrestrial photovoltaic; however, there are several advantages of FPV that contribute to the potential increase in its market share. In particular, its main advantage is that FPV is considered land-neutral since the land requirement is zero or significantly reduced compared to ground-based PV. This is a significant aspect to be considered, as the suitable land area for ground-based PV plants is either unavailable or expensive [96].

From a technical point of view, the main advantage would be an increase in the energy production of a floating system with respect to traditional PV, reaching in some cases the 10-12% [97]. There are three main reasons for this:

- The reduction in operating temperature due to the cooling effect of the water that tends to lower the module's operating temperature, thus increasing the power output [98]. In addition, it has been shown that the air temperature above the water is generally lower by about 1°C to 3°C; combining these effects results in 5°C to 15°C lower operating module temperatures [99];
- Less shading due to more open area and flat environment characterizing water basins. Moreover, to keep low the wind load, modules are usually mounted with a low tilt angle, thus reducing the inter-row shading [100];
- Less soiling due to dust; water bodies usually are less dusty. This is even more important considering that PV power plants are often built in desert locations to reduce their impact on land usage [101].

Other advantages of FPV include reduced evaporation from water reservoirs, improved water quality through fewer algae growth, and easy and modular installation with low anchoring and mooring requirements. Figure 6.1 represents the key components of a typical large-scale FPV system.

The general layout of a floating PV system does not differ too much from the standard land-based ones, except that PV modules, and often inverters, are mounted on a floating platform, as seen in the figure above. The DC generated by the modules is collected in a combiner box and converted into AC by the inverter. The significant differences with respect to a ground-mounted PV are the floaters, the mooring lines, and the anchoring systems. FPV systems can be installed in both natural and artificial reservoirs. Specifically, the latter

Table 6.1. Floating PV projects around the world.

	Year	**Size [MWp]**	**Investment [M€]**	**Location**	**Source**
1	2011	0.5	2.1	Italia, Bubano	[103]
2	2014	0.01	0.05	India, Rajarhat	[104]
3	2014	0.2	0.37	UK, Berkshire	[105]
4	2015	8	42.4	China, Hebei	[106]
5	2015	1	2.28	Japan, Osaka	[107]
6	2015	2	5.68	Japan, Shiroishi Saga	[102]
7	2016	2	4.92	South Korea, Boryeong Dam	[108]
8	2016	4.4	6.55	USA, Sayreville, NJ	[109]
9	2016	20	26.9	China, Huainan City	[102]
10	2016	6.3	7.8	UK, Queen Elizabeth II Reservoir	[110]
11	2016	2.99	4.2	UK, Manchester	[111]
12	2016	0.2	0.42	Portugal	[102]
13	2017	20	22.76	China, Hangzhou	[112]
14	2017	150	137.44	China, Huainan City	[113]
15	2017	40	46.6	China, Suixi, Anhui	[114]
16	2017	0.5	1.1	India, Kerala	[115]
17	2017	2.4	6.8	Japan, Sanuki, Kagawa	[116]
18	2017	1.5	3.7	Japan, Sanuki, Kagawa	[117]
19	2018	130	130.8	China, Fuyang	[118]
20	2018	100	121.5	China, Weishan	[119]
21	2018	40	45.7	China, Huabei	[120]
22	2018	0.1	0.2	Colombia, Medellin	[121]
23	2018	2	1.71	India, Greater Visakhapatnam	[122]
24	2018	1.24	1.29	Japan, Hyogo	[123]
25	2018	3.5	4.8	South Korea, Dangjin	[124]
26	2018	13.7	12.1	Japan, Yamakura Dam	[102]
27	2019	3	6.64	Japan, Kansai	[125]
28	2019	47.5	62	Vietnam, Binh Thuan	[126]
29	2021	58.5	99.5	Thailand	[127]

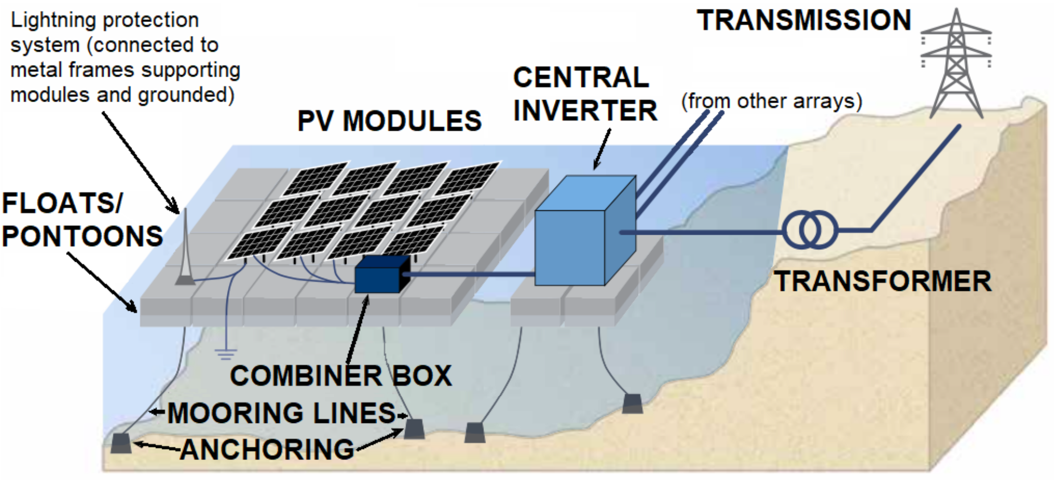


Figure 6.1. Typical layout of a floating PV system [102].

are subject to water level fluctuations up to ten meters due to global warming and climate change in general. Precisely for this reason, to ensure that the floating system can withstand these variations in the free water surface, it is necessary to design a robust but, at the same time, flexible anchorage. The floating system is fixed to the seabed through steel ropes with spring-loaded shock absorbers, sized on the shortest length to always work under tension. The weight the cables have to withstand is minimal as the water, and the floats fully absorb it. Still, the contribution of the horizontal forces must be considered since it is strictly dependent on the action of the wind that can create wave motion and also a specific lift on the panels. The FPV plants are usually characterized by low tilt angles, not only due to constraints but also to minimize the wind load on the floating structure. Low tilt values are optimal in areas close to the equator, but at higher or lower latitudes can generate more reflections and angular losses, reducing the system's performance. Lower operating temperatures can, at least partially, compensate for losses due to low module tilt.

The installed capacity of FPV globally reached 3 GWp in 2021, showing that this can be a practical alternative to utility-scale photovoltaic systems, reducing the total land usage. A deep analysis of the floating PV projects around the world, shown in Table 6.1, highlights that the first countries adopting this technology are the ones with low land availability or where the land cost is a relevant share of the investment for photovoltaic energy projects.

Many aspects of floating PV have been critically analyzed in literature [128, 129] and compared to other innovative floating techniques also in hostile environment[130] and semi-submerged configuration [131].

In this work, primarily we analyzed the technical, economic, and environmental aspects of floating photovoltaic systems. Then the attention is focused on a key point rarely investigated in the literature: the inspection and maintenance of these plants. Then, a market and economic analysis of FPV is performed. The latter was tested in a specific test case of an FPV made in Italy. Thanks to this, it was also possible to understand the significant criticalities that may emerge during the realization of FPV systems.

In Section 6.2, the most relevant techno-economic and environmental aspects of FPV are analyzed. In Section 6.3, the operation and maintenance of FPV are investigated. In Section 6.4 the potential market of FPV is shown and in Section 6.5 a detailed analysis on its cost is provided.

6.2 Techno-Economical and Environmental Overview

An increasing interest in FPV plants is now arising, thanks to their essential advantages compared to traditional installations on the ground or rooftop. The most important benefits are reduced land usage, improved performance, reduced investment cost, reduced water evaporation, and the possibility to combine them in innovative and hybrid applications.

6.2.1 Land Usage

The projected increase in world energy demand is estimated to be 50% by the year 2040 [132]. Due to the growing environmental concerns, most of this energy demand is expected to be covered by renewable energy sources, mainly photovoltaic. The projection shows that the total installed PV power will increase to 19 TWp before 2050 [133].

The main question is whether this growth can be sustained in the next few years, considering that a low energy density characterizes PV and that the land is becoming a critically limited resource in many counties [134].

Floating Photovoltaic seems to be a viable option to participate in this growth. Indeed, FPV technology overcomes the limits of land availability [128], allowing photovoltaic installations on canals, lakes, reservoirs, and oceans, thus limiting the land usage for power production [135]. Furthermore, this installation will reduce the placement of PV plants on cultivable land, reducing the so-called "food vs. fuel" controversy [136].

To evaluate the possibility of covering the energy demand with FPV, the photovoltaic geographic potential (PVGP) can be analyzed. This indicator is defined as the fraction of the solar irradiation received on the land that is available for a photovoltaic facility [137]. By calculating this value, it is estimated that 1% of natural basin areas can supply 20% of the world electricity demand with FPV plants [137].

There may be synergies between using water for food and installing floating PV plants, which can be a crucial solution to reduce the overall environmental impact [138]. Two solutions are now under investigation from different points of view: the "agrivoltaics" and the "aquavoltaics" [139]. These are the combination of FPV, respectively, with agriculture and aquaculture. In particular, aquavoltaics have been shown to produce the advantage of efficient water usage for food and power production generation[135].

6.2.2 Cooling System

A general problem of traditional photovoltaic installations is linked to the decrease in module performance by increasing the temperature: the PV cell efficiency decreases by about 0.5% for every 1°C [140]. In addition, excess heat is absorbed by the insulations [141], reducing the PV module's lifespan [142]. Considering all these elements, the PV module cooling has a crucial impact on increasing their performance [143].

The FPV has the advantage that the modules are installed in the water, benefiting from the microclimate that produces natural cooling and, thus, reduces thermal losses and degradation. In particular, due to the exposition of the PV modules to the water surface, the thermal dissipation coefficient increases up to 22 W/m^2K compared to traditional PV systems. Recent experimental studies show that the gain in energy production due to the lower operating temperature of FPV is up to 3% in the Netherlands and up to 6% in Singapore [133].

In addition, FPV can easily be equipped with a simple and effective active cooling that can further increase the overall system performance. Active cooling can be achieved by pushing fresh water in a meandering path in contact with the module backsheet. While passive cooling can increase energy production by 3-6%, active cooling can achieve a performance improvement between 9.5-9.7% [139].

Studies about the performance of modules immersed in water can be found in the literature. In this configuration, both module surfaces are in contact with water improving heat exchange, but, at the same time, we have a reduction in the amount of light reaching the photovoltaic module since water is an absorber of light, especially in the red-infrared wavelengths. In [144], the authors estimated that panels could achieve higher efficiency than ground-based modules when submerged at depths less than 10 cm. The results of the model developed in [144] were validated through a study in which modules were submerged at depths of 4 cm and 40 cm. The results showed that the module immersed at a depth of 4 cm improved its efficiency by 11%. By increasing the depth to 40 cm, the efficiency dropped by 23%.

6.2.3 Investment Costs

Geographical characteristics and the installed capacity of the FPV plant are factors that most influence the investment's costs. In general, PFV systems are more compact, which results in straightforward construction and decommissioning phases. The central aspect is the reduced number of fixed structures; in addition, the mooring of floating systems can be carried out in a reversible way, which is not possible for the foundations of onshore plants [128].

Due to the reduced total capacity of FPV installed and the small size of the single plants, capital expenditure is not about 25% higher than traditional plants. However, the increase in installed capacity and plant size will effectively reduce investment costs: many studies show that the Levelized Cost of Energy (LCOE) will decrease in the following years, making these systems more affordable in the future[135]. All these costs depend strongly on technology and the locations, so it is appropriate to perform an in-depth case study [129].

6.2.4 Water Evaporation

A significant additional advantage of FPV is the reduced water evaporations: a comparative study conducted on the same basin with and without FPV showed a 30% reduction in *blue gold* evaporation [145].

The amount of evaporated water depends not only on the percentage of the surface covered but also on the characteristics of the floating systems. By covering only 30% of the surface of a basin, it is possible to obtain up to 49% reduction in evaporation [146].

Floating PV can be a viable alternative to evaporation engines exploiting water basins for energy production. In fact, it has been demonstrated that the power that evaporation engines can produce can be obtained with FPV using only a fraction of the lakes, gaining both energy production and water saving [147, 148].

6.2.5 Different Photovoltaic Technologies

Several photovoltaic technologies already established for ground plants can also be adopted in FPV to increase energy production.

Firstly, bifacial photovoltaic modules can obtain an energy gain of 5.24% due to the solar irradiation reflected by the water surface. Since the analysis of PV systems is highly site-dependent, normalized annual energy yield has been chosen in recent studies as a meaningful parameter to compare different solutions. It shows that bifacial FPV systems may increase power production up to 13.5%, compared to monofacial configurations, especially in presence of diffuse radiation [149].

Tracking technology can also be integrated into FPV. As for traditional photovoltaic, different tracking systems can be designed: single horizontal axis, single vertical axis, and two-axis tracking systems. The single axis vertical is interesting because it allows a rigid rotation of large parts of the FPV plant.

Even though tracking increases the overall system complexity, it is easier for FPV than for ground-based plants due to the lower energy required to move the structure in the water and the lower stress induced by module weights. On the other hand, GPS control is often added to compensate for the errors introduced by external environmental factors.

The increase in cost related to the installation and maintenance of tracking systems is compensated by a significant increase in production. It has been calculated that a single axis system can increase the generation efficiency of 18-21%, while a due axis can achieve 25-30% [150]. These values have been validated with in-field experiments: a horizontal east-west system can increase the generation efficiency up to 15-18%; the horizontal north-south system can increase it up to 23-27%; the vertical tracking can increase it up to 28-31%; and finally, a dual axis system can achieve an increment of 42/27% [151].

6.2.6 Hybrid Systems

A "hybrid energy system" is intended a production from different sources at the same time and place. These sources can include both renewable energies and conventional power plants. Although their complexity may lead to optimization problems, they have several advantages in terms of energy supply balance, better system reliability, and higher energy density that can compete, in some cases, with conventional power plants[152].

This system can be based on integrating different technological photovoltaic installations, such as FPV with and without tracking systems, FPV with ground-mounted PV plants, and off-grid FPV with on-grid FPV [138].

Alternatively, hybrid systems can be obtained through an effective combination with other technologies, such as hydroelectric power plants, pumped hydro, offshore wind, wave energy converter, and compressed air energy storage [138].

Recent studies on the integrations of FPV with hydroelectric power plants show that installing FPV on the hydroelectric power plant basin surfaces can increase the total energy production to 65% while covering only 10% of the available water surface[153]. Additional studies showed that a 35.9% increase in the hydroelectric power plant energy production could be achieved by covering 2.4% of the existing basins [137].

The recent development trends of new PV technologies, such as perovskite solar cells, can allow the integration of FPV with underwater hydroponics (growing plants without soil using water-based mineral nutrient solutions)[154]. Possible agrovoltaic applications may be imagined with underwater hydroponic domes with transparent perovskite PV modules or marine use on vessels [155] Integration between these applications may be futurible, with a transparent concentrator on the deck of the ships and a PV system protected from the marine environment in the vessels' hold.

6.3 Operation and Maintenance Challenges

Even if the UAV monitoring of PV plants is a well-established technique, FPV UAV monitoring may present previously unconsidered issues.

6.3.1 UAV-Based Monitoring

Since 2014, laboratory and in-field tests have shown that Unmanned Aerial Vehicles (UAV) are effective in PV systems monitoring for detecting degradation and defects in the modules. In addition, UAV-based inspections are more reliable, fast, and cost-effective in comparison with traditional methods [92, 156].

A combination of thermal imaging and visual cameras is used to collect all the information needed for effective detection of PV module's different failures. All these images can be processed using an automated tool capable of detecting, identifying, and classifying all the defects in the images [157].

The inspection accuracy can be improved by exploiting the acquired images for a vision-based guidance method. This is aimed at correcting localization errors introduced by GPS systems. This method's main advantage is the possibility of reducing the flight height, achieving an accurate and high-resolution inspection [158].

UAV monitoring systems for PV plants may be considered a fully mature technique. However, further improvements may be obtained, and new challenges may be faced, especially for the novel operative environment, such as floating photovoltaic (FPV).

UAV monitoring of an FPV plant is affected by problems arising both from the water environment and from the unstable anchoring of the infrastructure. With FPV, previously unfaced problems may arise, for instance, optical disturbance on sensors due to sunlight reflection and waves glittering, difficulties in attitude control and stability due to heavier wind gusts, more difficult take of, landing, and navigation due to the random relative motion of the pontoon. Unnecessary maneuvers also lower UAV autonomy.

Different challenges should be faced when using UAVs in FPV applications. While multi-copters have already been adopted to aquatic operations [159, 160], their range remains short, leading to critical continuous takeoff and landing that can increase inspection times. Some new designs may mitigate this issue: existing UAV prototypes for the aquatic environment are equipped with autonomous PV recharge and active VTOL [161, 162].

Flight attitude control can be critical because small aircraft are notoriously more affected by wind gusts, thus resulting in attitude control problems and deviation from the original flight path. It is possible to use gyrocopter solutions to combine fixed wing and rotate wing UAV features to apply rapid course correction(due to lower stall speed), short covering flight, more stable cruise flight, short or vertical takeoff and landing (SVTOL/VTOL)[163]. An aquatic version of this solution may be futurible.

Finally, the navigation is more complex since, in FPV, the pontoon is moving; even if a perfect GPS positioning of the UAV is achieved, none can be said about his relative position in respect of the pontoon, eventually forcing a double check on pontoon GPS position and orientation (considering continuous random rotation along all axes), resulting in heavy computational effort in real-time. However, non-GPS navigation systems are available.

The first one is the optical navigation [164] that usually adopts a laser guidance system to avoid GPS failure or signal degradation problems [165]; optical navigation systems have already experimented in marine UAV [166]. Such navigation systems can be adapted to navigate in a relative coordinate system linked to the pontoon, whose precise position is uninfluent. The optical system can be adjusted following a visual path on the pontoon with artificial guide stars, as already experimented in similar situations [167].

The second one is based on microwave radar sensors that have already been used for altitude control, showing a better accuracy than laser [168]. Thirdly, inertial navigation systems seem to adapt more in GPS-denied or GPS-malfunctioning situations even if, having two moving objects in FPV, the relative optical navigation with artificial guide stars can be more valuable and easy to implement.

In addition to the above-mentioned issues, additional problems arise in the quality of the acquired images when UAVs are adopted for monitoring FPV. Sunlight reflection and glittering can significantly impact vision-based object detection over a marine environment. The area affected by reflections can be limited using rapid course corrections [169].

6.4 Potential Market

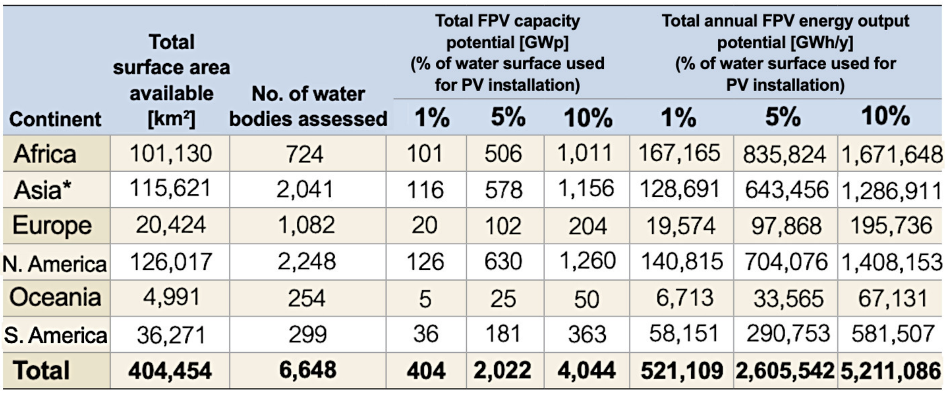
The floating PV potential is strictly correlated to the availability of distributed water bodies worldwide and policy constraints, costs, and environmental impact. The Solar Energy Research Institute of Singapore (SERIS) conducted an interesting study on the FPV potential covering 1%, 5%, and 10% of the surface of available artificial water bodies all over the globe, which can be seen in Figure 6.2 [102].

This study was conducted in 2018 and, among many considerations, assumed an average area factor of 100 W/m^2; it is essential to highlight that this value increases year by year with technology innovation - today is around 180 W/m^2 -, hence the results of the study are underestimated.

Even if 1% of the total surface area available were used, FPV capacity installation would quickly increase to over 400 GWp, which was the full cumulative capacity of standard PV systems installed up to 2017 (Fig.6.2) [170].

Moreover, if only 10% of the total surface area available were used, FPV technology would become a TW scale market. And this is even without considering natural water bodies and off-shore installation, where solar radiation is much higher.

Any country has already seen the significant impact that this technology could have on our path to a net-zero emissions economy. Asia has great potential, with the most floating PV capacity installed. China holds the pole position in the floating PV market, such as in standard solar installed capacity per year, and it has the highest production of solar panels. Moreover, in 2018, the largest floating PV power plant (150 MWp in Huainan City) was connected to the grid. Also, countries like Taiwan, Japan, Vietnam, South Korea, and the Netherlands invest a lot of research and resources in this market. From 2007 to 2021, as



Continent	Total surface area available [km²]	No. of water bodies assessed	Total FPV capacity potential [GWp] (% of water surface used for PV installation)			Total annual FPV energy output potential [GWh/y] (% of water surface used for PV installation)		
			1%	5%	10%	1%	5%	10%
Africa	101,130	724	101	506	1,011	167,165	835,824	1,671,648
Asia*	115,621	2,041	116	578	1,156	128,691	643,456	1,286,911
Europe	20,424	1,082	20	102	204	19,574	97,868	195,736
N. America	126,017	2,248	126	630	1,260	140,815	704,076	1,408,153
Oceania	4,991	254	5	25	50	6,713	33,565	67,131
S. America	36,271	299	36	181	363	58,151	290,753	581,507
Total	**404,454**	**6,648**	**404**	**2,022**	**4,044**	**521,109**	**2,605,542**	**5,211,086**

Figure 6.2. FPV potential assessed by available man-made reservoirs [102].

shown in Figure 6.3, the total installed capacity had exponential growth, reaching 3,1 GWp total installed capacity in 2021, with just slightly less momentum in the last three years. Then, in Figure 6.4, is depicted the share of FPV installed capacity per country.

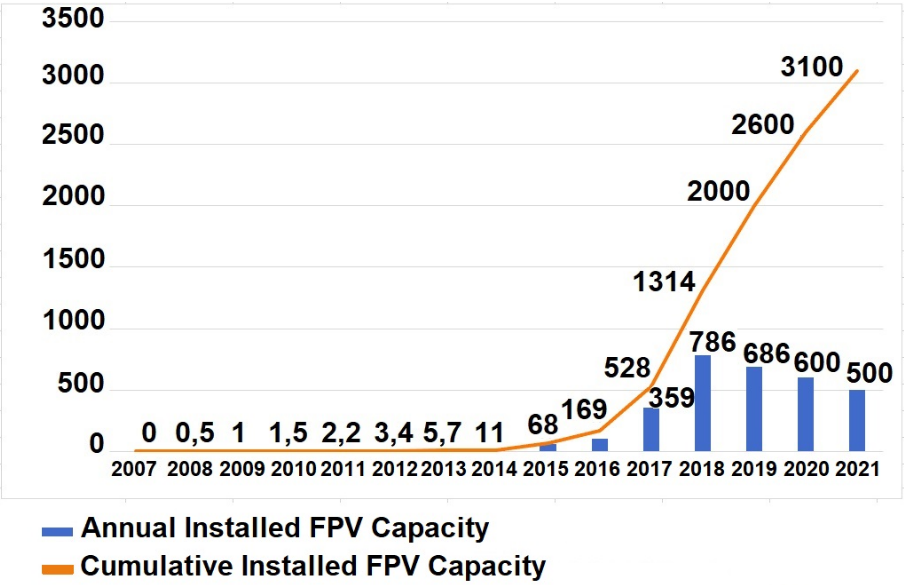


Figure 6.3. Global installed floating PV capacity and annual additions [GWp] [102, 170].

6.5 Floating PV and Ground-Base PV: Costs Breakdown

Any newly developed technology can be implemented only if it has a low negative impact on the environment and if it is economical for large-scale deployments. In this section, a techno-economic comparison is presented and discussed.

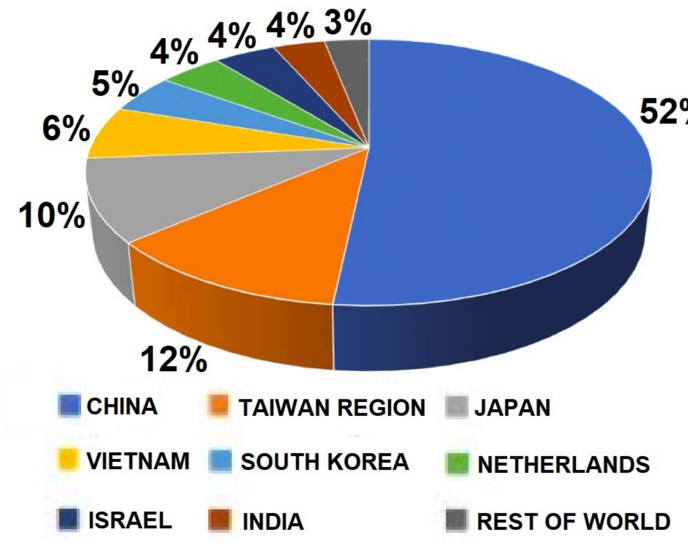


Figure 6.4. Global installed floating PV capacity share per country [171].

Unlike ground-based PV, floating PV is still in the first part of the learning curve. There are not enough projects deployed to accurately evaluate installation, maintenance, and operation costs. Support, anchoring, and mooring lines constitute a high cost for FPV, and they are continuously changing, optimizing, and improving. Therefore, the assessments will face drastic changes soon when the technological components of the entire system are established as well as the one of the GPV. Nevertheless, thanks to information and data collected from the available literature, a techno-economic comparison between floating PV and ground-based PV is presented here, analyzing the Capital Expenditure (CAPEX), the Operating Expense (OPEX), and the Levelized Cost Of Electricity (LCOE).

6.5.1 Capital Expenditure

The Capital Expenditure of a PV system is composed of the cost of modules, inverters, structure, the balance of system (BOS), engineering, procurement, and construction.

In 2020, ground-based PV utility-scale systems had a total average weighted installation cost of 0,8 €/Wp, an impressive 13% decrease with respect to the previous year, while, considering the last five years, the same value was around 1,21 €/Wp. The key drivers of lower module costs are the optimization of manufacturing processes, reduced labor costs, and enhanced module efficiency. Furthermore, as project developers gain more experience and supply chain structures continue to develop in more and more markets, declining BOS costs have followed [172]. Such precise evaluations are not available for floating systems since their early entry into the market. Various reports found in the literature, which evaluated distinct scenarios and made different assumptions believe that CAPEX costs for floating PV are 25-30% higher than standard PV, mainly due to floats, anchoring, and mooring lines [173, 135, 129] Calculating a 30% increase from the standard PV CAPEX found in the IRENA report, floating PV capital expense is expected to be in the range of 1,04 €/Wp and 1,57 €/Wp.

Through extensive, but not exhaustive, research from media releases and industry information, it was possible to summarise in Figure 6.5 29 different FPV projects CAPEX costs by capacity installed - the complete list is shown in Table 6.1. The average weighted CAPEX of these FPV systems, from 2016 to 2021, was 1,5 €/Wp (orange line), perfectly in line with the expected range of values just proposed.

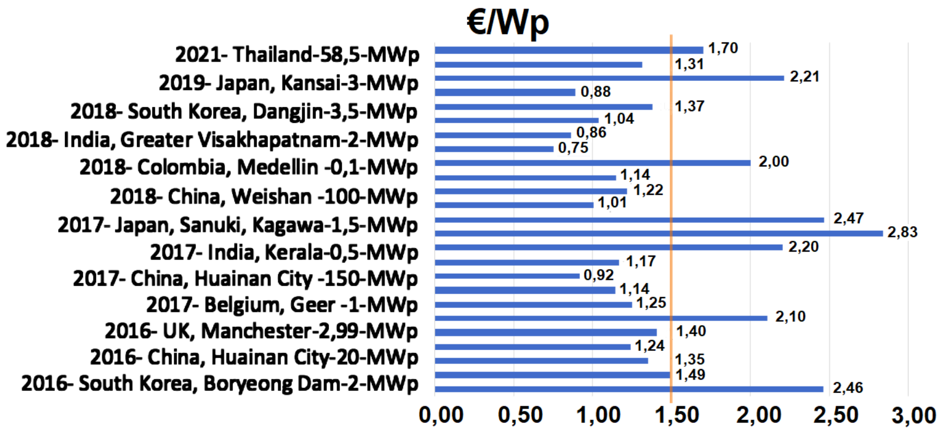


Figure 6.5. FPV CAPEX costs collected from media releases and industry information.

Comparing the total capital expenditure cost breakdown for the two technologies is now interesting. Verbruggen et al. [174] compared the initial investments of 50 MWp floating and ground-mounted PV systems and calculated the percentage shares of the various components (Fig. 6.6). Even though the total number of PV modules and inverters were the same for both projects, it can be seen that they have a lower percentage share in the floating system due to the higher initial investment. Moreover, the higher percentage share occupied by the mounting structure is clear, which is around 21% for the floating system against a much lower 16% for the ground-based one.

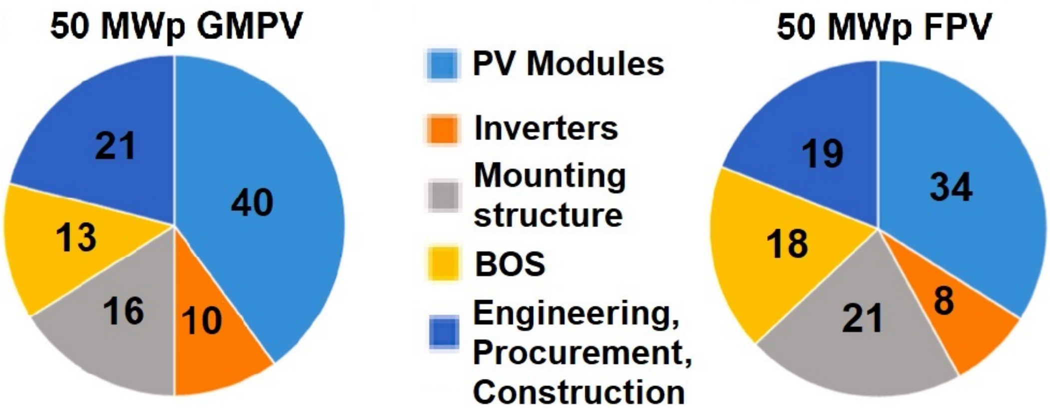


Figure 6.6. 50 MWp plants cost breakdown [175].

A similar analysis, comparing two installations of 1 MWp capacity, obtained compliant results [176]. The initial investment evaluation for the GPV was 630.700 $, while for the FPV, equipped with a cooling system, it was 803.692 $ (27,4% more). The mounting structure percentage share was 29% against an impressive 43%, respectively.

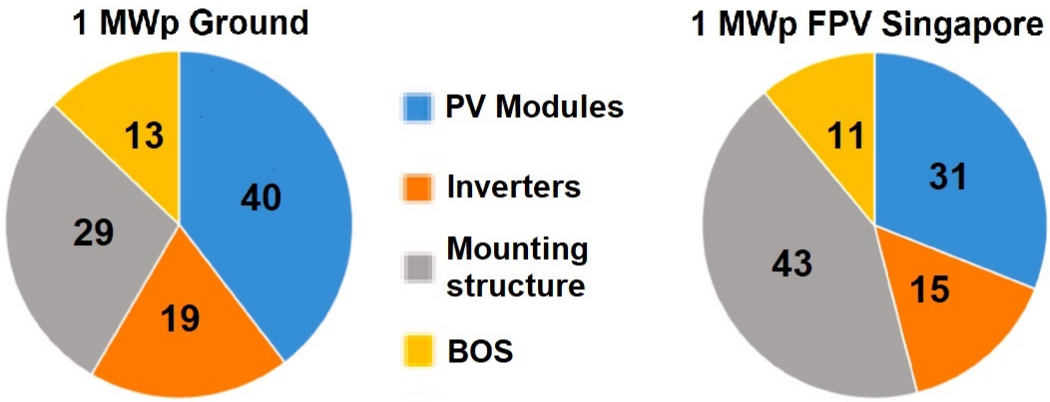


Figure 6.7. 1 MWp plants cost breakdown [176].

In the same study, Rosa-Clot also compared two new innovative solutions under investigation in the R&D field, the so-called Gamble Slender, and Gamble-2. The initial investment has been reduced due to a more straightforward mounting structure and an essential reduction of the required HDPE floats. These results, shown in Figure 6.8, highlight how FPV has the potential to be comparable and even cheaper to ground-mounted systems after a significant deployment in the market.

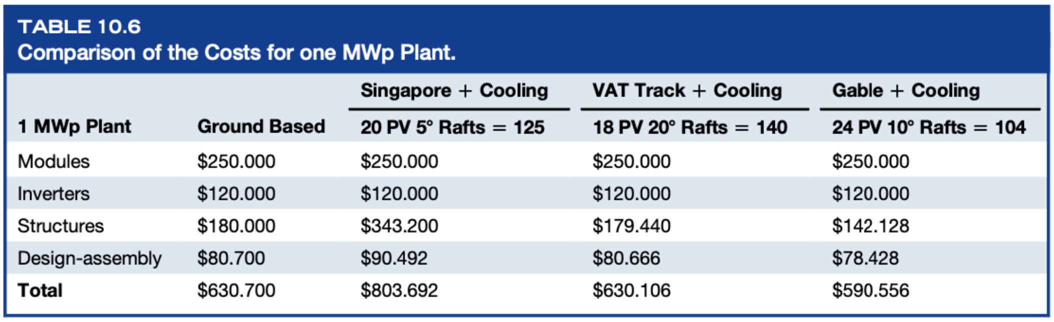


TABLE 10.6
Comparison of the Costs for one MWp Plant.

		Singapore + Cooling	VAT Track + Cooling	Gable + Cooling
1 MWp Plant	**Ground Based**	**20 PV 5° Rafts = 125**	**18 PV 20° Rafts = 140**	**24 PV 10° Rafts = 104**
Modules	$250.000	$250.000	$250.000	$250.000
Inverters	$120.000	$120.000	$120.000	$120.000
Structures	$180.000	$343.200	$179.440	$142.128
Design-assembly	$80.700	$90.492	$80.666	$78.428
Total	$630.700	$803.692	$630.106	$590.556

Figure 6.8. Costs breakdown [176].

Although FPV technology is costly in the present times, it has been observed that the development of PV module technology leads to a rapid reduction in costs. This phenomenon is also known as technology diffusion.

6.5.2 Operational Costs

Costs related to operational expenses are leasing or renting the space in which the system will be installed, operation and maintenance (O&M) [177], and insurance.

In the case of FPV systems, rent expense could be less expensive as the water surface cannot be used for other purposes (i.e., agriculture or construction). Still, evaluating land or water rental cost is challenging because it varies widely for different geographical areas.

As for rental, insurance cost depends on on-site location and weather conditions. According to the SERIS report, the insurance expense is about the same for GPV and varies between 0,25% and 0,5% of CAPEX [102, 178].

For ground-based PV, O&M cost varies from 9,1 to 16,4 €/kW in the United States and is around 9,1€ €/kW in Europe [172]; for floating PV, we do not have enough data for an accurate analysis.

The authors of the SERIS report believe that, even though it may be necessary to use boats and even drivers with specialized licenses, O&M cost is comparable to the one of a ground-mounted PV since FPV tends to incur minor soiling from dust. The water required for the cleaning is right below it.

However, as Rosa-Clot highlighted in [176], corrosive bird droppings and their effects should not be underestimated since they could lead to the formation of hot spots, significantly deteriorating PV module performance and reliability. This is why Rosa-Clot believes O&M is more expensive for FPV.

In addition to the previous points, it is reasonable to think that decommissioning is much cheaper for FPV systems since there is no fixed structure, except for the mooring blocks, which can be easily moved.

6.5.3 Levelized Cost Of Electricity

The LCOE is a commonly used metric that analyses the life cycle cost ratio and a project's lifetime energy production.

LCOE is a good indicator of cost-effectiveness because it can be calculated without requiring assumptions about the purchase price or the selling price of electricity, as it is when calculating the Pay Back Time or the Net Present Value.

For what concerns the ground-mounted PV, in the IRENA report, we read that the global weighted-average LCOE of utility-scale PV plants declined by 85% between 2010 and 2020, from 346 €/MWh to 42 €/MWh. This 2020 estimate also represents a 8,7% year-on-year decline from 2019 [172].

For floating PV, costs are still unclear. Many novel concepts have to find their way into the market, and few projects are grid-connected with respect to ground-mounted PV. They are concentrated in a few geographical areas, above all Asia.

In a recent study by S. Oliveira-Pinto and J. Stokkermans [129], the LCOE of two floating PV systems utilizing two different supports - HDPE and Galvanised steel - was evaluated and compared to the expected LCOE of a ground-based system. The comparison was conducted in three distinct geographical areas: Barrow Gurney in England (45,1 MWp), Balbina dam in Brazil (162 MWp), and Almeria in Spain (113,6 MWp).

The calculated LCOE ranged from 45,7 €/MWh in Almeria to 87,4 €/MWh in Barrow Gurney for the floating system. For the ground-based systems in the identical location, the LCOE was 30,1 €/MWh and 53,9 €/MWh, respectively, showing a remarkable difference in costs between the two technologies (more than 50%).

Another result is found in the SERIES report, in which a comparison of two 50 MWp PV plants in a tropical area was conducted. LCOE of FPV, which was assumed a Performance Ratio (PR) 5% higher with respect to the same system but on the ground, was still higher than the GPV, respectively 67,8 €/MWh and 62,4 €/MWh, but only by about 8%.

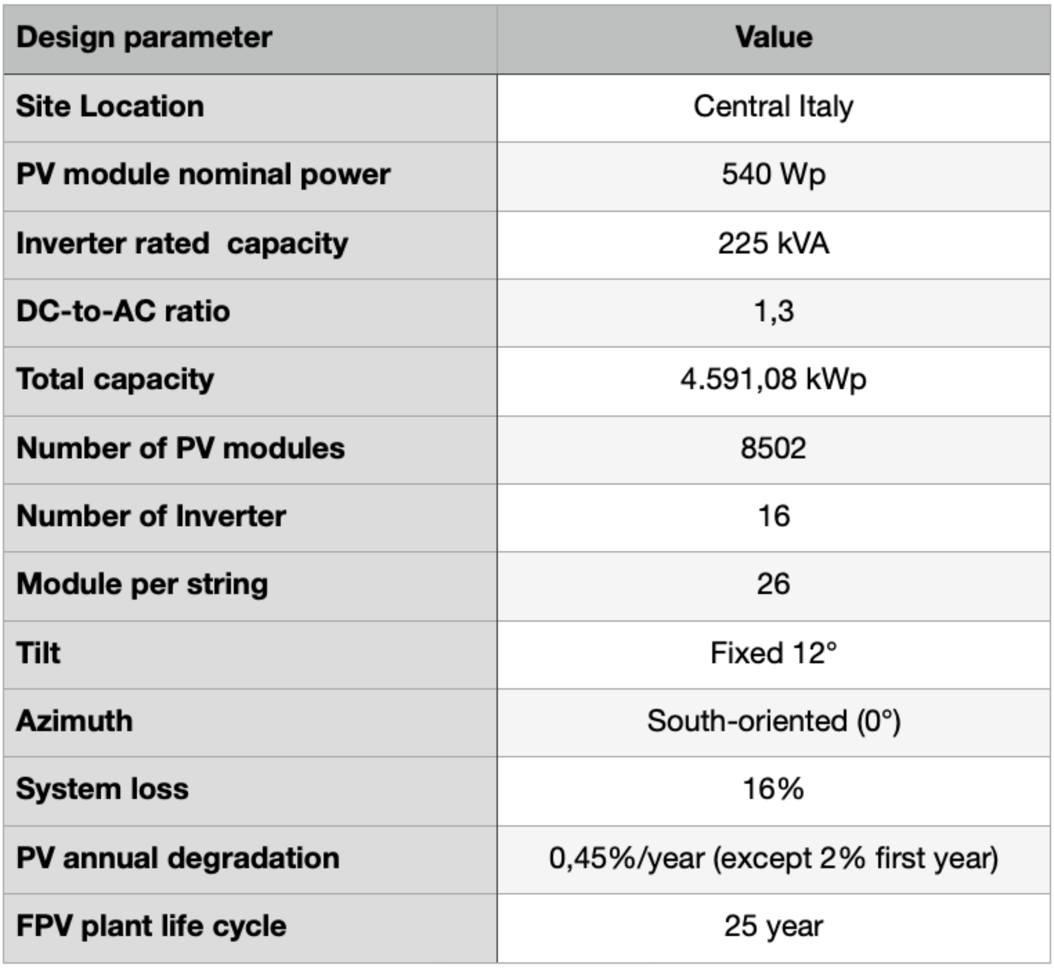
As a general consideration, the LCOE for FPV is still higher with respect to the well-established ground-based technology, mainly due to higher CAPEX costs. However, the higher energy yield of the floating technology makes it still an attractive solution.

6.6 Case Study

A case study of Floating PV in Italy has been followed in all its design and installation phases. The chosen site for installing the FPV plant is located in central-east Italy. The water body is a collection pond, with a total water area of around $3.7 ha$. The chosen azimuth angle corresponds to a south-oriented system, which returns the highest annual energy production with respect to an east/west-oriented system. The floating solar island area is planned to be 36.725 m^2, covering just 10,1% of the total basin surface.

Made from recyclable High-Density Polyethylene (HDPE), the floating PV system supports PV modules above water while withstanding long-term environmental hazards, such as wind, rain, and snow. Due to constraints imposed by the Region, the floating PV modules were limited to sticking out from the basin surface of a maximum of 40 cm; therefore, the chosen tilt angle resulted in being 12°. Since the adopted simulation software, Photovoltaic Geographical Information System (PVGIS), provides results for a standard mono-facial PV system, to consider the higher energy yield of an FPV, as found in the literature [102], it is assumed, for the Base Case scenario, an increased PR of 5%. Another 15% is added to consider the higher energy production of a bi-facial PV module.

The FPV annual electricity generation resulted in 6,73 GWh (during the first year), and its Capacity Factor (CF) resulted in 16,72%. Then, we assumed the electricity purchase and selling price for the first year, respectively 0,15 and 0,06 €/kWh, and a yearly increase in



Design parameter	Value
Site Location	Central Italy
PV module nominal power	540 Wp
Inverter rated capacity	225 kVA
DC-to-AC ratio	1,3
Total capacity	4.591,08 kWp
Number of PV modules	8502
Number of Inverter	16
Module per string	26
Tilt	Fixed 12°
Azimuth	South-oriented (0°)
System loss	16%
PV annual degradation	0,45%/year (except 2% first year)
FPV plant life cycle	25 year

Figure 6.9. Design Parameters.

electricity price of 2%.

Due to NDA, sharing the specific costs of the projects is impossible, but the CAPEX resulted in 1,13 €/Wp, in line with the literature results. The cost breakdown share of the initial investment is reported in Figure 6.10.

The break-even point, thus the Pay Back Time (PBT), is reached after 7,49 years, and the IRR is 16,73%. The resulting LCOE is 56,75 €/MWh, 35,13% higher than the average value of 42,0 €/MWh for a utility-scale ground-mounted PV. As expected, the FPV is more expensive than a GPV with the same design parameters.

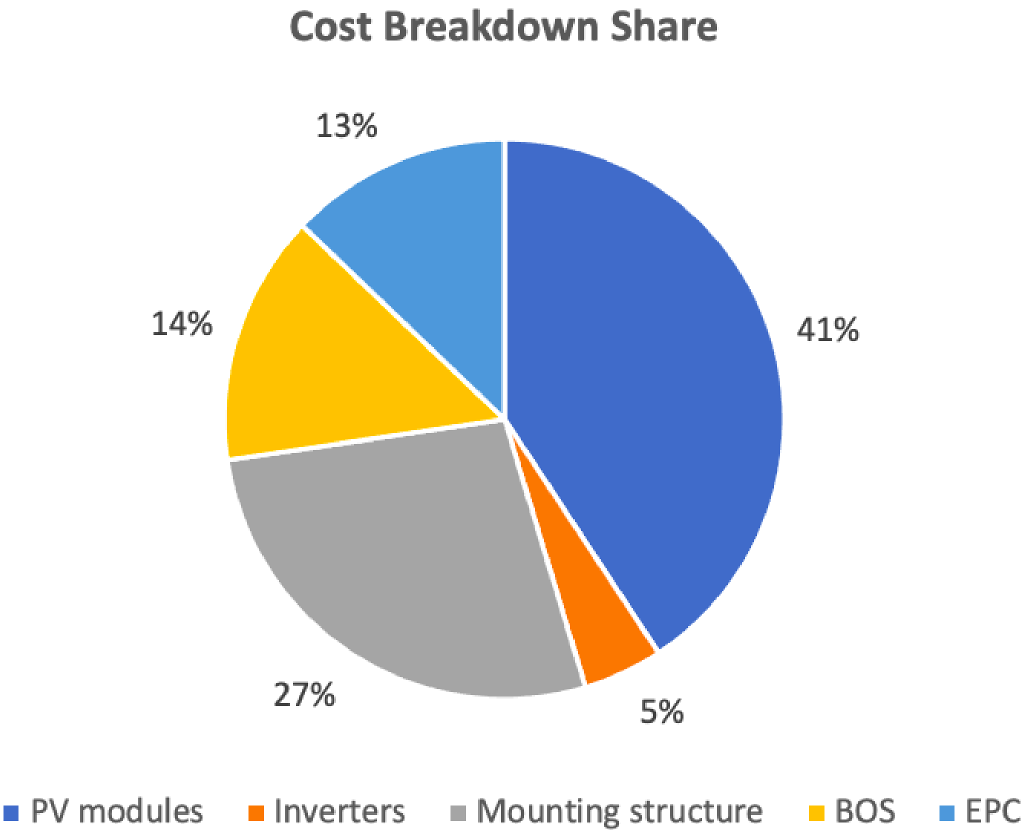


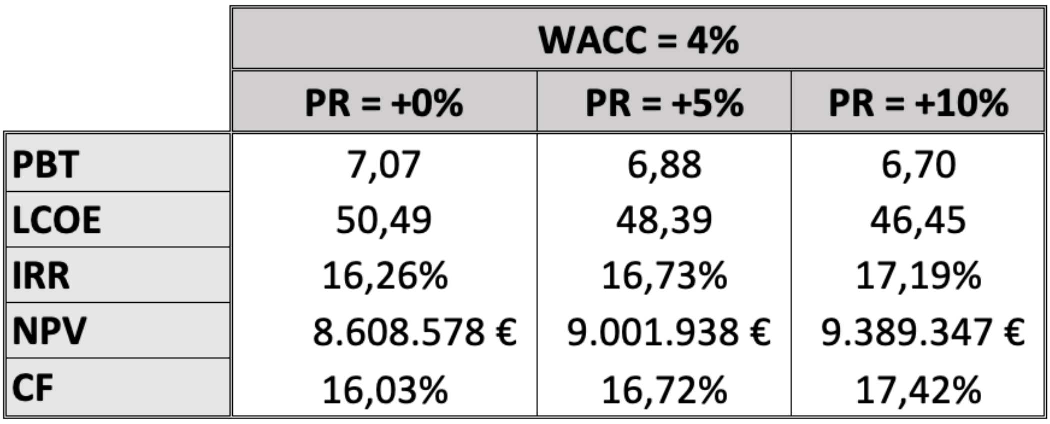
Figure 6.10. Cost breakdown.

6.6.1 Three Scenario Comparison

Here are reported and compared the energy outputs and the economic viability analysis of the FPV project in three different scenarios:

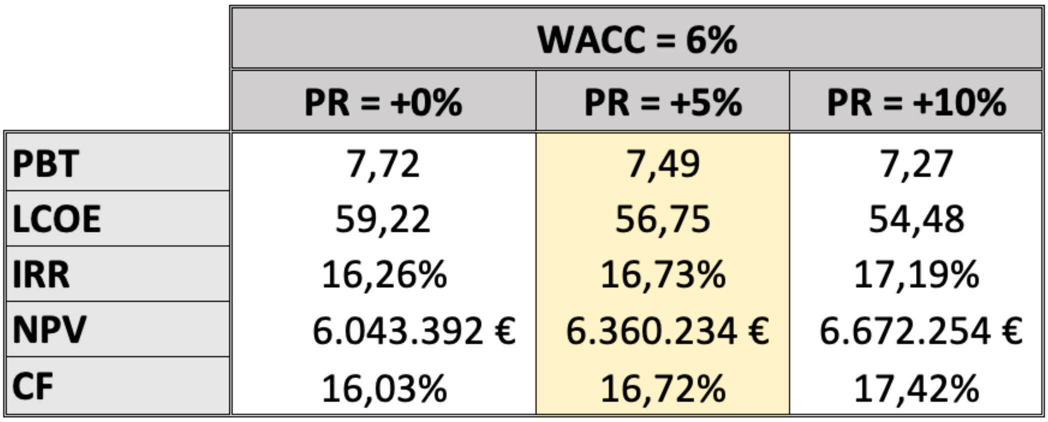
- An underestimated scenario in which the FPV produces the same amount of energy produced by a GPV plant.
- A conservative scenario, in which the PR is 5% higher for FPV;
- An optimistic scenario in which the PR is 10% higher.

For each of these scenarios, three different Weighted Average Cost of Capital (WACC) have been taken into account, 4% (shown in Figure 6.11), 6% (Figure 6.12), and 8% (Figure 6.13).



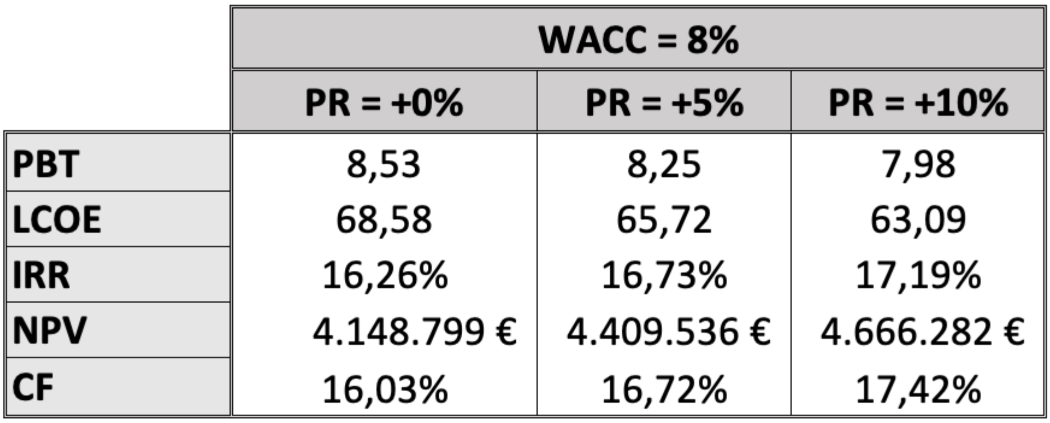
	WACC = 4%		
	PR = +0%	PR = +5%	PR = +10%
PBT	7,07	6,88	6,70
LCOE	50,49	48,39	46,45
IRR	16,26%	16,73%	17,19%
NPV	8.608.578 €	9.001.938 €	9.389.347 €
CF	16,03%	16,72%	17,42%

Figure 6.11. First scenario (4% WACC).



	WACC = 6%		
	PR = +0%	PR = +5%	PR = +10%
PBT	7,72	7,49	7,27
LCOE	59,22	56,75	54,48
IRR	16,26%	16,73%	17,19%
NPV	6.043.392 €	6.360.234 €	6.672.254 €
CF	16,03%	16,72%	17,42%

Figure 6.12. Second scenario (6% WACC).



	WACC = 8%		
	PR = +0%	PR = +5%	PR = +10%
PBT	8,53	8,25	7,98
LCOE	68,58	65,72	63,09
IRR	16,26%	16,73%	17,19%
NPV	4.148.799 €	4.409.536 €	4.666.282 €
CF	16,03%	16,72%	17,42%

Figure 6.13. Third scenario (8% WACC).

The worst LCOE (in the +8%WACC and +0%PR scenario) is 79,3 €/MWh. The best LCOE (in the +4%WACC and +10%PR scenario) is 52,1 €/MWh. The worst and the best

LCOE are higher, respectively 88,81% and 24,01%, with respect to the average ground-based PV LCOE.

The PBT varies between 6,7 and 8,53 years, while the IRR and the Net Present Value (NPV) indicate that, in every scenario, the floating PV investment is evaluated as profitable (considering 25 years of life cycle). However, legal permissions issues emerged to be the main drawback in Italy.

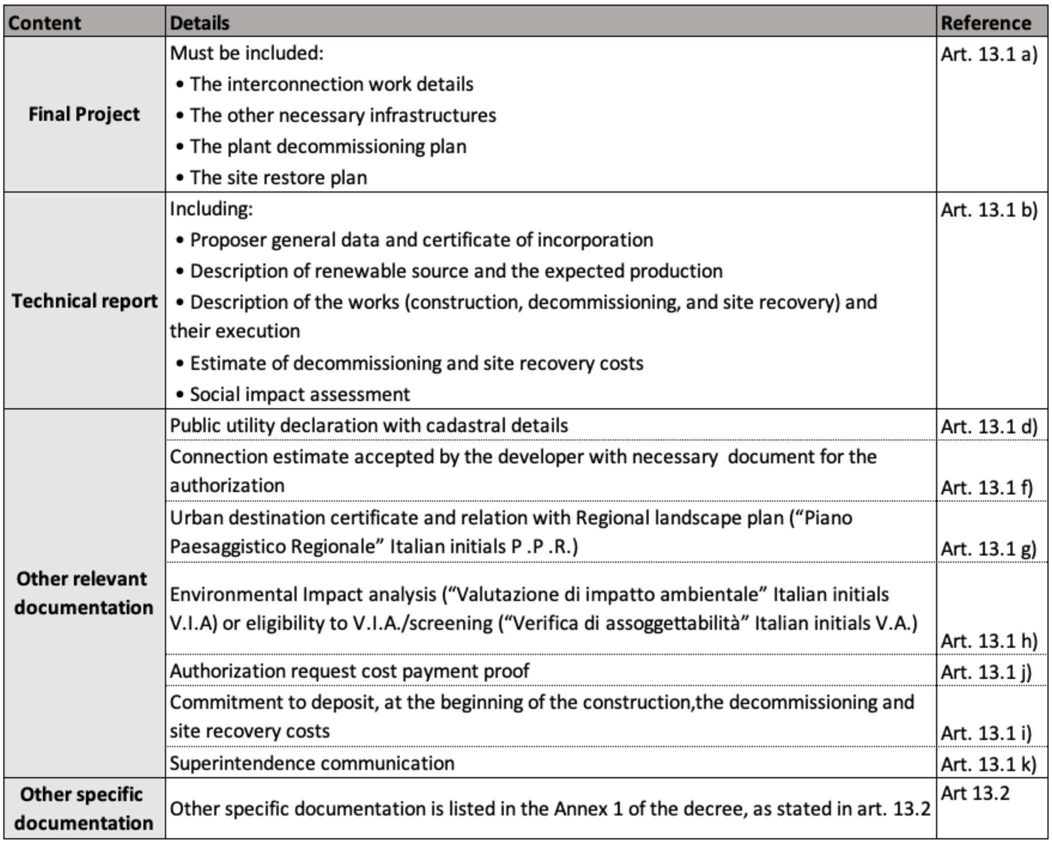
6.6.2 Italian Authorization Process Criticality

The construction and commissioning of large-scale renewable plant systems are regulated by [179, 180, 181]. Moreover, the grid-connection procedure is regulated by [182], which must also be considered.

The three main authorization processes available in Italy are the "Autorizzazione Unica" (AU) (art.12 of [179]), the "Procedure Abilitativa Semplificata" (PAS), and the "Comunicazine al Comune." For large-scale systems (capacity higher than 1 MWp), the AU must be obtained: it is the process that requires the most documentation to be evaluated, and it can take up to 90 days.

The AU must be obtained for power plants with a capacity higher than 1 MWp: the procedure requires the most documentation to be evaluated, and it can take up to 90 days. This authorization is granted by the Region or the competent Province at the end of the procedure called "Conferenza dei Servizi," in which all relevant administrative departments participate and evaluate the submitted documents. The documents submitted for the AU procedure, published in art. 13 of [181], are summarized in Fig.6.14.

The [181] regulates the authorization procedure for plants powered by renewable energy sources (RES) in order to ensure their proper integration in the territory. These guidelines establish administrative modalities and technical criteria applying to the procedures for the construction and operation of electricity generation plants powered by renewable energy sources, for the modification, upgrading, total or partial renovation, and reactivation of the same plants, as well as for the connection works and infrastructures required for the construction and operation of the same plants.

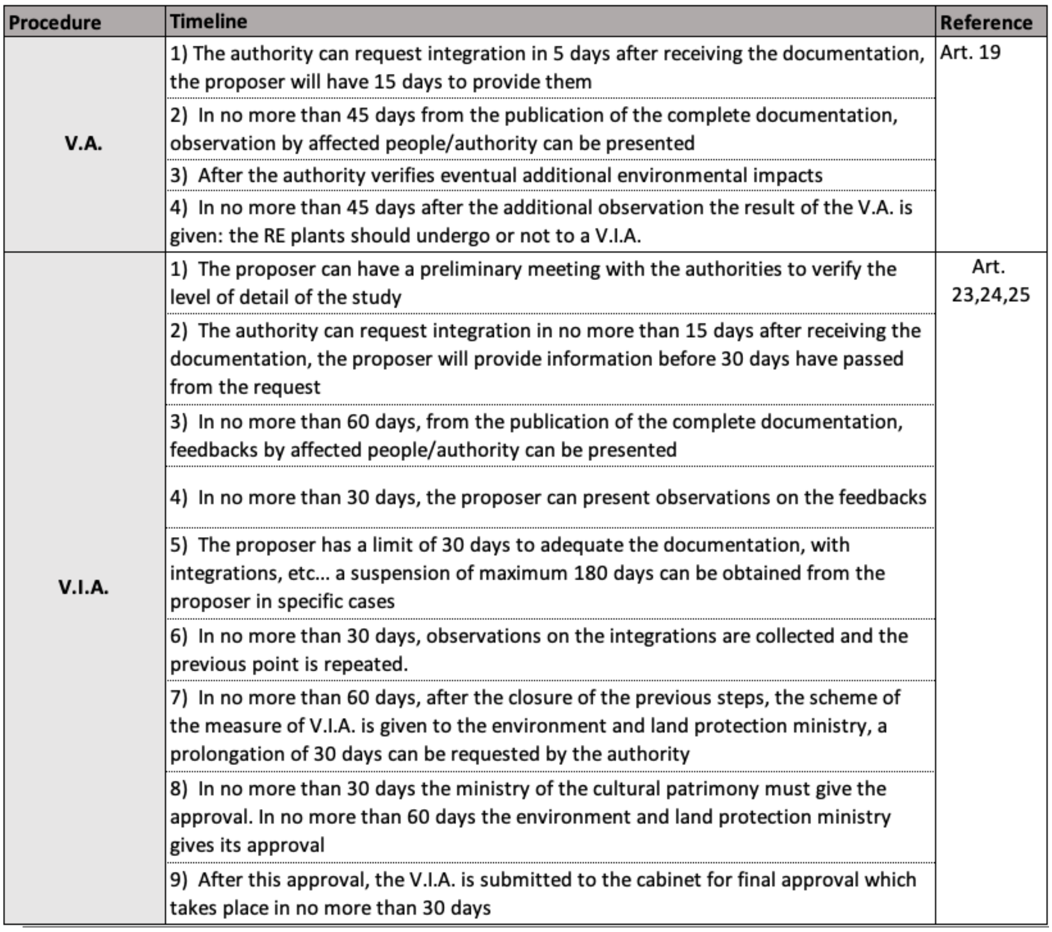


Content	Details	Reference
Final Project	Must be included: • The interconnection work details • The other necessary infrastructures • The plant decommissioning plan • The site restore plan	Art. 13.1 a)
Technical report	Including: • Proposer general data and certificate of incorporation • Description of renewable source and the expected production • Description of the works (construction, decommissioning, and site recovery) and their execution • Estimate of decommissioning and site recovery costs • Social impact assessment	Art. 13.1 b)
Other relevant documentation	Public utility declaration with cadastral details	Art. 13.1 d)
	Connection estimate accepted by the developer with necessary document for the authorization	Art. 13.1 f)
	Urban destination certificate and relation with Regional landscape plan (“Piano Paesaggistico Regionale” Italian initials P .P .R.)	Art. 13.1 g)
	Environmental Impact analysis (“Valutazione di impatto ambientale” Italian initials V.I.A) or eligibility to V.I.A./screening (“Verifica di assoggettabilità” Italian initials V.A.)	Art. 13.1 h)
	Authorization request cost payment proof	Art. 13.1 j)
	Commitment to deposit, at the beginning of the construction,the decommissioning and site recovery costs	Art. 13.1 i)
	Superintendence communication	Art. 13.1 k)
Other specific documentation	Other specific documentation is listed in the Annex 1 of the decree, as stated in art. 13.2	Art 13.2

Figure 6.14. Single authorisation procedure minimal documentation [181]

In the same [181], Art. 14.7 b) states that renewable energy systems with a specified capacity of 1 MW or more must undergo an Environmental Impact Analysis (VA) process. An Environmental Impact Assessment (VIA) is a process designed to recognize, delineate and evaluate the impacts on the environment, health, and human well-being prior to the construction of a power plant. Both VA and VIA are regulated by [180]; the timeline for both procedures is shown in Fig.6.15.

For VA, the required documentation is a preliminary environmental study, including a description of the project (i.e., physical characteristics, location, site conditions), a description of the environmental components affected by the project, and possible environmental impacts (i.e., emissions, waste generation). For VIA, the required files are in D.Lgs 152/2006 Art. 23, including a technical-economic study of the project; environmental impact study (also referred to as SIA); non-technical summary; transboundary impact analysis (if any); notification; payment voucher; results of public project preview (if any). The main document



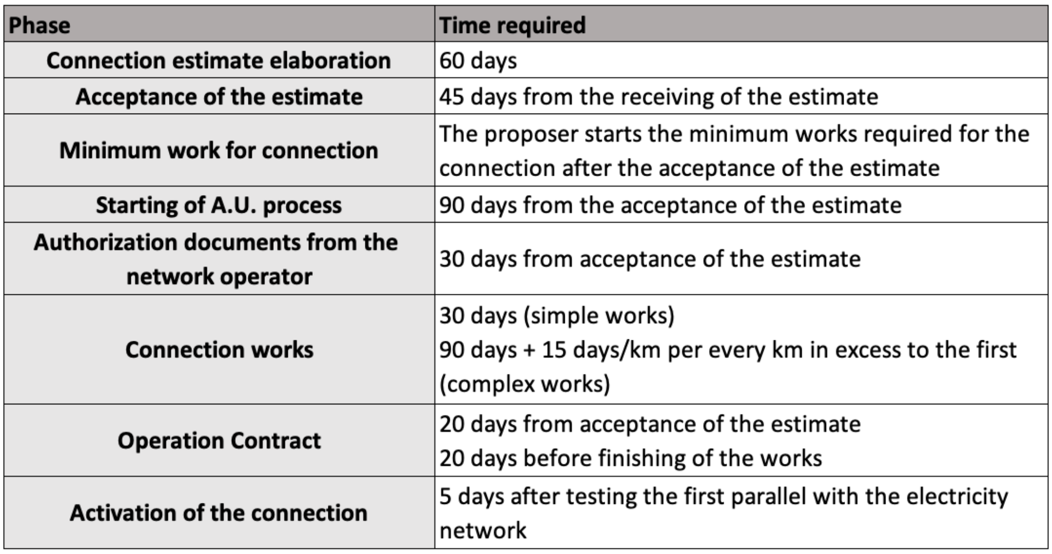
Procedure	Timeline	Reference
V.A.	1) The authority can request integration in 5 days after receiving the documentation, the proposer will have 15 days to provide them	Art. 19
	2) In no more than 45 days from the publication of the complete documentation, observation by affected people/authority can be presented	
	3) After the authority verifies eventual additional environmental impacts	
	4) In no more than 45 days after the additional observation the result of the V.A. is given: the RE plants should undergo or not to a V.I.A.	
V.I.A.	1) The proposer can have a preliminary meeting with the authorities to verify the level of detail of the study	Art. 23,24,25
	2) The authority can request integration in no more than 15 days after receiving the documentation, the proposer will provide information before 30 days have passed from the request	
	3) In no more than 60 days, from the publication of the complete documentation, feedbacks by affected people/authority can be presented	
	4) In no more than 30 days, the proposer can present observations on the feedbacks	
	5) The proposer has a limit of 30 days to adequate the documentation, with integrations, etc... a suspension of maximum 180 days can be obtained from the proposer in specific cases	
	6) In no more than 30 days, observations on the integrations are collected and the previous point is repeated.	
	7) In no more than 60 days, after the closure of the previous steps, the scheme of the measure of V.I.A. is given to the environment and land protection ministry, a prolongation of 30 days can be requested by the authority	
	8) In no more than 30 days the ministry of the cultural patrimony must give the approval. In no more than 60 days the environment and land protection ministry gives its approval	
	9) After this approval, the V.I.A. is submitted to the cabinet for final approval which takes place in no more than 30 days	

Figure 6.15. VA/VIA procedure timeline [180, 183]

in the VIA procedure is the SIA, an analysis of the interactions between the environment and the plant that will be built.

According to Article 17.3 of [181], the Region must distinguish unsuitable areas for each technology within its district according to the size of the plant, in accordance with national guidelines, and the municipality can impose stricter restrictions. The non-suitability of an area for the installation of RES plants is not to be understood as a prohibition but rather as an indication of an area in which the planning of specific types and/or sizes of plants would have a high probability of a negative outcome of the assessments during authorization.

Grid connection solutions are part of the required documentation for the AU, [182] is the corresponding regulations. The grid connection solution found for this project was part of the necessary documentation for AU validation, and the timeline for this option is shown in Fig.6.16.



Phase	Time required
Connection estimate elaboration	60 days
Acceptance of the estimate	45 days from the receiving of the estimate
Minimum work for connection	The proposer starts the minimum works required for the connection after the acceptance of the estimate
Starting of A.U. process	90 days from the acceptance of the estimate
Authorization documents from the network operator	30 days from acceptance of the estimate
Connection works	30 days (simple works) 90 days + 15 days/km per every km in excess to the first (complex works)
Operation Contract	20 days from acceptance of the estimate 20 days before finishing of the works
Activation of the connection	5 days after testing the first parallel with the electricity network

Figure 6.16. Main steps in the LV/MV connection

6.6.3 Italian PV Market Perspectives

Regarding the "Renewable Energy" section, Italy intends to pursue a target of coverage, in 2030, of 30% of the final gross energy consumption from renewable sources, outlining a path of sustainable growth of renewable sources with their full integration into the system.

The most significant contribution to the growth of renewables derives from the electricity sector, which by 2030 is expected to reach 16 Mtoe of generation from RES, equal to 187 TWh. The intense penetration of renewable electricity production technologies, mainly photovoltaic and wind power, will allow the sector to cover 55,0% of gross final electricity consumption with renewable energy, compared to 34,1% in 2017 [184].

Fonte	2016	2017	2025	2030
Idrica	18.641	18.863	19.140	19.200
Geotermica	815	813	920	950
Eolica	9.410	9.766	15.950	19.300
di cui off shore	0	0	300	900
Bioenergie	4.124	4.135	3.570	3.760
Solare	19.269	19.682	28.550	52.000
di cui CSP	0	0	250	880
Totale	**52.258**	**53.259**	**68.130**	**95.210**

Figure 6.17. PNIEC 2030 target [184]

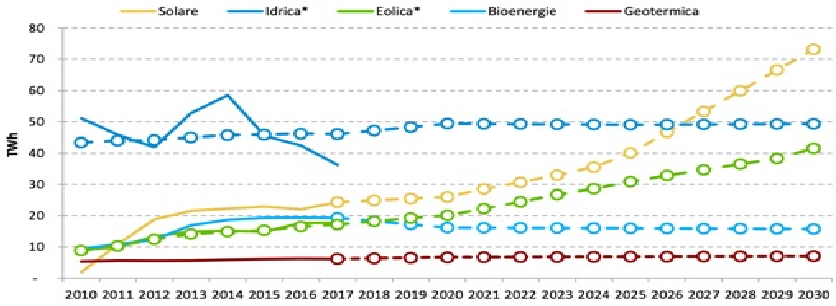


Figure 6.18. PNIEC 2030 projections [184]

Chapter 7

Integration of Energy Storage Systems (ESSs) in a REC

7.1 The Role of a ESSs in a REC

Although the ultimate goal of energy communities is not the generation of financial benefits, it is worth noting that appropriate means of economic support could incentivise the participation of citizens, especially those with limited financial means. Means of support independent from the grid could be tax exemptions or rewards for energy transfer within the community. In [185], the authors also analyzed the unanswered questions arising from the possibility for consumption and generation units to participate in more than one energy community. Energy communities are also seen, especially for rural communities, as a means to combat the risk of energy exclusion and energy poverty. Residents in multi-apartment buildings benefit significantly from the purchase of electricity from a photovoltaic system attached to the building, resulting in almost no grid costs. The savings of the remaining members are lower as they only benefit from the electricity leftovers of their colleagues. It should therefore be emphasised that the use of a single stand-alone photovoltaic system in an energy community improves its overall profitability but results in large inequalities between members. In these cases, advanced democratic power-sharing models, such as the one developed in this study, must be used. The possibility of incorporating ESSs (e.g. batteries and super-capacitors) that allow for an equitable management of the energy flow between members should also be considered. For renewable generation plants, there can often be a time shift between the time when energy is produced and the time when the end user needs it, or there may be a surplus of energy that is fed into the grid. Due to reduced revenues from feeding renewable energy into the grid, mechanisms that promote self-consumption are becoming increasingly important. Demand Response (DR) techniques and local storage are widely used mechanisms to achieve higher levels of self-consumption. The implementation of a shared storage system within an energy community is an alternative scenario that allows community members to store excess renewable energy for later use. Of course, this creates additional challenges in managing the storage system and the available energy resource in an equitable manner. An energy management system (EMS) that plans the energy consumption of energy community participants and the energy that each member can receive from the storage system becomes necessary at this point. Energy communities are conceived as small-scale operational and technological integrated systems that help optimise the generation, distribution and consumption of energy. The concept refers to a set of loads (e.g. households), distributed generation (DG) (e.g. small-scale RESs) and possibly ESSs that operate as a single controllable system that supplies energy to the area in which it works [186, 187]. Since a large portion of electricity is consumed in the residential sector, it is crucial to involve citizens in the planning and efficient use of electricity. Furthermore, the share of electricity used by household appliances and electronics in an average household accounts for approximately two-thirds of total electricity consumption [188]. Therefore, managing the energy consumption of household appliances can play an important role in saving costs and reducing the environmental impact of electricity consumed in the residential sector. As a result, DR programmes have been defined that offer various economic and technical benefits for utilities and consumers [189]. In particular, DR programmes aim to reshape consumers' energy profiles to improve grid reliability and efficiency and postpone the expansion of generation capacity [190, 191]. Participants can take actions in response to a DR programme through load management schemes such as demand limiting, demand shedding, demand shifting and on-site generation [189]. Recently, increasing attention to

DR is being paid to the residential sector, motivated by the vision of smart homes whose appliances can be controlled and integrated into the energy management system. DR can be implemented as incentive-based or price-based programmes. Incentive-based schemes compensate participating users for reduced demand by offering discount rates separate from electricity prices [192]. Price-based schemes provide customers with time-varying tariffs, which set different electricity prices at different times. These types of schemes may confuse customers, so scheduling techniques are needed to help them manage their load. [190]. Some of the implemented price-based schemes are Time of Use (ToU), Critical-Peak Price (CPP) and Real-Time Price (RTP) [192, 193]. The RTP in DR programmes is usually based on the wholesale price of the day before or in real time [194]. Increasing self-consumption within an energy community can increase the profitability of grid-connected PV systems, which is important for increasing the number of installations. In electricity grids with a high level of PV penetration, an increase in self-consumption can also reduce the stress on the grid if the peak supply of PV systems is reduced. The integration of shared storage systems within RECs, in conjunction with the use of DR programmes, would allow greater utilisation of RESs while also maximizing self-consumption. In this scenario, DR techniques allow peak-shaving actions to be implemented both by reducing the renewable energy fed into the grid and by limiting its withdrawal from the grid. In addition, the growing penetration of electric vehicles within the automotive market allows for a further increase in the flexibility of energy communities, enhancing their storage capacity and thus self-consumption. The main storage systems used are lithium-ion battery packs with high energy density. The main problem with batteries is that they are unable to respond to abrupt changes in load, a problem that can be overcome through the use of supercapacitors, devices with high power density instead.

Energy storage has a key role in the penetration of renewable energy sources. Supercapacitors represent a new form of energy harvesters and their characteristics such as high power density, fast charge/discharge response, and long life cycle allow to use them for renewable energy applications.

In the last decade, the most challenging issues are represented by climate change, global warming and energy transition [6]. After the Paris Agreement, the European Commission started a deep review of the common energy regulatory framework, promoting the renewable energies as key point for a decarbonised energy system. The result is represented by the Clean Energy Package for all Europeans [4], a set of eight laws that shapes the EU energy policies.

The CEP aims for a 40% greenhouse gases reduction by 2030 and, for the same amount of time, for a 32.5% of improvement in energy efficiency. In Europe, the major part of buildings consist of multiple units which are responsible for about the 40% of energy consumption [195]. The European Commission is proposing an indicative goal: the 49% of the buildings energy need has to be provided by renewable energy sources [196]. This target can be reached only promoting the aggregation of users in RECs [197].

In chapter 4 we have proposed a novel power sharing model [198, 27] for the democratic sharing of energy produced by common RESs in RECs, that is properly tailored to be realized in existing multiple units buildings. The key feature, which is the cornerstone of the new PSM, is that only the energy generated by common (photovoltaic) RESs can be shared among the users which remain passive with respect to the distribution system operator. The PSM complies with the regulatory framework of several nations and is suited to be easily implemented whenever a common surface (e.g., a communal terrace) is available for the installation of a RES.

The backbone of the microgrid underlying the new PSM is a dc link which allows for the integration of any distributed resource (e.g, energy sources, energy storage systems, capacitors) with high level of efficiency [29]. In this work, we investigated how to integrate a supercapacitor (SC) bank in the dc link for buffering renewable energy fluctuations and for power quality improvements among the users. We consider and compare several models of SCs available in literature and propose a first interface with the dc link. The analysis is carried out in the Matlab/Simulink environment.

7.2 Supercapacitors Modelling

A photovoltaic system is characterized by a low-level of reliability in power systems due to the fluctuations of its production caused by the variations of the solar irradiance [199]. These variations may lead to over-production of electric energy with respect to the energy demand at one time, and lack of production at another time. To increase the reliability of photovoltaic generators, Battery Energy Storage Systems (BESSs) play a significant role. BESSs are also widely used for advanced power applications, e.g., to improve stability, power quality, and reliability of supply [200, 201]. However, BESSs are not able to respond immediately to abrupt generation/load variations. To this end, the most suitable device is the supercapacitor that is characterized by a higher power density and an extremely high number of charge/discharge cycles without degradation [202]. In particular, the SCs are exceptionally effective when repetitive pulsed power is required [203]. Moreover, it can be effectively joined to a BESS to obtain a hybrid system [204] whose advantage is a faster dc-link voltage restoration with an effective power sharing between the BESS and the SC. The combined use of batteries and SCs represents a solution that can cover a wide range of power and energy requirements and allows the reduction of the stress on the batteries, increasing their lifetime, and the minimization of power fluctuations.

In this section we selected from the literature six representative supercapacitor nonlinear models, in order to compare them and select the most suitable one in terms of accuracy and numerical efficiency. The selected models are [205, 206]:

1. Stern-Tafel model,
2. Zubieta model,
3. Series model,
4. Parallel model,
5. Transmission Line model,
6. Thevenin model.

7.2.1 Stern-Tafel Model

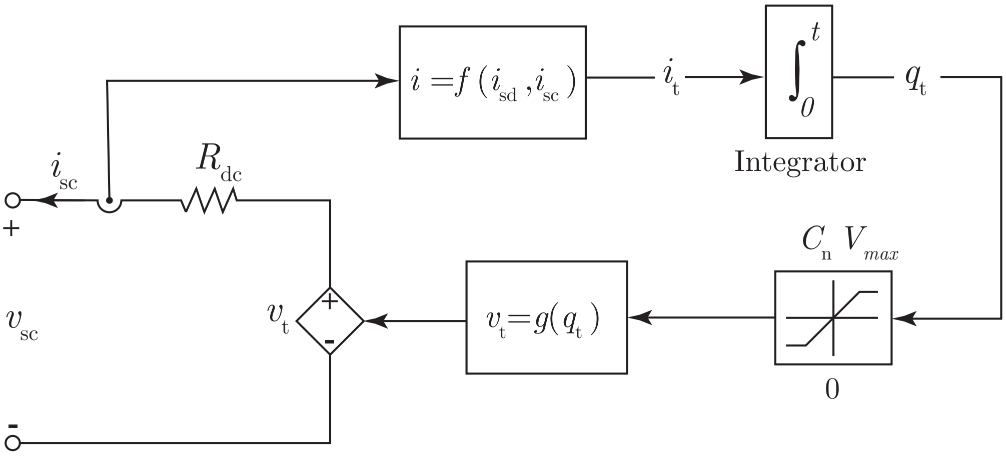


Figure 7.1. Electric representation of the Stern Tafel model.

The model is shown in Fig. 7.1 where the SC port variables are the positive output current i_{sc} and the voltage v_{sc} that depends on the voltage drop on an internal dc resistance and a current-controlled voltage generator v_t [207].

The total current i_t is function of the i_{sc} and the self-discharge current:

$$i_t = i_{sc}\left[1-u(t)\right] + i_{sd}u(t) \ , \tag{7.1}$$

where $u(t)$ is the unit-step function whose value changes from zero to one at the time instant when the current $i_{sc}=0$. The self-discharge current i_{sd} is given by

$$i_{sd} = N_e I_f \exp\left[\frac{\alpha F_c\left(\frac{V_{init}}{N_s}-\frac{V_{max}}{N_s}-\Delta V\right)}{RT}\right] , \tag{7.2}$$

where I_f is the leakage current, V_{init} represents the initial voltage, α is the charge transfer coefficient, ΔV corresponds to over-potential, R is the ideal gas constant, N_e is the number of layers of electrodes, and T is the absolute temperature. Once i_t is known, it is time-integrated to obtain the charge q_t that is limited between the extreme values zero and $C_n V_{max}$, where C_n is the nominal capacitance and V_{max} is the maximum permissible voltage. The voltage v_t of the current-controlled voltage generator is function of the total charge as

$$v_\mathrm{t} = \frac{N_\mathrm{s} q_\mathrm{t} d}{N_\mathrm{p} N_\mathrm{e} \epsilon A_\mathrm{i}} + \frac{2 N_\mathrm{e} N_\mathrm{s} RT}{F_\mathrm{c}} \operatorname{arcsinh}\left(\frac{q_\mathrm{t}}{N_\mathrm{p} N_\mathrm{e}^2 A_\mathrm{i} \sqrt{8RT\epsilon c}} \right) , \tag{7.3}$$

where N_p represents number of parallel supercapacitor cells, N_s is the number of series supercapacitor cells, d is the molecular radius, c the molar concentration, A_i is the interfacial area between electrode and electrolyte, F_c is the Faraday constant, and ϵ is the absolute permittivity of the electrolyte material.

Basically, the Stern-Tafel Model is an electrochemical model [208] that reproduces the double layer capacitance (C_t) combining in series both the Helmholtz's capacitance C_H and Gouy-Chapman's capacitance C_GC as

$$C_\mathrm{t} = \frac{N_\mathrm{p}}{N_\mathrm{s}} \left(\frac{1}{C_\mathrm{H}} + \frac{1}{C_\mathrm{GC}} \right)^{-1} , \tag{7.4}$$

where

$$C_\mathrm{H} = \frac{N_\mathrm{e} \epsilon A_\mathrm{i}}{d} \tag{7.5}$$

$$C_\mathrm{GC} = \frac{F_\mathrm{c} q_\mathrm{t}}{2 N_\mathrm{e} RT} \sinh^{-1} \left(\frac{q_\mathrm{t}}{N_\mathrm{e}^2} A_\mathrm{i} \sqrt{8RT\epsilon c} \right) . \tag{7.6}$$

The implementation of the model in the Matlab/Simulink environment is shown in Fig. 7.2.

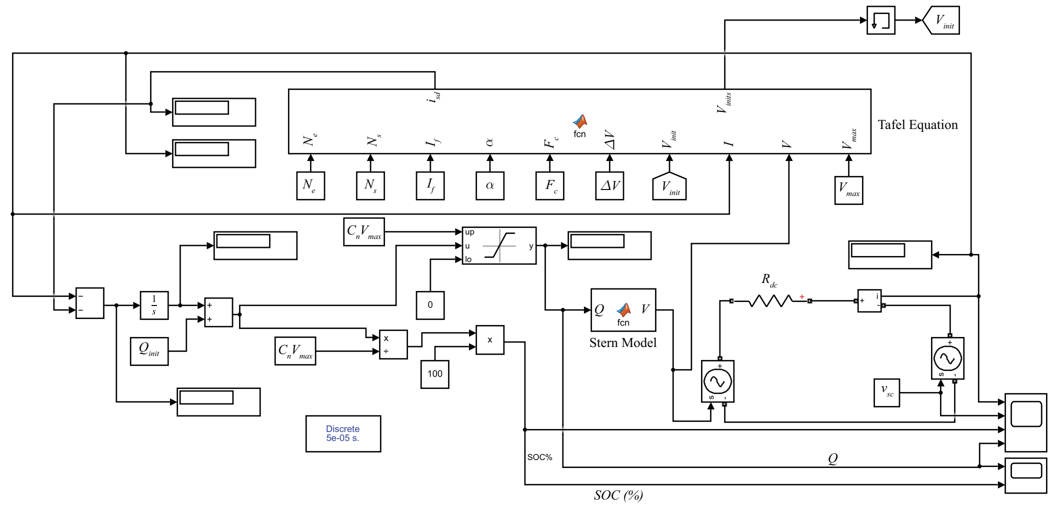


Figure 7.2. Simulink implementation of the Stern-Tafel model.

7.2.2 Zubieta Model

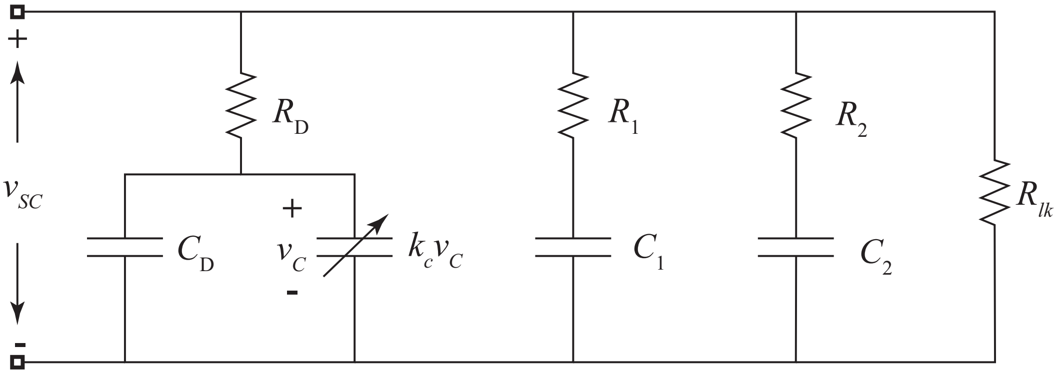


Figure 7.3. Electric circuit of the Zubieta model.

The model circuit, shown in Fig. 7.3, consists of three parallel branches. Each branch has a different RC time constant: the first branch, composed by the elements $R_0 - C_0$ and the voltage-dependent $k_C v_C$ capacitor, dominates the behavior of the SC in the time range of seconds; the second branch, with the series $R_1 - C_1$, provides the response in the range of minutes; the third branch, with the series $R_2 - C_2$, determines the behavior of the SC for a time longer than minutes. Finally, a leakage resistor R_{lk}, parallel connected to the previous branches, reproduces the self discharge property.

Fig. 7.4 shows the model in the Matlab/Simulink environment. The total capacitance and current of the voltage controlled capacitance are defined, respectively, as:

$$C\left(v_C\right) = C_0 + k_C v_C \tag{7.7}$$

$$i_C = \frac{\mathrm{d}Q}{\mathrm{d}t} = \frac{\mathrm{d}\left[C\left(v_C\right) v_C\right]}{\mathrm{d}t} = \left(C_0 + 2k_C v_C\right)\frac{\mathrm{d}v_C}{\mathrm{d}t}\ , \tag{7.8}$$

where C_0 represents the linear capacitance which is the electrostatic capacitance of the capacitor and k_C is a positive coefficient representing the effects of the diffused layer of the SC.

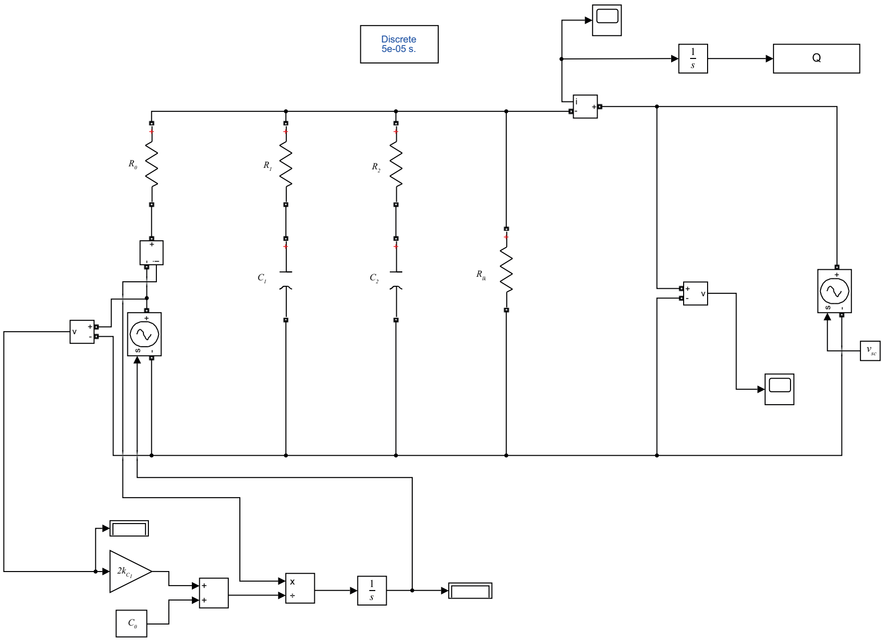


Figure 7.4. Simulink implementation of the Zubieta model.

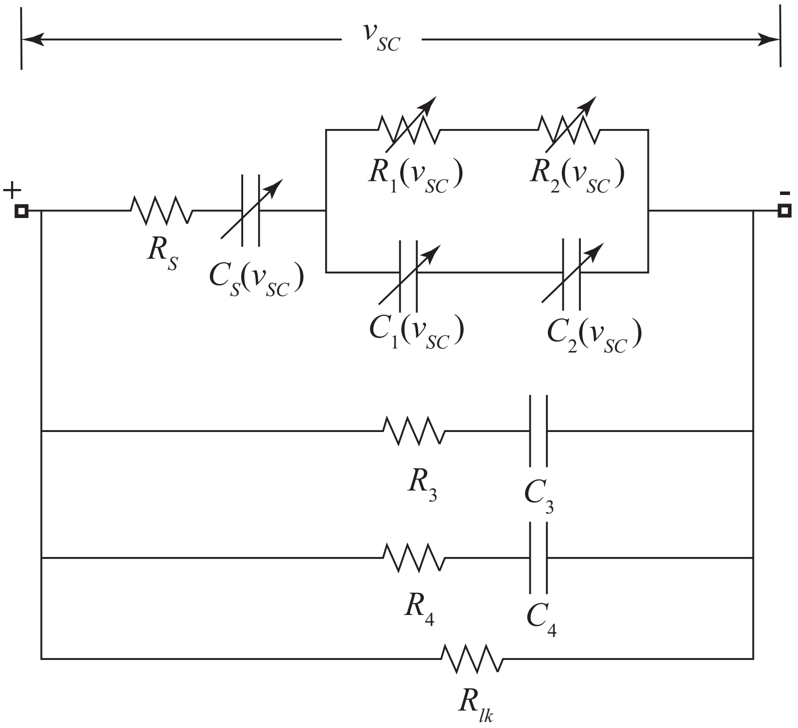


Figure 7.5. Electric circuit of the series model.

7.2.3 Series Model

The equivalent circuit of the series model, shown in Fig. 7.5, is obtained by means of ac impedance approach: it is represented by two parallel RC circuits composed by R_1 (v_{sc}), C_1 (v_{sc}), R_2 (v_{sc}), C_2 (v_{sc}) connected in series with another RC circuit compound by R_{s} and C_{s} (v_{sc}). Most recently, the equivalent circuit has been improved according to model proposed by Buller and Zubieta [209]: three branches have been added in parallel, composed of the series $R_3 - C_3$, $R_4 - C_4$ and the leakage resistance R_{lk}. Fig. 7.6 shows the model in the Matlab/Simulink environment.

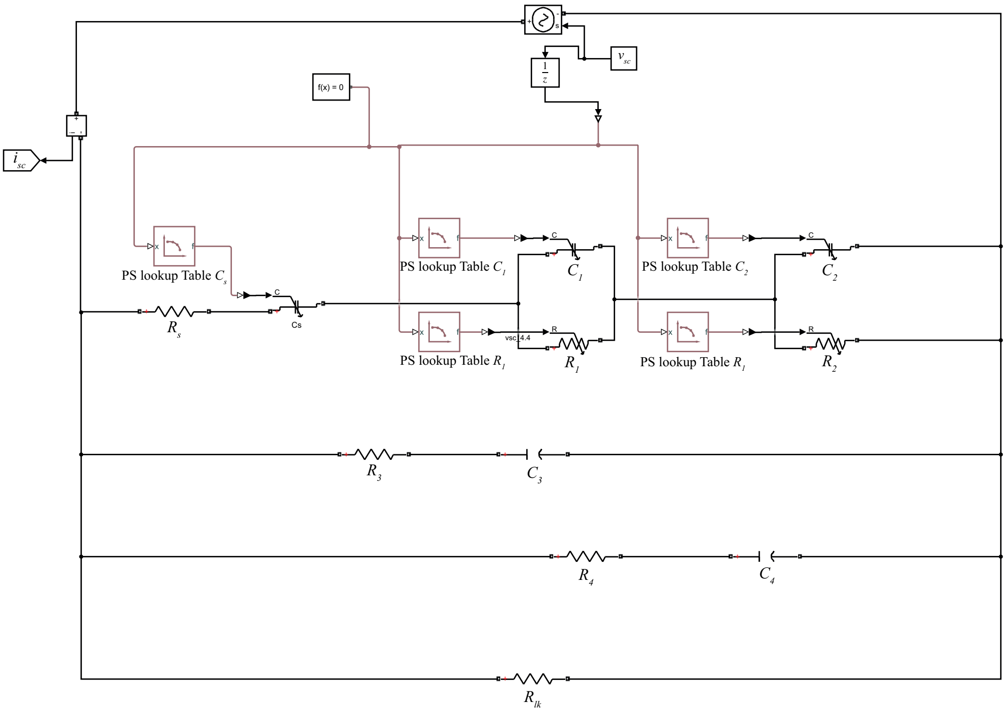


Figure 7.6. Simulink implementation of the series model.

7.2.4 Parallel Model

The parallel model, shown in Fig. 7.7, is more complex than the series one, but it usually allows to reach a better accuracy. Fig. 7.8 shows the model in the Matlab/Simulink environment.

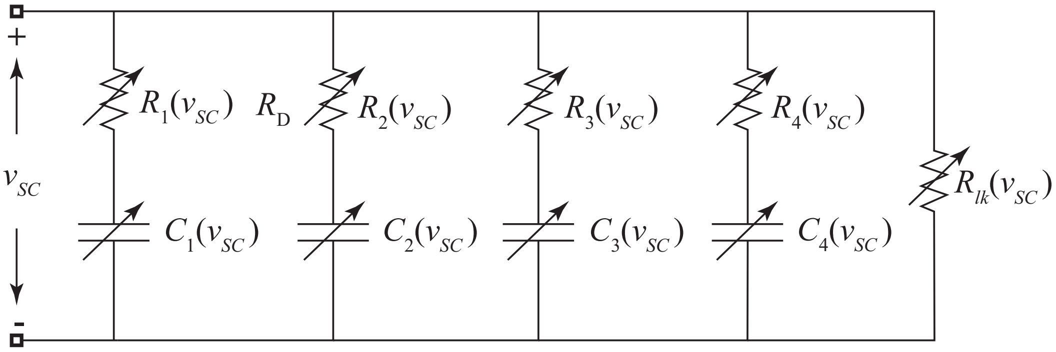


Figure 7.7. Electric circuit of the parallel model.

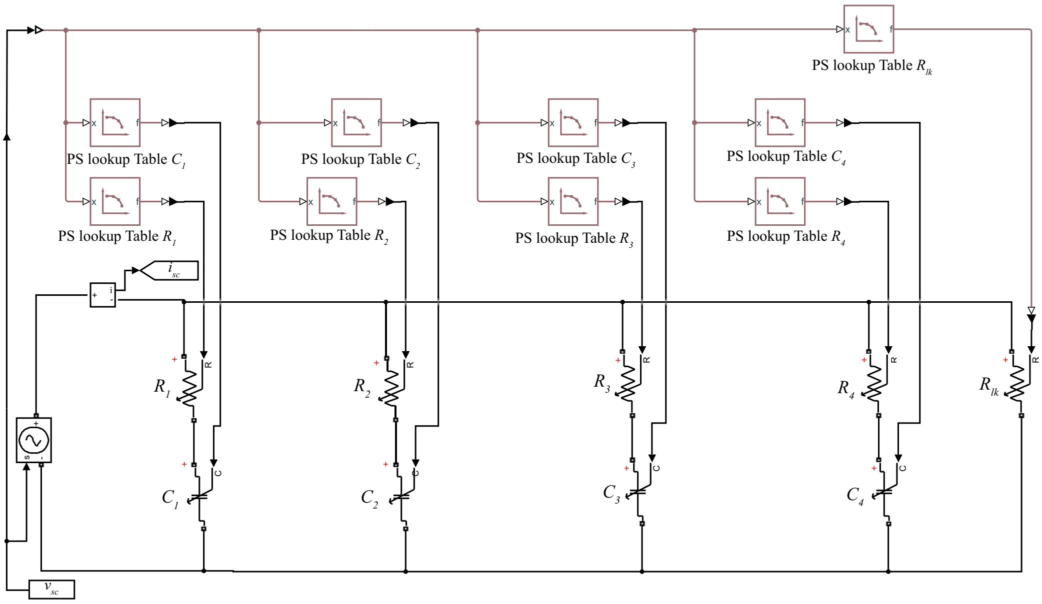


Figure 7.8. Simulink implementation of the parallel model.

7.2.5 Transmission Line Model

This model, shown in Fig. 7.9, is able to reproduce the frequency response of the SC from 10 mHz to 1 kHz through a ladder network with $n - RC$ tanks. In the present case, it is composed by four tanks $R_i - C_i\ (v_i)$ with $i = 1, 2, 3, 4$. The ladder network is closed on a leakage resistance R_{lk}. The model implemented in Matlab/Simulink software is shown in Fig. 7.10.

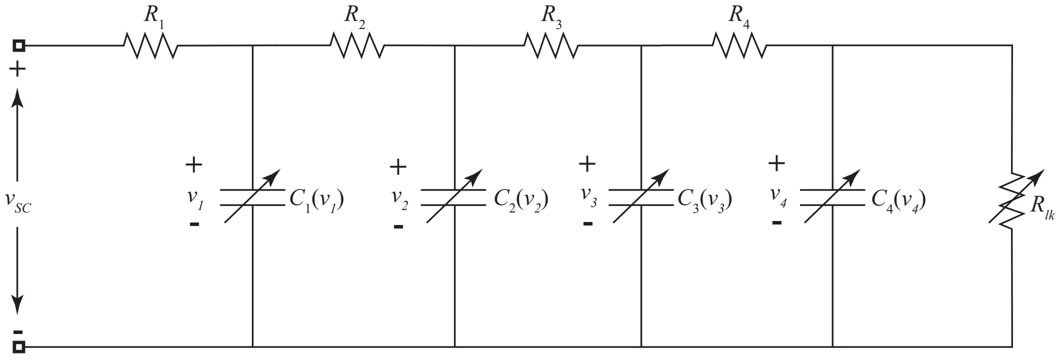


Figure 7.9. Electric circuit of the transmission line model.

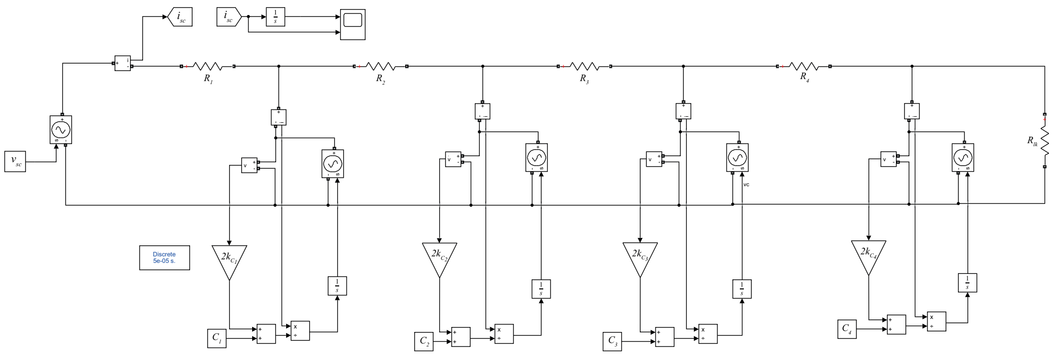


Figure 7.10. Simulink implementation of the transmission line model.

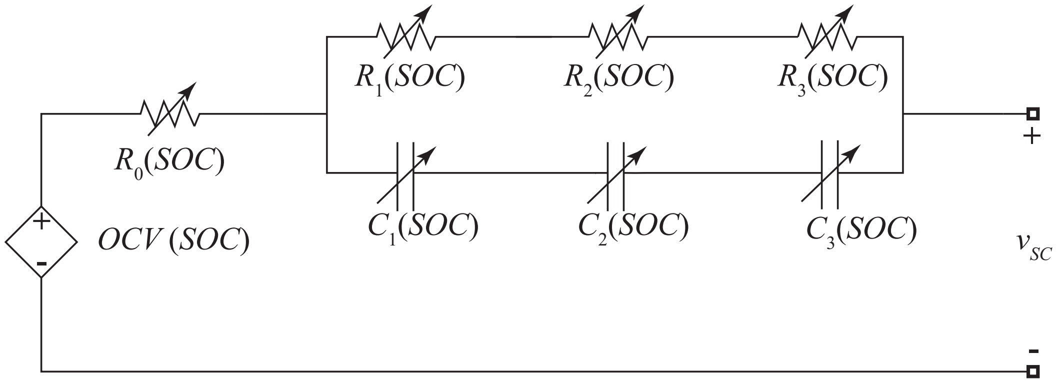


Figure 7.11. Electric circuit of the Thevenin model.

7.2.6 Thevenin Model

Fig. 7.11 shows the equivalent electric circuit of the Thevenin model that consists of three nonlinear state-of-charge (SOC) dependent resistors and capacitors and a non-linear SOC-controlled voltage-source. The SOC is defined as:

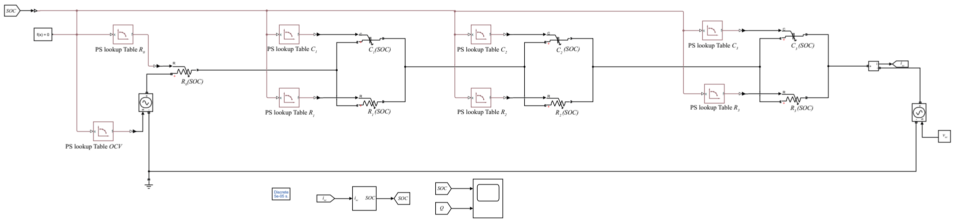


Figure 7.12. Simulink implementation of the Thevenin model.

$$SOC = \frac{Q_{\text{init}} - \int_0^t i(\tau)d\tau}{Q_{\text{T}}} , \tag{7.9}$$

where Q_{init} is the initial supercapacitor charge, Q_{T} represents the total SC charge, and $i(\tau)$ is the supercapacitor current.

The implemented model is composed as follows: the three RC branches $R_i - C_i$, with $i = 1, 2, 3$, allow to obtain a better accuracy and reproduce the supercapacitor dynamic while the internal resistance R_0 is tuned to fit the static behaviour. Fig. 7.12 shows the model in the Matlab/Simulink environment.

7.3 A New REC architecture for the Integration of Supercaps

The majority of the European buildings consist of multiple units which share common areas. The cluster of the units represents the condominium that manages CSs (e.g., elevators, lighting) and the common areas. A point of connection to the Distribution System Operator provides power to the CSs separately from the private users.

The Fig. 7.13 shows the new architecture proposed for a renewable energy community using supercapacitors. The new PSM consists of several users which are passive towards the grid: in fact they are able to receive just their power demand. A common PV system produces the energy shared among the users and the excess power is injected into the grid by means of the BN, usually represented by the POC of CSs. The energy can flow only from the common generator to the user and never from user to user, therefore the users' inverters run in unidirectional way. The new architecture introduces a double-stage boost converter system, a dc/dc Bidirectional Converter (BC) and a Supercapacitor. The BN is the only active node of the system: in this way the PSM can be applied to existing or new buildings, according to national rules. Each user is provided with a POC to the DSO and a unidirectional inverter that, in full accordance with power sharing rules, feeds the users' load in a democratic way. The users are connected to the common renewable generating system through the Power Sharing Link. The PV system, along with the first boost converter, the bidirectional converter and the supercapacitor represent the new CPSS. Any branch connected to the dc bus and equipped with a boost converter and a VSC, represents a end-user. This boost converter could feed a potential user's dc load. A supervisor manages the PSL splitting among the users the energy generated by the RES.

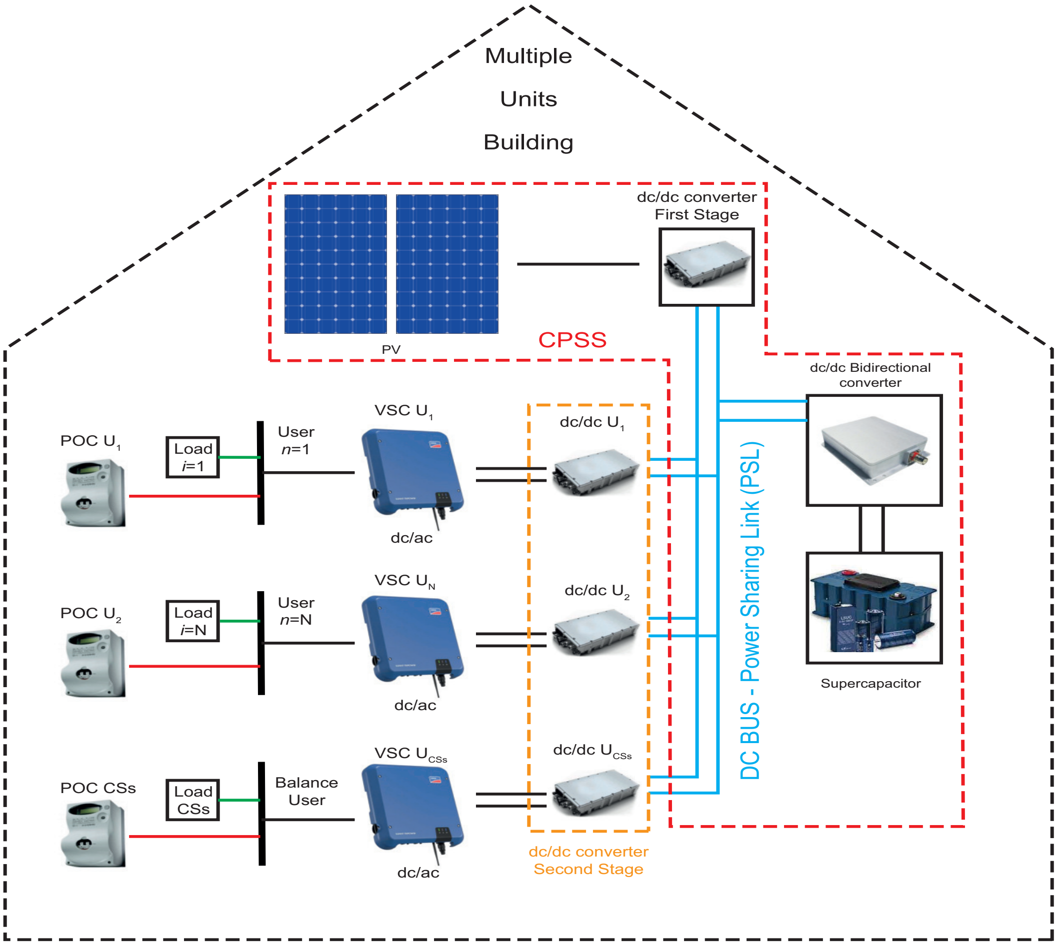


Figure 7.13. Architecture of a REC for Power Sharing

7.4 Results

We investigated the behaviour of several supercapacitor models implemented in Matlab/Simukink environment. The analysis was carried out using the supercapacitors' parameters provided in [206]. The Fig. 7.14 depicts the charge/discharge cycle of a SC, computed by means of the proposed models and tested under variable voltage, showing its hysteretic performance. At the end of the discharge process, the hysteresis results in a residual charge despite the voltage is equal to zero: this is due to the rough and porous structure of the electrode and electrolyte interface in SC.

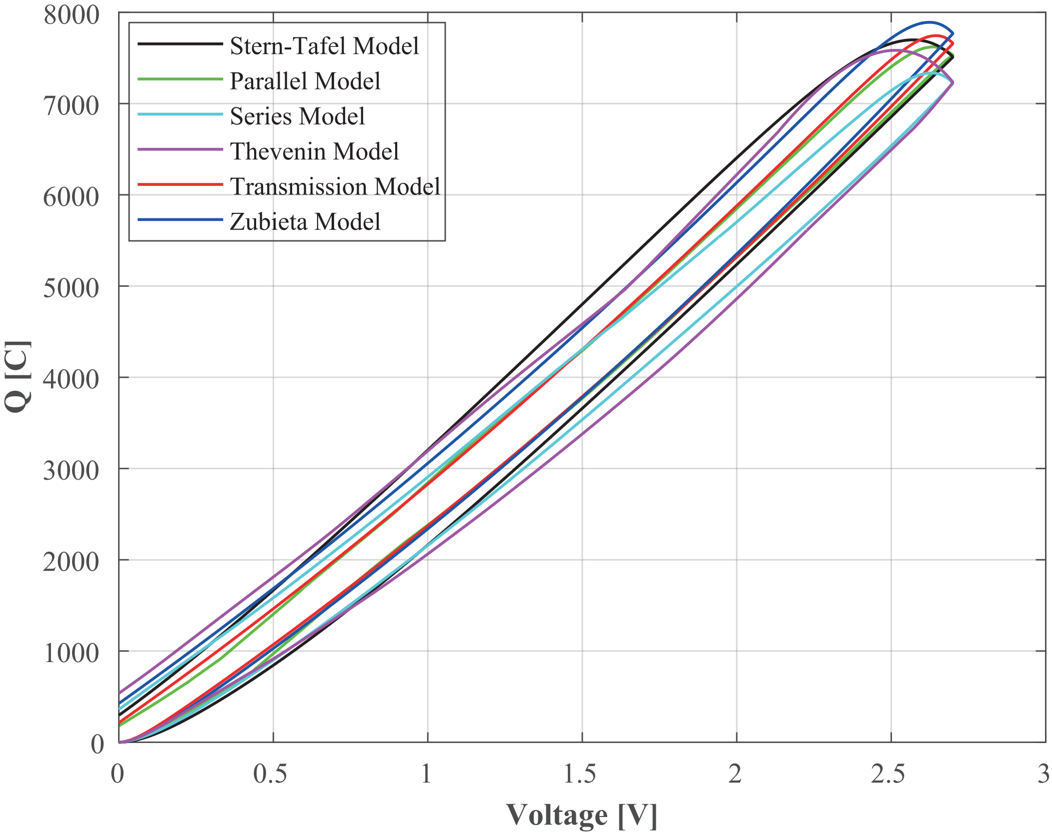


Figure 7.14. Comparison of the charge-discharge cycle among the SC models.

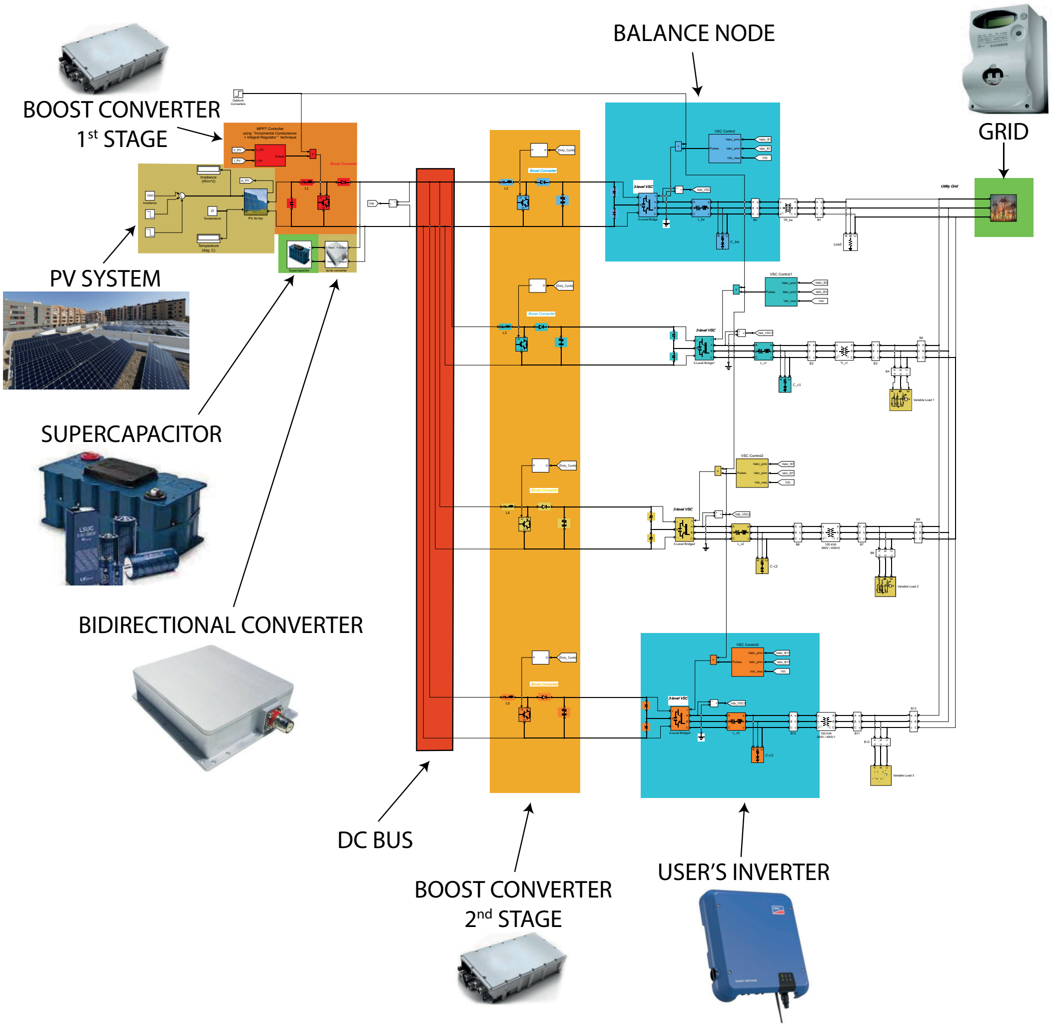


Figure 7.15. Topology of the REC/PSM in Matlab/Simulink environment.

Finally, we carried out a preliminary analysis in Matlab/Simulink software about the integration of a supercapacitor in a REC controlled under the new PSM [198]. The Fig. 7.15 shows the topology of the model consisting of:

- A common PV system with a rated power output of 15.25 kwp;
- A first boost converter that increases the PV output voltage up to 500 V;
- A dc bus where all users are connected through a second boost converter and a unidirectional inverter;
- A BN, the only prosumers represented by the CSs and where is reversed the excess

power produced by the common renewable energy system;

- A SC linked to dc bus by means of a dc/dc bidirectional converter.

Fig. 7.16 shows the time-trend of the dc link voltage under transients with and without the SC. We observe how the use of the SC decreases the dc link voltage overshoot during the start-up transient. Moreover, for abrupt changes in irradiance, the SC keeps the voltage of the dc link at the set-point value.

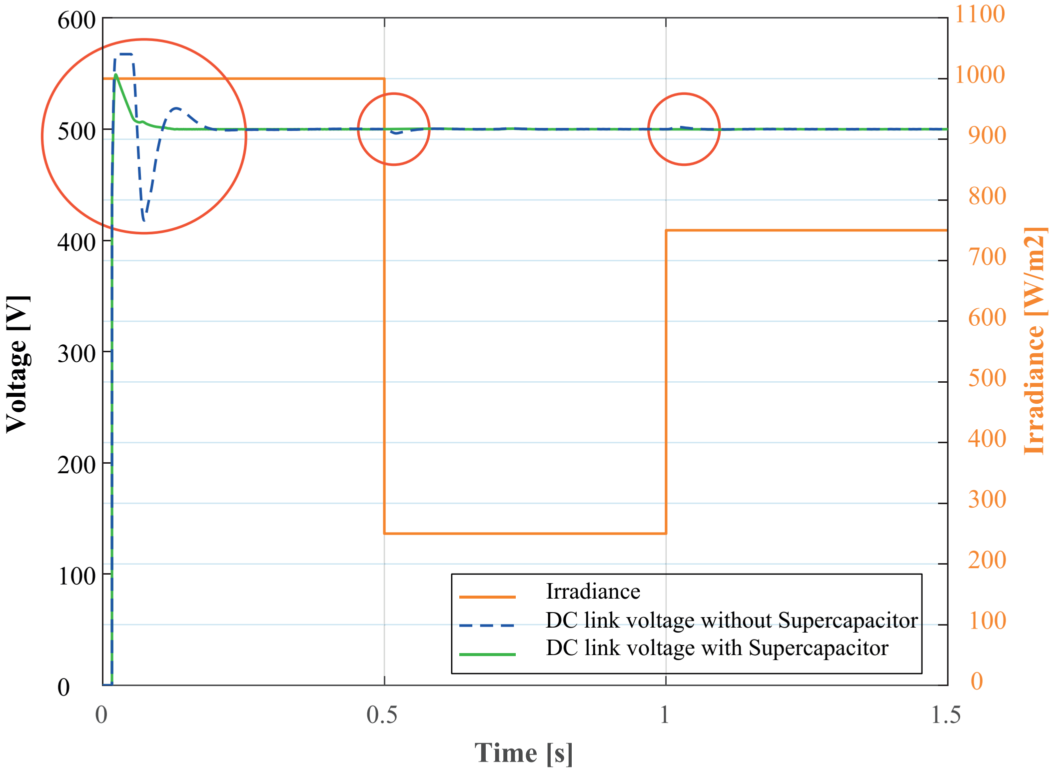


Figure 7.16. DC link voltage for variable irradiance

Chapter 8

Conclusions

European energy policies promote the constitution of ECs at the level of buildings and clusters of buildings as an optimal way towards a clean energy transition. In this new scenario, users play an active and direct role. The ability to integrate common generators into the building systems and share the produced energy respecting national regulatory systems is a key-point of these ECs.

In this work an innovative power-sharing model has been proposed; it is suitable for multi-tenant/user buildings and can be extended to group of buildings. The power-sharing model is directly applicable for both existing and new buildings, regardless of the adopted national regulatory system.

The power-sharing model relies on three distinguishing features:

- the system architecture is based on a common dc bus that is used to deliver the energy produced by the generator to different consumers, with the presence of a balance node used to feed into the grid the in excess produced power;
- the control strategy is based on an equal sharing of the available output energy of the common generator, based on the instantaneous demands of the users and according to the nominal power of the installed inverters;
- the system architecture supports only a unidirectional power flow from the common generators to the users, avoiding any exchange of power among the users and

preventing them from supplying power into the grid, thus complying with any regulation framework.

The control strategy has been deeply investigated and a Matlab/Simulink model has been developed to assess the feasibility of the proposed architecture. The next step was to insert supercapacitors within the proposed architecture. The aggregation of users in RECs allows the sharing of energy produced by common RESs integrated in the buildings. The biggest problem of renewable energy systems is their intermittent operation, reason why they should be coupled with BESS and/or SCs. In this work, we investigated the use of SCs in a REC under the proposed PSM. The SC helps to buffer renewable energies fluctuations and to improve the power quality provided to end-users. We investigated the behaviour of several models of SCs available in literature in the Matlab/Simulink environment and we developed a REC/PSM model to evaluate the feasibility of the proposed architecture. Connecting the supercapacitor to the dc-link required the use of a voltage-controlled bi-directional converter that worked as both a boost converter and a step-down converter. The results shown above demonstrated the effectiveness of the supercapacitor in increasing the stability of the dc-link. The next planned steps will focus on the integration of battery energy systems and electric vehicles, to implement grid-to-vehicle and vehicle-to-grid advanced services. Further research directions will consider the investigation of more advanced converter schemes and the possible evolution towards dc distribution end users' networks.

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