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Voltage Regulation in Smart Grids through Self-Regulating Prosumer Communities

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Abstract

Decentralized electricity production, especially from renewable sources, keeps on expanding its portion of market share in the Italian energy landscape. European directives actively incentivize this trend which is an essential part of the effort for the energy transition. Every citizen with enough initial capital can join this paradigm shift by installing photo-voltaic panels and becoming a prosumer, able to self-consume electricity and sell the excess part.

However, the power grid is a very delicate system and actors that want to interact with it must follow strict regulation which ensures grid security. Moreover, the traditional power grid lacks the infrastructure necessary for handling decentralized generation and may experience malfunctioning under reverse power flows and unexpected voltage violations.

Smart grid technologies promise to solve this issue, and, at the same time, to provide the context for the development of new energy markets, such as peer-to-peer trading.

Currently a central authority, usually the DSO, limits the behavior of prosumers, for example with zonal prices, in order to ensure grid security. Arguably, this centralized control goes in opposition with the European sentiment of a free market and the will to include everyone in the energy transition.

This thesis proposes a decentralized policy for executing grid operations through voluntary price adjustments inside prosumer communities. Members will be able to autonomously change their behavior according to the risk of causing issues in the grid. The objective is to guarantee grid security while increasing the profit of those prosumers who choose to self regulate.

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Chapter 1

Introduction

The power grid is a dynamic and complex system with the function of delivering electricity from power plants to consumers.

Since its initial development in the late 19th century, the power grid has continued to change and to adapt to the different needs of the population, while maintaining its primary objective. The first power plant in Italy (and on continental Europe) was the Centrale Santa Radegonda, built in Milan during the 1883. Its power was mainly used for the city's illumination.

From that moment on, many projects started being developed on the national territory, both from the public and the private sector. Electricity introduced itself in many industrial processes, soon it became a necessity for the industrialization of the nation, as well as for its citizens.

In the post World War II period and during the Italian economic boom, the parliament nationalized the power grid by establishing the Ente Nazionale per l'Energia Elettrica (Enel). Its goal was to allow electricity access to everyone. Huge investments have been injected in the power grid in order to build the required infrastructure, with the consequence of accelerating economic growth even more. Eventually the process had to slow down due to the oil crisis, which saw a fast increase of oil prices followed by extreme inflation.

The power grid of that period has been build following a unidirectional framework. Geographical areas of the grid were meant either for energy production or for energy consumption, and it was assumed that power needed to flow only from the firsts to the seconds. This kind of design is a characteristic of the centralized management of the system.

As the European Union entered the political and economical landscape, a new wave of initiatives promoting the unification of national power grids started taking place. This brought a lot of changes, such as the liberalization process and the will to establish a single electricity market.

The liberalization of the energy market saw a decoupling which allowed private companies to enter production and distribution. Transmission has been kept under the territorial monopoly of Terna S.p.a. with the role of managing the entire system on a higher level of abstraction, while allowing other actors to provide services thought the market. This constituted a very important change in the history of the electric grid, because it increased competition and promoted faster innovation.

The political will of the European Union is to create an European Single Market for electricity. New infrastructure will be needed for increasing cross border capacity, and new regulation will make it possible to integrate national energy markets into a single one.

These changes are revolutionizing the traditional power grid. They are indeed very important, but, arguably, the European resolution for addressing the climate emergency and promoting the energy transition is even more ambitious and impressive.

Europe has set many targets for the reduction of greenhouse gases and the increase of the share of energy produced thanks to renewable sources. By 2050, the whole union is expected to reach carbon neutrality. Phasing out fossil fuels is not an easy task, and the power grid will need to change itself yet again for making this vision a reality.

One of the main changes will regard distributed generation. This phenomenon is characterized by the production of energy in geographical zones that where traditionally intended for energy consumption only. Distributed generation introduces reverse power flows, which the traditional grid is not equipped to handle, and many other related problems which can compromise grid security. This new way of interacting with the grid is the result of both the liberalization of the sector and the development of renewable energy generators which can be built anywhere and by anyone. This trend is expected to increase, in fact, the Europe Union itself is promoting active participation in the power grid.

Part of the effort for the energy transition will be played by a new actor called the "prosumer". Prosumers are all those consumers which have decided to invest in energy generation thus becoming producers as well. The European Union is the main regulatory body for prosumers and prosumers communities. Its directives are implemented at a national level by local governments.

There are two main types of prosumer communities: Renewable Energy Communities and Citizen Energy Communities. They are composed of groups of people, usually located in the proximity of the electric power plant owned by their community, that share energy and potentially sell the excess to the main grid. Prosumer communities have as their main goal the benefit of their own members, and are financed mainly by public investments.

Prosumer communities are able to sell excess electricity while also potentially providing additional services like demand response, which consists in automatically changing consumption patterns according to the current state of the grid.

Smart grid technologies promise to help the integration of active prosumers by making it easier to measure the state of the grid and to allow two-way communication between them and the Distribution System Operator. These new technologies are cheaper than installing traditional equipment, and they provides the foundation for new kind of interaction between the power grid and its users.

Direct communication between prosumers has the potential to enable new ways for exchanging electricity. Peer-to-Peer energy trading is an emerging way to sell and buy energy between grid participants. It works in a similar way as traditional auction systems, but participants are allowed to choose their trading partner autonomously. This system makes it much easier to join the energy market, and may allow much more active participation. However it comes with a lot of challenges. On the economic level, p2p allows anyone to buy and sell at any price. This doesn't integrate well with the wholesale day-ahead market, which establishes a single price of electricity for each zone. On the technical level, the autonomous injection of power at any point in the grid highly increases the difficulty in grid management and the risk of causing faults and possibly blackouts. Moreover the penetration of non dispatchable energy sources (such as photovoltaic panels) reduces overall system inertia and makes the system less stable and less predictable.

P2P risks to become a liability for System Operators, which already need to handle many problems, while it should be an asset instead.

This thesis explores the possibility of trusting prosumers with the ability to autonomously and voluntary regulate their behavior for the benefit of the entire grid. A self regulation mechanism is proposed for limiting voltage violation while providing profits to virtuous actors. A multi agent simulation is used for testing the possibilities and limits of this novel idea.

The objectives of the thesis are:

- To develop a simple model for simulating an isolated prosumer community with internal p2p energy trading
- To implement a self regulation algorithm for the collective management of the grid
- To perform a sensitivity analysis in order to understand the effects on the grid and on the market caused by the adoption of this voluntary policy

After this introductory part, the rest of the thesis is divided in chapters which go into more details and explain terminology and context:

- Chapter 2 - **Distribution Network**, will go more in depth into the history and management of the distribution network. It explains important grid operations, such as frequency control, voltage regulation and line congestion. Finally it introduces the concept of Smart Grids.
- Chapter 3 - **Prosumer Communities** talks about the energy transition, which is the context for this new kind of actors. It then gives some information about their regulation and business models. A few case studies are provided for understanding the current development of this phenomenon
- Chapter 4 - **Energy Markets** delineates both traditional and p2p energy markets. It gives an basic explanation of how energy in managed (and traded) and possible future developments.
- Chapter 5 - **Simulation** details the structure and design of the simulation of the prosumer community used for testing the self regulation algorithm. Relevant pseudo code and optimization problem are shown as well.
- Chapter 6 - **Case Studies** shows the results of the simulation and it interprets their meaning.

Each chapter is divided into sections and subsections. Usually the key information of each part is provided at the beginning in a bullet list. The bibliography reference are all collected in the last pages.

Chapter 2

Distribution Network

2.1 History

- Electrification in Italy began in the late 19th century, with the first regulatory frameworks emerging in the early 20th century, often characterized by mixed private and state-led models.

- The power grid was nationalized in 1962 as a post-war effort to bring electricity to every single household.

- In 1999 the distribution grid was liberalized allowing private companies to manage it and access the electricity market.

- The consequences of liberation are both positive, like an increase in efficiency, and negative, speculation on energy prices. Currently this change is helping the energy transition by allowing people to sell energy generated from renewable sources

The evolution of the distribution network in Italy, and in general of the entire power grid, is a process that involves all aspects of society: industry, law, economics and the general population. It shows how needs have evolved during time, from the first pioneering systems, to the current era of smart grids. If the grid started as a way to bring electricity from point A to point B, now it is becoming a collaborative effort, where individual and structural choices not only affect the market, but the climate and, as a consequence, everyone on this planet as well. This section gives a chronological summary of how the power grid grew over time, while talking about its regulation, and economical aspects.

2.1.1 Early Electrification

The early electrification efforts were promoted by both the private and public sector. Electricity was mainly used in order to power industries and provide illumination to the streets. The first power plant in Italy, which is currently dismantled, was built in the center of Milan during the 1883. It symbolized the beginning of the electrification era, which completely changed society. The role of the government was to assign permits to different industries and create a balance between the needs of the public and those of the industries.

As the electricity sector kept growing, regulatory frameworks became a necessity, both in Italy and in other countries of the European Union. Italy started to license electrification permits by granting monopolies over cities, dividing the territory into well defined areas. Companies had to provide a minimum amount of illumination and satisfy other system reliability requirements. Power plants were often financed by loans and equity emitted by banks. This model helped the growth of electrification, especially in urban centers which saw the first results of this revolution.

The primary forces that created a demand for electricity where industrialization and urbanization. This justified the large investments made by both the government and the banks. Financial incentives included private capital, bonds, and government subsidies, which still persists to this day, even if under different regulation. Italy was one of the first countries to invest in electricity, but the same soon happened in all other European countries as well. [1]

Electrification had a profound effect on all aspects of daily life. On one hand it improved living conditions, increased production (also by extending working hours) and allowed for more security during night. On the other hand it increased the disparities between urban and rural area, and started the process of social stratification which kept growing until our days. Electrical energy is able to generate value at a level far exceeding from that of pre-industrial labor, those who had access to electricity where able to gather much more resources than the rest.

Engineers like Thomas Edison and Galileo Ferraris discovered and developed new application for electricity which allowed for the creation of power plants and distribution systems. The creation of the first high-voltage power lines marked a new step in this process and it required a much tighter regulation because of both the physical risks caused by electricity and the strategic risks that an unregulated national transmission network could have caused to the community. Institutions like ENEA had the responsibility to research the new advancements and create the foundation for new regulation.

2.1.2 Nationalization

During the mid 20th century, Italy began a nationalization process of the power grid. This action was part of the post world war reconstruction. Other countries of Europe followed the same trend towards a centralized planning and public ownership of the infrastructure.

Italy nationalized the electricity sector with the foundation of Ente Nazionale per l'energia Elettrica in 1962. Enel had the monopoly over production, transmission and distribution of electric energy. Other countries in Europe nationalized their electric sector as well, like France with EDF. The trend was to keep the sector under the control of the state, because it was recognized as one of the most important assets. The main goal was to provide electrification to the entire territory, including rural areas, and to support industrial growth. As the European Union started to join the political landscape, thanks to the creation of The European Coal and Steel Community (ECSC) and agreements like the Treaty of Rome (1957) and EURATOM, the electric sector started cross-border interactions as well.

Central planning allowed the movement of large quantities of capital for the investments required in the construction of new infrastructures. Enel invested heavily in the construction of power plants and high-voltage transmission networks. The result was a better exploitation of resources and an efficient delivery to the entire peninsula. This economic model relied on public and private funding, and introduced a lot of liquidity in the economy.

Electrification contributed to Italy's post war recovery. It improved the general quality of life including education, health care and created new economic opportunities. Moreover, the electrification of the rural areas reduced their disparities with the urban counterpart and boosted the agricultural sector as well. The period between 1950s-1960s was called Il miracolo economico Italiano (Italian economic miracle) and the electrification of the country has played a big role in it.

2.1.3 Liberalization

During the late 20th century, the policy framework in Europe regarding the power grid changed completely. What first was seen as a national asset to control centrally, now it was seen as a public market, where different actors can interact and provide services to each others. The reasons for this change are multiple, some of them include an improvement in efficiency, but also a way to reduce national debt. Moreover liberalization is regarded as a step towards an European Single Market for energy.

The EU Electricity Directive 96/92/EC initiated the liberalization process, mandating the separation of generation, transmission, and distribution activities to foster competition. Subsequent directives (2003/54/EC, 2009/72/EC) reinforced these reforms, promoting market access and consumer choice. In Italy, the Bersani Decree (1999) and Letta Decree (2014) implemented these EU mandates, introducing capacity divestitures, unbundling of transport networks, and antitrust measures to limit market dominance by incumbents such as Enel. [2]

Liberalization introduced competition in generation and retail markets, leading to more efficient pricing and investment in new technologies. However, the economic benefits were unevenly distributed. While industrial and commercial consumers gained from lower prices and supplier choice, residential consumers experienced limited price reductions, especially in gas markets. Market concentration remained high, with former monopolists retaining significant market share, leading to oligopolistic conditions and limited consumer switching. [3]

Liberalization altered the relationship between consumers and utilities, introducing choice but also increasing complexity and risk of energy poverty. In Italy, the transition from regulated tariffs to market-based pricing sparked public debate and resistance, with many consumers preferring the security of regulated prices. The liberalization process also highlighted social inequalities, as vulnerable populations struggled with higher energy costs and market volatility. [4]

The Italian market reforms included the introduction of the Day Ahead Market (MGP), adjustment markets, and the role of independent system operators (TSOs/DSOs) like Terna. These reforms aimed to improve market flexibility and renewable integration. [5]

2.1.4 The Modern Era

The climate emergency of the 21st century has set in motion many transformations in all aspects of society and economics. Following this trend, the power grid infrastructure is undergoing a paradigm shift towards a decentralized system, with the inclusion of electricity generation powered by renewable resources.

The European Green Deal and Fit for 55 targets mandate a 55% reduction in greenhouse gas emissions by 2030, with Italy's National Energy and Climate Plan (NECP) outlining renewable energy expansion and grid modernization. Regulatory bodies such as ARERA in Italy and ACER in the EU oversee market functioning and infrastructure development, ensuring compliance with climate and energy security objectives.

Significant investments (e.g., Italy's PNRR) have been allocated to smart grid projects, renewable energy plants, and digital infrastructure to support demand response programs, prosumer communities and other similar initiatives. The economic viability of these projects is supported by subsidies, carbon pricing, and market mechanisms promoting renewable integration. Cities like Milan, Rome, and Turin are leading in infrastructure development and innovation, reflecting Italy's advanced position in smart grid deployment.

The rise of rooftop solar, energy communities, and digital platforms democratizes energy access and participation. Italy is increasing the rate of smart meter installations, enabling detailed billing and time-of-use pricing, fostering consumer engagement and energy conservation. Social programs such as Italy's Bonus Energia aim to alleviate energy poverty, reflecting ongoing efforts to balance market liberalization with social equity.

The 2022 energy crisis, primarily caused by the Russia-Ukraine war, required a fast reactions by Europe and new plans for ensuring a stable source of energy. New regulation promoted energy independence with a focus on self consumption. Technologies like hydrogen and battery storage are being examined as well, and some possible applications have been described. The TIDE reform from the European Union changed the rules of the energy markets for a better integration of alternative energy sources. [6]

2.2 Management

- The The Italian electric distribution network is regulated by ARERA, an independent regulator which sets quality standards, tariffs, and ensures fair competition.

- The distribution network is operated by approximately 140 Distribution System Operators (DSOs). The largest one is owned by the Enel Group.

- Significant investments supported by both Europe and Italy are promoting the modernization of the grid and the development of renewable power plants.

2.2.1 Regulation

The Italian electric distribution network is the final power of the power system, with the role of delivering electricity from substations to the end users. This network is undergoing a rapid transformation driven by the energy transition and the integration of smart grid technologies.

The regulatory framework of the Italian electric distribution network is set by the independent regulator Autorita' di Regolazione per Energia Reti e Ambiente (ARERA). ARERA's role is to manage fair competition in the energy market by setting quality standards, regulating tariffs, and applying national and European law. It protects consumers by monitoring contracts, especially those with dynamic pricing, and it mitigates risks caused by price volatility.

ARERA collaborates with European regulation bodies, such as the Agency for the Cooperation of Energy Regulators (ACER). This allows for direct communication with the Europe Union regulatory framework and it makes it easier to find a way to implement European directive in the context of national law. An example of a directive, which is still being working on, is the Clean Energy Package, which is waiting to be fully implemented because it is facing some resistance from the government.

The Ministero dell'ambiente e della sicurezza energetica and the Ministero delle imprese e del made in Italy complement ARERA's regulatory role by passing emergency decrees and taking a seat in the Italian Parliament. These ministries coordinate with ARERA and local DSOs creating a net of various entities holding stakes in the power grid.

Local authorities include regional governments and municipalities. They are the final layer of the regulation structure and they often act as primary actors in the realization of new projects. Their role is to facilitate the energy transition by applying regulation according to their particular regional contexts.

2.2.2 Ownership

The Italian distribution network is owned by both the private sector, with approximately 140 DSOs, and the public sector. The ENEL Group still manages a large part of the energy market, even after the liberalization of the market. Other significant DSOs are A2A, ACEA and Ireti. New DSOs are emerging which provide energy mainly through renewable sources. They often provide services that help people becoming energy independent as well.

Terna S.p.a, which is the Transmission System Operator (TSO) of Italy, owns the transmission grid and the connection points (substations) with the distribution grid.

The real ownership of the infrastructure is almost never of a single entity, since a lot of it has been created thanks to subsidies. This means that a lot of stakeholders are involved in the ownership and the decision making process. Moreover AREA regulates and sets limits on grid operations in order to maintain a balance between all actors.

While investments in the distribution grid continue to increase, private citizen have the possibility to join the grid and own or manage a fraction of it, thanks to the implementation of prosumer communities. Often they delegate the actual grid operations to a third party which is better suited for such a role.

2.3 Frequency control

- Frequency stability in European grids relies fundamentally on the instantaneous balance between electrical load and generation.
- The main way of producing electricity is through synchronous rotors. Their rotational frequency is directly proportional to the frequency of the current.
- The rotational torque of the generators provides inertia to the system. Inertia slows down the fall of current frequency in the case of failures.
- The transition to inverter-based generators (for example in photovoltaic panels) reduces the inertia of the power grid and makes it more difficult to keep it stable.
- Frequency control is structured in a hierarchical architecture of three levels which restore the nominal frequency over different time scales.

Frequency control is one of the main operations for a Distribution System Operator. The underlining principle is that the frequency of electricity is proportional to the rotational torque of generators. In order to maintain the nominal electricity frequency, which in Europe is 50 Hz, rotors must keep a constant angular velocity. This can be archived when production matches load, and any deviation from this balance will cause and acceleration or deceleration of the rotational frequency. The consequences of a sharp decrease in frequency are widespread blackouts and possible damage to electric appliances. The European Network of Transmission System Operators for Electricity (ENTSO-E) mandates frequency quality standard.

2.3.1 Physical Fundamentals

The stability of the European grid is based on the principle that generation must instantaneously match electrical load. This balance allows the rotational kinetic energy of generators connected to the grid to remain constant. The kinetic energy E_k stored in a rotating mass with moment of inertia J and angular velocity ω is given by:

$$E_k = \frac{1}{2} J \omega^2$$

This energy acts as a temporary reservoir that absorbs or releases power during imbalances, thereby stabilizing the grid frequency. The dynamic behavior of synchronous generators under power imbalances is described by the swing equation:

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e$$

where P_m is the mechanical input power, P_e the electrical output power, and H the inertia constant of the generator. ω_s is connected to the frequency of the rotor and δ to its angle. This equation quantifies how the generator's rotor speed (and hence system frequency) changes in response to power imbalances. The inertia constant H (in MWs/MVA) is a measure of the generator's ability to resist frequency changes and is a key parameter in determining the system's dynamic response.

Inertia is the aggregate rotational kinetic energy stored in all synchronous machines connected to the grid. It provides a natural damping effect against frequency fluctuations caused by sudden load changes or generation trips. Historically, European grids have relied heavily on synchronous generators (e.g., thermal, hydroelectric) that inherently provide inertia. However, the rapid integration of inverter-based renewable energy sources (IBRs) such as wind and solar power, which contribute negligible inertia, has led to a significant reduction in system inertia-from 92% of total generation in 2012 to 79% in 2021, with projections indicating a further decline to 44% by 2030. This reduction increases the grid's vulnerability to frequency instability because the natural buffering effect of inertia is diminished. [7]

The reduced inertia leads to higher rates of change of frequency (RoCoF) following disturbances, increasing the risk of triggering frequency protection devices and potentially causing system splits or blackouts. European regulations now mandate that Transmission System Operators (TSOs) procure inertia as an ancillary service through transparent and market-based mechanisms to maintain grid stability.

Inverter-Based Resources, which dominate renewable energy integration, lack the rotating masses necessary to store kinetic energy and thus do not contribute to system inertia. Their intermittent and variable output further complicates frequency regulation. The European grid must therefore adopt innovative control strategies, such as synthetic inertia from storage systems or grid-forming inverters, to compensate for the declining natural inertia and maintain frequency stability. [8]

2.3.2 Dispatchable Generation

Dispatchable generators are power plants that can adjust their output on demand to balance supply and demand. They include thermal plants (coal, gas, nuclear), hydroelectric dams, gas turbines, and battery storage systems. These generators provide the flexibility and control necessary for frequency regulation by responding to grid operator signals.

In contrast, non-dispatchable generators, such as wind and solar power plants, produce power based on resource availability and cannot be directly controlled to match demand.

Different types of dispatchable generators can be used for matching different kinds of load. The main characteristics of dispatchable generators are start up and response times. Gas turbines can start and reach the desired output within minutes, they are most useful for emergencies and for matching peak load. Coal and nuclear require hours, so they should be used for the base load. Hydroelectric plants provide fast response times as well, but they are limited by external factors such as environmental regulations and the quantity of water available in their reserves. Battery storage is increasingly popular and they are often included in a solar panel installation. It has one of the fastest response times and it can provide synthetic inertia.

Dispatchable generators follow the droop speed control in order to maintain a constant frequency in the grid. As the detected frequency decreases, the rotational torque will increase and viceversa. The relationship that connected them is given by the droop curve, which is constantly updated and sent to each power station. This mechanism allows cooperation without communications.

The following formula shows the linear relationship between the required ΔP necessary to cause a Δf in the electricity frequency.

$$\Delta f = -R\Delta P$$

where R is the droop coefficient and it differs for each power plant. This droop characteristic is a simplified model that allows generators to operate autonomously and it is a required service that they must provide to the grid.

2.3.3 Frequency Response

Frequency response is the name of the procedure that follows a failure in the power grid which causes an imbalance between load and generation. As soon as the system detects it, the execution of a series of steps will guarantee the return to a balanced condition. Fast reaction times are needed to order to avoid a collapse of the electricity frequency (which is caused by the grid imbalance).

Frequency response is divided into three levels.

The first level is the primary control, which has the aim of slowing down the frequency drop. It is also called Inertial Response or Governor Action. The inertia of generators allows them to continue spinning for a few second, thus gaining some time before the secondary control can take action. The Governor Action is performed by local controllers which automatically adjust the turbine speed according to the electricity frequency.

Secondary control, or Automatic Generation Control (AGC), operates on a timeframe of minutes. It is automatic, but it requires the centrialized intervention of the TSO. In order to restore the nominal frequency, the TSO will ask those generators which provide this kind of ancillary service to start up, or shut down. They are called reserves, and are able to react in a very short period of time, but they are not expected to stay online indefinitely.

Tertiary control (Manual Reserve Activation and Economic Dispatch) operates over 15 minutes to hours and focuses on re-establishing reserve margins and optimizing generation schedules. It integrates with the intraday but it may pay more than market price because of the emergency situation. Tertiary control involves manual activation of reserves and economic dispatch of generation resources, including flexibility providers such as demand response and storage. This layer frees the reserves from the work of keeping the frequency constant and allows them to replenish and get ready for a new future imbalance. []

2.3.4 Standards

ENTSO-E's operational guidelines and European Network Codes, such as Commission Regulation (EU) 2017/1485, establish a harmonized regulatory framework for frequency control and electricity balancing across Europe. These codes define frequency quality standards and mandate TSOs to procure balancing services through market-based mechanisms. The framework ensures non-discriminatory access, transparency, and competition in balancing markets, fostering cross-border cooperation and grid stability.

2.4 Grid Management

- Distribution grids are affected by many difficulties such as voltage violations, line congestion, reverse power flow, and electric losses.

- Voltage regulation is managed by both traditional electrical means and smart mechanisms.

- Line congestion can be avoided by optimizing the location of energy production and by building new infrastructure

- Reverse power flow is an increasingly occurring problem caused by decentralized production. Legacy systems were not created with this new dynamic in mind and are vulnerable to faults and may lack protection devices.

- Electric losses cause inefficiencies and economic losses in the grid which can be mitigated by voltage regulation and other means.

Other than frequency violations, distribution networks face many other technical difficulties that may hinder their ability to deliver electricity. Central planning is a way to optimize the status of the grid, usually through a power flow calculation, but it is an available solution only when all generators are owned by one entity. In the current electricity market, the number of actor which are interested in selling electricity, or providing other kind of services, is increasing. This requires a collaborative effort in the management of the distribution grid. Moreover, distributed generation is causing reverse power flows which were not an intended behavior in the design of the classical power grid, and they may require smart grid technologies in order to be properly managed.

2.4.1 Voltage Regulation

Voltage levels inside substation must be kept close to their nominal value. Traditional ways to regulate voltage include tap-changing transformers and capacitor banks. However they were designed for unidirectional power flow and are not sufficient for managing voltage fluctuations caused by power injection from the consumer side of the power grid. Voltage regulation in power grid must consider this new factor and be able to adapt to the intermittent nature of renewable energy sources and other ways to inject electricity in the grid (e.g. electric vehicles). [9]

Smart grids may employ a distributed battery energy storage systems with the ability to inject and store electricity as a way to stabilize voltage fluctuations. Together with distributed production, they can give rise to a unified control strategy for the management of the grid, addressing other problems like congestion and electric losses as well. Another way to control voltage is Voltage/VAR Optimization (VVO). [10] [11]

The steady state voltage drop or rise over an electric line is given by:

$$\Delta V = I(R\cos(\phi) + X\sin(\phi))$$

where I is the current, R and X are the line resistance and reactance, $\cos(\phi)$ is the load power factor and $\sin(\phi)$ is the load reactive factor. Voltage sensitivity to active and reactive power injections is expressed by the partial derivatives $\frac{\delta V}{\delta P}$ and $\frac{\delta V}{\delta Q}$, which can be used in order to change production output for managing voltage. [12]

Inverter-based DERs may employ droop control in order to manage voltage and power output:

$$V = V_0 - k_p P - k_q Q$$

where V_0 is the reference voltage, k_p and k_q are droop coefficients for active and reactive power, respectively. [13]

The standard which defines the voltage characteristics in public distribution systems is defined in EN 50160. It sets the required voltage parameters and quality requirements that distribution system operator must meet when delivering electricity to consumers.

2.4.2 Line Congestion

Distribution lines have a limited capacity for carrying power. Line congestion is defined as a situation where too much power is running through a line. The consequences of line congestion can be limited, as an increase in energy losses, or important, as infrastructural damage. Distributed generation may increase the risk of line congestion because residential line are usually small and they may not have enough capacity for carrying all the power generated from renewable resources to the rest of the grid. [13]

Line congestion affects energy security and it increases costs, thus it needs to be properly managed.

There are multiple ways to avoid line congestion, both technical and economical. Real-time thermal rating (RTTR) is a technique which aims to maximize load without compromising safety. Market re-dispatch can be mandated when a risk of causing congestion is detected in the current configuration. Topology optimization is a type of operation in an active distribution network which allows for the reconfiguration of the grid in order to directly control the power flows over the lines. Other techniques include flexibility markets and demand response. [14]

Smart technologies allow the solution of technical problems without the need to spend a lot of capital in the construction of new infrastructure.

2.4.3 Reverse Power Flow

Traditional grid are designed for delivering electricity from the power plants to the consumers. All infrastructure has been optimized with a unidirectional power flow in mind. Distributed generation can invert this behavior and cause a reverse power flow, going from residential areas back to the generators. This phenomenon may accidentally trigger safety mechanisms and make it harder to manage voltage violation and electric losses.

Bidirectional communication between DERs and the DSO may prevent accidents from happening and increase the protection of the system. Moreover, the deployment of grid forming inverters may make the grid more responsive to reverse power flow. These devices are better equipped than grid following inverters at injecting power from DERs into the power grid.

Other solution include conductors upgrades, or new infrastructure like energy storage.

2.4.4 Electric Losses

Electric losses in the power grid refer to all that energy (usually dissipated through heat) that is lost during the delivery from the generator to the consumer. There are three main kind of variable losses: resistive losses, capacitative losses, and inductive losses. These losses depend on how much current is running through the electric equipment. Transformer as subject to core (fixed) and copper (variable) losses. Harmonic distortions caused by power electronic can increase the amount of losses in transmission.

In smart grid, DERs can reduces losses because they minimize the distance between the generator and the consumer.

Resistive losses are calculated as:

$$P_{loss} = I^2 R$$

Inductive losses are calculated as:

$$P_{loss} = I^2 X_L$$

Capacitative losses are calculated as:

$$P_{loss} = V^2 / X_c$$

In transformers, core losses are calculated as $P_{loss} = V_{rated}^2 / R_{core}$ while copper losses have the same formula as resistive losses.

EU directives with the goal to incentive energy saving focus on limiting electric losses as well, suggesting the use of modern equipment.

2.5 Smart Grid

- The bridge between traditional distribution networks and the new decentralized distribution network consists in the smart grid technologies.
- The Advanced Metering Infrastructure provides a bidirectional communication channel between an household and their utilities company.

- Phasor Measurement Units (PMUs) are usually mounted inside substations and they measure sinusoidal quantities in very short time intervals.
- SCADA systems, which are already implemented as the normal control system of substations, should modernize their software and connect to these new technologies.
- The other side of this digitalization process is cybersecurity threats that are increasingly afflicting the power network

The idea of a decentralized network requires new technologies that can make it real. The power grid is already making an extensive use of digital technologies for managing itself and measuring its state, but the interfaces required for the last mile are missing. In particular households are not equipped for measuring a reverse flow of energy and the last nodes of the network do not have any significant measurement unit, because they have always been considered part of a (almost) static network. Smart grid technologies promise to overcome this challenges and to allow the creation of a more decentralized network where each person can participate in energy production, possibly thanks to a renewable source. There are many products that contribute to this category of technologies, but the main ones are the Advanced Metering Infrastructure (AMI), which allows two way communication between consumers and the network, Demand Response (DR), which is enabled by AMI, Phasor Measurement Units (PMUs), a very precise instruments for reading the state the network, and Supervisory Control and Data Acquisition (SCADA), which is a control system architecture widely used in substations. However by improving the digitalization of the power grid, cybersecurity becomes increasingly relevant as the grid increases its attack surface. [15]

2.5.1 Advanced Metering Infrastructure

The function of the Advanced Metering Infrastructure (AMI) is to support communication between utility companies, final consumers and the DSO. Transmission between all the parties should be secure and truthful, especially from the consumer side, and, in some cases, it should be possible even without the use of internet or other commonly used communication technologies. Thanks to AMI, consumers will be able to adapt their behavior to varying energy prices and avoid excess usage when it is needed. Moreover prosumers will be able to measure how much energy they are introducing in the net.

The main components of the AMI are smart meters, communication networks, protocols, and data analysis systems. Smart meters are able to measure data at each end point of the network, communication networks allow the transmission of data, and data analysis systems, like Data Concentrators, Head-End Systems and Meter Data Management

Systems, aggregate and analyze all data in order to send signals that allow consumers to align the usage with the current state of the market and the grid. Additionally, more data will allow the creation of better demand forecasting algorithms. [16]

AMI presents several possible difficulties. The main one is the cost, replacing all current meters with new ones can be a large expense. And even after the installation of a smart meter, this choice may not show any kind of effect in the short term cause consumers may not have appliances that are able to participate in demand response or to listen to other kinds of signals from the network. Another issue is interoperability between different vendors. There are many protocols that can be used, but the integration between each other may not be immediate. Finally AMI may pose some privacy concerns for the final user, who should always be conscious of how their data is shared.

Demand Response (DR) refers to the ability of consumers to change their consumption according to signal sent by the grid. Smart grids incentivize consumers to adjust electricity usage according to grid or market conditions. DR strategies include price-based, incentive-based, and direct load control approaches, which are possible thanks to real-time communication and automation mechanism installed inside households. [17]

DR programs enhance grid stability by reducing peak demand, which lowers capital costs and defers infrastructure upgrades. They also facilitate the integration of renewable energy resources by coordinating demand with variable supply. AI driven analytics and IoT devices optimize DR by forecasting demand, personalizing incentives, and automating load adjustments. [18]

Successful DR implementations, such as those by PJM Interconnection and the UK's National Grid, demonstrate significant cost savings and improved grid reliability. However, challenges remain in interoperability, consumer privacy, and financial incentivization, which limit participation and effectiveness. [19]

2.5.2 Phasor Measurement Units

Phasor Measurement Units (PMUs) are advanced devices that measure electrical phasors with high precision. A phasor is a complex number denoted by an amplitude A and phase θ and it represents a cosine wave of known frequency ω. Current and voltage are assumed to be phasors because the frequency of electricity should always stay constant for the proper working of the power grid. Each measurement is marked with the timestamp of its reading and they are all synchronized by using the GPS (or via other methods). PMUs provide up to 120 measurements per seconds, which is a far higher rate than what other standard devices are capable of. This level of high resolution can highly decrease the time for assessing faults and can help activate protection schemes.

Wide Area Monitoring System make extensive use of PMU as they improve the observability of large geographical areas which allows for better control and faster reaction times. The standard for PMUs has changed over time. IEEE C37.118 is the currently established one, and it has been revised a few times across the years. PMUs should always follow the latest standard in order to have comparable data.

PMUs are an indispensable part of modern grid control. They provide a continuous measurement of electric phasors which far excess the discrete readings provided by standard devices connected to SCADA systems. They are necessary for the integration of renewable energy sources which main disadvantage is their variable output and impossibility to provide dispatchable generation.

2.5.3 SCADA

Supervisory control and data acquisition (SCADA) is a control system architecture composed of electronic devices, computer, communication networks and graphical user interfaces. They allow operators to control substations and the power network both in real time and under a scheduled plan (usually decided according to the electricity market, or standard procedure following a fault in the network). SCADA connects data acquisition devices, remote terminal units, and programmable logic controller. They collect real-time data, detect faults and react to grid conditions. [20]

Legacy SCADA have been modernizes to IP-based architectures. This allows for better interoperability and integration with other smart grid technologies.

SCADA are divided into 5 levels:

- Level 0: Sensors, actuators and other field devices
- Level 1: Industrialized I/O
- Level 2: Supervisory computer, used for controlling the status of the substation or power plant
- Level 3: Production control level, used for monitoring production level and targets
- Level 4: Production scheduling level

However SCADA systems face several vulnerabilities due to legacy communication protocols that don't always include standard mechanisms for ensuring confidentiality and protection of the systems. Since SCADA networks are physically secured and disconnected from the internet, this may not be an immediate problem, however, as technology improves, new kinds of threat models may require an upgrade for these control systems.

2.5.4 Cybersecurity

The security of the power grid is of top importance. Modernization increases its attack sources and cybersecurity needs to be included in its design in order to defend against potential attackers.

There are different kinds of threat models. The required level of cybersecurity depends on which kind of attack it is even possible to execute. Possible attacks include unauthorized access, data spoofing, and control system compromises. They can be archived with, for example, physical tampering, network-based intrusions, or supply chain attacks. [21] [22]

As the grid gets increasingly more modernized, cybersecurity threats become more important and urgent to address. The most dangerous attackers can be state sponsored actors or internal criminal organizations.

Some element of the power grid may present the following vulnerabilities [23]:

- Lack of protection at the physical layer: An attacker may physically damage components causing outages, or they may tamper with equipment
- Heterogeneous Communication Protocols: Numerous protocols, especially outdated ones, are more difficult to keep secure and they provide a larger attack surface
- Lack of Encryption and Authentication: Plain text communication isn't protected and all data may be intercepted by an attacker that gains access to the network
- Software Weaknesses: Computers used for control may pose the greatest risk to the infrastructure. The risk increases if they are running outdated software and are connected to the internet

Notable incidents include the 2015 Ukraine power grid attack, during the current Russo-Ukrainian War, and the Stuxnet, a computer virus discovered in 2010 which target was specifically the SCADA systems. In an increasingly geopolitically unstable world, this kind of attacks will keep on increasing in number and magnitude.

Some possible counter measures and mitigation measures that can help secure smart grids include technical ones, such as intrusion detection systems, blockchain for data integrity, zero-trust architectures, and anomaly detection systems for the control network, as well as regulatory ones, such as mandating consulence from cybersecurity firms. [24]

As prosumer communities expand, more people will start joining the network and the attack surface will keep on growing. New kinds of attacks may arise which don't target SCADA systems directly, but the network that provides data to them and to other components of the power grid. [25]

Chapter 3

Prosumer communities

3.1 Energy Transition

- The European Union's Renewable Energy Directive (RED III) mandates at least 42.5% renewable in the energy mix by 2030 while aiming for a 45%. [26]
- Italy's National Energy and Climate Plan (NECP) and National Recovery and Resilience Plan (PNRR) commit to follow Europe's directives with the help of large investments. As part of Fit For 55, Italy is expected to produce at least 65% of energy from renewables before 2030.
- Italy's renewable energy capacity keeps on growing, particularly with solar and wind. Renewable energy, as 2023, covers 19.6% of final energy consumption. [27]
- EU and Italian legislation include extensive incentives and regulatory frameworks to accelerate renewable deployment.
- Some challenges still remain especially, in the transport sector, which could see a change as electric vehicles gain in popularity.

As part of the effort to fight against the current climate crisis, Europe is pushing for the adoption of renewable energies, in what is called the Energy transition. The European Union has established a comprehensive legislative and policy framework to drive the shift from fossil fuels to renewable energy sources, which sets legal binding targets for 2030 and 2050. Italy, as one of the main EU members, has aligned its national energy and climate plans with those of Europe, implementing a robust regulation and by investing significant capital in the deployment of renewable energy.

This chapter will first introduce the concept of the energy transition, talking about both Europe and Italy. This will create the context for renewable energy communities, or prosumer communities, which are one of actors that are participating in the energy transition. Three sections will talk about the regulation of prosumer communities, their business model and finally some examples of them will be shown.

3.1.1 European directives

The EU's energy transition is regulated by many directives that describe a progressive phasing out of fossil fuels and an in increase in renewable sources, with the objective to archive climate neutrality by 2050. The year 2030 is set to be an intermediate goal when most of the emissions should have already been eliminated. The European Green Deal, approved in 2020, sets the overarching ambition to reduce net greenhouse gas emissions by at least 55% by 2030 and to reach climate neutrality by 2050. This ambition has become legally binding through several directives which have to be implemented by the member states. The most notably ones are the Renewable Energy Directives (RED II and RED III), the Energy Efficiency Directive, and the REPowerEU Plan. [28]

The Renewable Energy Directive was adopted in 2009, and it confirmed the agreement between state members for the target of 20% renewable energy share in gross final energy consumption by 2020. The directive was recast in 2018 (RED II) and again in 2023 (RED III), raising the 2030 target to at least 42.5% renewable energy share, with a goal of 45%. The 2023 revision introduced new measures to promote the development and deployment of renewable technologies. New investment are allowing the creation of pilot experiments and the construction of new infrastructures. [29]

The Energy Efficiency Directive complements RED by mandating energy savings and efficiency improvements across sectors. Its goal is to reduce the absolute amount of energy consumption while keeping a robust economy. This proposal is further enhanced as part of the REPowerEU Plan, launched in 2022, which responds to geopolitical energy security concerns caused by the Ukrainian-Russian war. By reducing the dependency on Russian fossil fuels, Europe can promote domestic renewable energy production and increase the diversification of the energy market. [30]

The EU is currently on track to meet its 2030 emissions reduction goals, with renewables covering 19.6% of energy consumption in 2023. The EU's strategy includes different targets for each sectors, such as heating and cooling, transport, industry and buildings. Moreover it includes a framework for electric vehicles and smart recharging. Hydrogen and fuels of non-biological origin are included as part of the strategy for sectors where electrification is not yet possible. [31]

The EU's commitment to renewable energy is supported by substantial investments. A vast number of funds provide instruments for the energy transition, such as the European Investment Bank which stopped supporting traditional fossil fuel projects, The European Fund for Strategic Investments, Horizon Europe which will invest around 5.6 billion euros in research and innovation, Just Transition Mechanism with 150 billion euro, The Innovation Fund which aims to create financial incentives for investing in low-carbon technologies, and many others.

3.1.2 Italy's implementation

Italy has transposed EU renewable energy directives into national law and developed policies accordingly in order to facilitate the energy transition. The National Energy and Climate Plan (NECP) and the National Recovery and Resilience Plan (PNRR) are the two main regulatory frameworks of Italy's strategy. [32]

Italy's NECP, submitted in 2019 and then updated in 2024, describes the steps necessary for decarbonization by 2050, with an intermediate target for 2030. The plan requires a phasing out of coal as a source of energy by 2025, and an increase of renewable energy usage to 55% of the total generation of electricity by 2030. Moreover an improvement of energy efficiency across all economic sectors is necessary for a reduction of emissions. The NECP was written considering different factors such as environmental, economic, and social sustainability. Distributed generation and renewable energy communities are the main contributors for this change, together with the electrification of consumption and industrial processes. The plan addresses energy security by diversifying supply sources and modernizing the grid infrastructure. [33]

The PNRR dedicates 39% of its total budget (194.4 billion euro) to archive climate objectives, including renewable energy usage, energy efficiency, and sustainable mobility. [34] The plan supports the development of renewable energies and the circular economy, with improvements in waste and water management. Sustainable mobility includes investments in rail transport electrification and electric vehicles. The PNRR aligns with the EU's REPowerEU initiative to reduce dependence on Russian fossil fuels and accelerate the energy transition.

Italy's NECP and PNRR are aligned with the EU's Fit for 55 package and the European Green Deal. The plans include incentives for renewable energy projects, such as feed-in tariffs and tax credits, and it simplifies regulations for accessing permits. Italy has introduced specific decrees to support the creation and expansion of renewable energy communities, which can be powered by biogas, solar panels and wind farms. [35]

Italy's renewable energy capacity has grown rapidly reaching 74 GW in 2024. Solar photovoltaic (PV) and wind energy have seen the most significant increases, with solar capacity reaching 37 GW and wind 12 GW. Hydroelectric power remains one of the largest and most stable renewable source, delivering up to 19 GW from the 16 GW of 2000. Renewables are now able to meet a substantial part Italy's electricity demand. In fact more than half of the total capacity is provided by renewable sources.

Italy has developed many large-scale renewable energy projects, including onshore wind farms in Apulia, Sardinia, and Basilicata, even if many of them have been blocked by ecological and other kind of concerns. New proposal include technologies such as agrivoltaics and floating solar plants, but they are still in their initial phases. The country is also developing offshore wind farms and green hydrogen initiatives to further diversify its renewable portfolio.

This expansion towards the energy transition is the result of more investments in the renewable energy sector with respect to the fossil fuel industry. The PNRR's Super Bonus 110% and other tax incentives have stimulated investment in the construction of energy efficient buildings and the installtion of renewable energy power plants. As a consequence it created new jobs while supporting the economic recovery post-COVID-19.

Italy has made notable progress in reducing greenhouse gas emissions. They have reached their peak in 2004 with 8.61 tons of CO2 and have decreased until 5.27 in 2023. The country's energy consumption has declined as well. It remained almost constant from 1990 and started declining from 2006. This may be explained by an economic restructuring and energy efficiency improvements. The transport sector is characterized by a slower modernization process. The country isn't very competitive in the adoption of electric vehicles, compared with other members of the EU, and the infrastructure necessary for this change is lagging behind. Especially in the Pianura Padana, traffic is still one of the main causes of air pollution. In order to stay on target for 2030, Italy must continue expanding renewable energy capacity and improve energy efficiency.

3.2 Regulation

- Italy regulation framework for prosumer communities includes the Legislative Decree 199/2021, which implements the EU Directive 2018/2001 (RED II). It defines the Renewable Energy Communities (RECs) and Collective Self-Consumption (CSC).

- More recent national legislation (2022-2024), including the Ministerial Decree 414/2023 and the ARERA Resolution 727/2022, clarify governance, incentives, and grid integration rules.

- Regional governments supplement national law with local regulations and incentives, allowing the creation of different prosumer models (residential, commercial, agricultural, industrial, and others).

- The National Recovery and Resilience Plan provides investments to support energy communities, and it helps the inclusion of vulnerable consumers and small municipalities.

- Despite regulatory progress, some challenges remain for the process of prosumer communities creation, and further social acceptance and education is needed for a faster energy transition.

Prosumer communities in Italy are part of the country's strategy for the energy transition. They consists in citizens or businesses coming together to produce and consume electricity locally, with the possibility to sell it back to the grid. The Italian regulatory framework distinguishes between two main types of prosumer communities: Renewable Energy Communities and Collective Self-Consumption. Other types are available with some changes from their regulation. These frameworks are designed to promote energy democracy and decarbonization, while limiting their actions in order to guarantee grid stability and manage their impact on the main electricity market. [36]

The European directive RED II sets the foundation for Italy's law regarding prosumer communities. It got implemented with the Legislative Decree 199/2021 and its following revisions and extension. The decree defines the conditions under which prosumers can operate. It supports many prosumers models, with different governance types and eligibility criteria per incentives. Moreover it makes a distinction between residential, commercial, agricultural and industrial communities. The decree defines RECs, CSCs and other types of prosumer communities, each with their own particular eligibility criteria, governance models, and economic incentives. [37]

Renewable Energy Communities are a collective entity of citizens based on voluntary participation. They are autonomous and controlled by members or local authorities located in the proximity of the renewable energy projects owned and developed by the community. The objective of RECs is to provide benefits to the community rather than financial profits. The activities of a REC include production, consumption, sharing, storage and sale of energy from renewable sources. REC can interact with the rest of the market directly or through an aggregator. The directive uses the term "proximity" to indicate that members of REC must be located near the power plant that they own or operate. Different countries can transpose this definition according to their own law. [38]

The goal of Citizen Energy Communities is to supply affordable electricity (including but not limited to renewable energy), to their members or associates, rather than focusing on profit. CECs allow their members to became more resilient and participate in the electricity market, from which they might be excluded while acting as individuals. Similarly to the RECs, the purpose of CECs is to satisfy the needs of the community instead of making a profit. The difference is that CECs can produce electricity from traditional sources as well. Moreover CECs must have a limited amount of members, compared to RECs. CECs' members are not required to be in the proximity of their energy sources, and they must not produce energy as their primary economic activity.

The Jointly Acting Renewables Self-Consumers are groups of at least two prosumers located in the same building or multi-apartment block. They are allowed to produce, consume and store energy. They can sell it if that doesn't consists in their primary economic activity. This kind of community allows for a third-party ownership of their power source.

Active Customers are able to function as prosumers, while not being required to be part of a prosumer community.

The last two types of prosumers are not implemented yet by Italian law.

The Ministerial Decree 414/2023 (published in January 2024) further clarifies criteria for suitable areas for renewable energy projects and it sets the rules for accessing incentives from the National Recovery and Resilience Plan (PNRR) and other types of investments. The ARERA Resolution 727/2022 defines technical rules for energy sharing and self-consumption schemes. [39]

The Italian government supports prosumer communities through premium tariffs, paid directly to communities for incentivizing self-consumption, capital grants and tax incentives.

Regulatory ambiguity regarding the exact meaning of some directives and other feasibility concerns can pose some difficulties in the creation of new communities. In particular:

- Proximity Requirements: The definition of "proximity" for community members remains unclear, leading to legal disputes and administrative complexity.

- Economic Viability: Low incentive rates and high upfront costs hinder project development, especially for smaller communities.

- Technical Constraints: The grid infrastructure needs to be modernized by expanding capacity and in installing metering (AMI).

- Administrative Burden: Complex authorization procedures and requirements pose barriers, particularly for grassroots initiatives and individual citizens.

3.3 Business models

- Ownership models include cooperatives, joint ventures, and private collective schemes
- Costs include upfront installation and maintenance.
- Energy bill savings and feed-in tariffs (e.g., Scambio sul Posto) are possible revenue streams.
- Financial mechanisms range from public grants to municipal investments. Communities may ask for crowdfunding and bank loans as well.

Even if the regulations describes prosumer communities as non-profit entities, the choice on whether to join them or not will inevitably depend on profit incentives as well. Being part of a prosumer communities should be less expensive than buying electricity directly from the main grid. Ownership and business models are required in order to determine who is going to receive the benefits of being part of the community and how much. [40]

3.3.1 Ownership

Renewable energy prosumer communities in Italy adopt diverse ownership and governance structures. Each one of them if defined by different decision making processes, and a different balance between risk allocation and revenue distribution. The two main models observed are cooperative-based and joint ventures. [41]

Cooperative-based models are the most prevalent and they often take the legal form of cooperative sociali. These cooperatives are controlled by their member, with profits typically reinvested into the community itself or distributed as dividends. The cooperative structure facilitates a democratic decision making process and shares the risk among the collective. It is a form of community that increases engagement and social cohesion. For instance, the Municipality of Assisi's REC operates under a cooperative framework, enabling clusters of prosumers and consumers to collectively invest and benefit from renewable energy generation. This model emphasizes social and environmental benefits over pure financial returns, aligning with the Italian regulatory framework's goals. [42]

Joint ventures often involve partnerships between citizens, small and medium enterprises, and municipalities. These hybrid ownership models allow for projects of a larger scale because they can access both public and private capital. They may be assisted by experts and receive financing and regulatory support more easily. This kind of model gives less decision power to its members, but it is still a viable solution for archiving carbon neutrality. The choice of ownership model affects how risks are allocated and how revenues are distributed. The objective of a prosumer community can be to reinvest in the community or to have a return on investment. Often times the two objectives can be present at the same time. Cooperatives tend to prioritize social benefits and long-term sustainability. Joint ventures may focus more on financial returns and scalability. [33]

3.3.2 Revenue

Energy bill savings allow members of a prosumer community to spend less money on energy consumption and thus to increase the share of income that they can spend on other activities. Renewable energy is cheaper to produce, since access to solar light or other sources is done locally and doesn't necessitate transport. However the initial investment cost may overwrite future savings. [33]

Feed-in tariffs and premiums provide financial incentives for injecting power into the grid. An example of such incentives are Scambio sul Posto and Ritiro Dedicato. With these contracts, the market operator becomes the only consumer and uses prosumers for energy generation. Since it is the only consumer, it can activate and deactivate their production according to the needs of the grid.

Moreover prosumer communities can provide **Ancillary services**. The most common one is demand response. An alternative is a Virtual Power Plant, which functions in a similar way, but it is more proactive.

3.3.3 Financing

Italian renewable energy prosumer communities employ a variety of financing mechanisms to overcome capital barriers and sustain operations.

Public grants are a primary source, with the Italian government and EU funds (e.g., Horizon 2020 and the National Recovery and Resilience Plan) providing substantial support. The Legislative Decree 199/2021 and Ministerial Decree 414/2023 outline grants covering a sizable part of the initial investment required for REC projects, aimed at small municipalities and citizen initiatives. However these grants require rigorous documentation and compliance which may increase the difficulty in obtaining them.

Crowdfunding is an innovative financing tool that allows everyone to invest a small amount in a project in order to reach the required capital. Platforms such as Produzioni dal Basso facilitate community investment in renewable energy projects. Crowdfunding can aggregate many small investments from a lot of people and follows a different set of regulations. [43]

Bank loans and green bonds are financing instruments which have often been used for providing capital. Ethical banks like Banca Etica provide green financing, which respect sustainability goals. Access to credit is more difficult for smaller communities with limited collateral or financial history.

Third-party ownership and leasing models are another solutions for reducing up-front capital requirements. These models allow communities to avoid large initial investments by leasing equipment or partnering with commercial service providers. This model may reduce the independence of the community, since it would become dependent on the project developer.

3.3.4 Risks

Renewable energy prosumer communities in Italy face several financial risks that affect their profitability and sustainability. [44]

Regulatory uncertainty is a risk because sudden changes in legislation may turn a good financial decision into a bad one. The regulation of prosumer communities isn't well consolidated yet and it may see changes in incentives, tariffs, and grid access rules. Communities must follow complex administrative procedures, and often they need the help of experts in the sector.

Low energy prices in the wholesale market can reduce revenues from feedin tariffs and energy sales, impacting profitability. This risk is mitigated by the premium tariff structure, but it remains a challenge for communities reliant on market-based revenues.

Member dropout and insufficient participation threaten the financial stability of cooperative and collective models. Engaging members and ensuring equitable benefit distribution is critical for maintaining community cohesion and project viability.

Scalability is a challenge due to funding constraints and regulatory limits on project size and grid integration. A project that doesn't scale may not be able to stay active on a long-term.

3.4 Case Studies

- Energy prosumer communities play an important role in Europe's energy transition. They give more choices to citizens regarding their energy consumption and allow them to potentially make a profit.

- Italy is exploring this new territory with a lot of pilot projects and successful self sustained communities.

- The success of prosumer communities depends on community engagement, planning, the correct utilization of local resources and smart technologies.

- Other countries in the rest of Europe are experimenting with prosumer communities as well.

Prosumer communities are composed of individuals or companies that are able to produce electricity as well as consuming it. They are able to sustain themselves for most of their needs, but they can buy and sell energy from and to the main grid as well. They contribute to the European Union objective of energy transition towards a carbon free future. They allow citizen to take control of their energy usage and to create a more decentalized system that is not dependent on fossil fuels. [45]

CANTICO ETS (Comunità assisana per la neutralita' e la transizione inclusiva e condivisa), in the municipality of Assisi, is the first REC in Umbria. It is financed by multiple sectors, citizens, industries, religious entities, associations and local institutions. Its objective is to reduce energy poverty and to guarantee autonomy to its members. It operates as a non profit and it will reinvest its revenue in projects for energy access for people at risk. [46]

The RECOCER Project (Regia Coordinata dei processi di costituzione di Comunità Energetiche Rinnovabili) is a project in Friuli Venezia Giulia spanning 15 municipalities. Its goal is to create the expertise needed for creating and managing CERs. It facilitates the creation of new business models under the framework of Citizen Energy Communities defined in RED-II. It is financed by Horizon Europe and the PNRR. It receives technical support from the Politecnico di Torini and the Energy Center. The main project ended in 2023 with the creation of a CER, but more municipalities have signed for a new project starting in 2025.

the SCORE project (Supporting Consumer Co-Ownership in Renewable Energies) uses Consumer Stock Ownership Plans, inclusive financing techniques and energy efficiency measures for helping consumers becoming active participants. It takes place in Italy, Poland and Czechia. It focuses on more vulnerable people and it addresses gender disparities, income inequalities and lack of access to ICT solutions.

REScoop.eu (Renewable Energy Source Cooperative) is the European federation of renewable energy cooperatives. It advocated for a decentralized and renewable energy system and aggregates many cooperatives in Europe.

Schoonschip is a collective in Amsterdam that emphasizes sustainable living and renewable energy sources. This project demonstrates the benefits of collective energy production and consumption, showcasing a successful implementation of an energy prosumer community. The success of Schoonschip lies in its focus on residential users and the intelligent management of demand and supply, which has led to significant reductions in energy consumption and emissions. The project highlights the importance of community engagement and the role of energy prosumer communities in promoting sustainable development

Compile is an international project that has created 5 pilot studies in Europe for RECs. It focuses on Slovenia, Span, Croatia, Portugal and Greece. It helps the integration of renewable in rural areas and in towns as well. Social cohesion and community is one of the strengths of its projects. Some of them are financed by privates, some from crowd funding, others from the public sector.

The PROSEU project (Prosumers for the Energy Union), funded by the European Union's Horizon 2020 research and innovation program, aims to enable the mainstreaming of the renewable energy prosumer phenomenon into the European Energy Union. This project focuses on collectives of renewable energy prosumers and investigates new business models, market regulations, infrastructural integration, technology scenarios, and energy policies across Europe.

The European Energy Communities Facility is a significant initiative that aims to support the development of energy communities across Europe. This project builds on successful experiences from various European countries and provides funding and technical assistance to help reduce barriers in setting up energy communities. The facility aims to support at least 140 energy communities in developing and implementing solid business plans for their renewable energy projects. The success of this facility can be attributed to its comprehensive approach, which includes providing technical assistance, training, and capacity building to local initiatives, thereby promoting a bottom-up approach to the energy transition

Chapter 4

Energy Markets

- The Italian electricity market is structured around a day-ahead market (MGP), intraday market (MI), and ancillary services markets, all managed by Gestore dei Mercati Energetici (GME).
- Italy's day-ahead market used to have a uniform national price (PUN) which has been phased out this year (2025) in order to align with the standards of the European market.
- The intraday market operates continuous trading sessions integrated with the European Single Intraday Coupling (SIDC) via the XBID platform, which enables cross-border trading.
- Ancillary services provides vital functions to the grid, especially in the case of malfunctions. New technologies involve demand response and electricity storage.
- The regulatory framework is led by ARERA, implementing EU directives and national legislation.

The Italian electricity market is characterized by a complex interplay of market mechanisms, regulatory frameworks, and different actors. Since the market liberalization, initiated in 1999, Italy has progressively allowed the private sector to provide services and manage the power grid. This liberalization effort stems from European directives, and one of their objective is to go beyond national borders and to create a single European market. Italy is following this path by integrating its electricity market with European neighbors through market coupling and crossborder trading. The Italian electricity market, along with other energy markets in Europe, will soon be part of the European Single Electricity Market.

The Gestore dei Mercati Energetici (GME), established in 1999, acts as the market operator responsible for managing electricity market alongside other energy markets. Market participants submit their bids indicating the quantity of electricity they are willing to buy or sell and at what price. GME aggregates these bids and determines the market-clearing price and quantities of electricity traded.

4.1 Traditional Energy Markets

4.1.1 Day-Market Market

Il Mercato del Giorno Prima (Day-Ahead market) is a wholesale market for trading energy the day before the physical consumption. Producers and consumers send offers according to their forecasts, setting a price limit and a power limit. The market operator aggregates the offers and sets the price of energy for the entire day accordingly. [47]

In the MGP, each day has a set energy price and it is the same for all participants. Until 2025, the entire country of Italy was sharing the same price, called Prezzo Unico Nazionale (PUN). A new decree, which follows directives from the European Union, has phased out the PUN in favor of zonal prices. This new approach may increase the competition between different kind of producers and eventually help the energy transition.

The market operator decides the price for the next day at the end of the MGP auction. The market clearing price is set to the intersection between the cumulative supply and demand curves. This approach minimizes marginal utility and marginal profit. The final price could be set a little lower than the optimal one, in order to allow more market liquidity in the Infra-day Market.

The ENTSO-E promotes guidelines and projects for managing national energy markets, while promoting steps towards unification. The Capacity Allocation and Congestion Management (CACM) is a set of guidelines set by the ENTSO-E that regulates cross border markets. It sets, among other policies, the maximum capacity that cross border lines can have in order to not compromise the European power grid security. The Single Day Ahead Coupling is an effort to create a single pan European day-ahead market. Opening the markets promotes competition and better compliance with European guidelines.

4.1.2 Intraday Market

Il Mercato Infragiornaliero (Intraday market) enables market participants to adjust their positions in real-time, managing forecast errors, especially from renewable energy sources, and balancing supply and demand fluctuations within the day. The market operates through three MI-A auction session and one MI-XBID continuous trading session, allowing participants to buy and sell electricity for delivery on the same day.

The three MI-A trading sessions are distributed throughout the day, and accept bids and offers. At the same time interconnection capacity is allocated between Italian and other geographic zones. The continuous MI-XBID trading sessions follows similar rules to MI-A and it is divided into three phases. All phases of MI-A and MI-XBID do not overlap with each others. This structure enables market participants to respond dynamically to changing conditions, such as renewable energy output variability or unexpected shifts in demand.

GME manages the intraday market in Italy, facilitating continuous trading and ensuring market transparency and integrity. Additionally, Italy participates in the European Single Intraday Coupling (SIDC) which integrates intraday markets across European countries.

The prices in the intraday market are determined by the current supply and demand of electricity. They fluctuate during the continuous trading session and can differ from the price set the day before in the day-ahead market. There are many factors that require a new negotiation of energy, they are generation failures, unexpected demand changes, environmental influences over energy production. In order to meet the real-time needs of the power grid, a large number of actors is required in the intraday market. Participants include, among others, producers, load aggregator, ancillary services providers and Balance Responsible Parties (BRPs). [48]

Italy's intraday market uses the XBID platform for cross border trading with other European countries. Its trading capacity is limited by the maximum capacity set by Terna and other TSO.

4.1.3 Ancillary Markets

Ancillary services are essential for maintaining grid stability and reliability. These services are divided into two main groups depending on whether they are related to frequency regulation or not. Those related to the frequency are: inertia, primary frequency control and secondary frequency control. An example of the last two is, respectively, Frequency Containment Reserve and Frequency Restoration Reserve. These reserves must be ready to get activated when needed and they can be used for this purpose only. Other services include: reactive power control, voltage control, congestion management, system restart, scheduling and dispatch, loss compensation, load following and system protection.

Ancillary services are provided through the Ancillary Service Market, in Italian "Mercato dei Servizi di Dispacciamento" (MSD) and they give the tools to the TSO, Terna

S.p.a in Italy, to manage the network.

The MSD is divided into two phases: MSD ex-ante and Mercato del Bilanciamento (MB). In the first phase Terna verifies the results of the MGP and MI and set the required reserves for handling possible problems in the network. In the second phase operators can resubmit offers and bids in order to meet those expectations.

Ancillary markets include demand response programs and electricity storage services which can help in lowering peak demand and storing excess energy. They provide flexibility to the market with fast response times. Storage batteries are usually deployed near distributed renewable generators as they can provide synthetic inertia as well. [49]

Some services are expected to be provided by producers as a part of being able to trade in the market, and they are not remunerated. They include the Primary Frequency Reserve and the Voltage Regulation.

ARERA sets regulatory frameworks ensuring that ancillary service providers meet technical and operational standards. Compliance is monitored through reporting and enforcement mechanisms, with penalties for non-compliance.

4.1.4 Regulation

The Italian Regulatory Authority for Energy, Networks and Environment (ARERA) is the primary regulator overseeing the electricity market. ARERA ensures market transparency, competition, and compliance with national and EU regulations. Its role is to set tariffs, monitoring market behavior, and enforcing rules to prevent market manipulations.

The Italian Competition Authority, Autorita' Garante della Concorrenza del Mercato (AGCM) works alongside ARERA to ensure competitive market conditions, investigating anti-competitive behavior and enforcing competition law.

Italy's electricity market is designed by national legislation such as Legislative Decree 79/1999 (Bersani Decree), which initiated market liberalization, and subsequent decrees that mandated the separation of markets, i.e. unbundling. EU directives, including Directive (EU) 2019/944 and the Clean Energy Package, provide the overarching framework for market integration, renewable energy promotion, and consumer protection.

ARERA supports the deployment of renewable energy power plants by regulating many mechanisms, such as feed-in tariffs and access to financial incentives. The goal of this policies is to increase the share of renewable energy production up to 42.5% by 2030. This target is set by European directives and adopted by Italy.

ARERA and AGCM jointly monitor the market for compliance with regulations, including penalties for market manipulation and non-compliance.

Another important regulator is Gestore dei Mercati Energetici (GME) which operates in the Italian Power Exchange (IPEX), managing day-ahead and intraday markets. GME ensures market neutrality, transparency, and compliance with regulatory requirements. Terna S.p.A., the TSO, manages the transmission grid and ancillary services markets, ensuring system balance and grid stability.

Major utility companies such as Enel, Eni, A2A, and Edison dominate generation and supply. [50] These companies are vertically integrated and are the most known and trusted in both generation and retail sectors. Independent power producers and renewable energy operators are expanding and contributing to an increase in diversity in the market.

Balance Responsible Parties are a new figure in the electricity market, introduced by the 2025 TIDE regulation. Their role is to ensure system balance by managing imbalances between generation and demand. Consumers range from large industrial users to residential customers, with prosumers and renewable energy communities emerging as new actors able to act on both sides of production and generation, while increasing their own independence.

4.1.5 Future Trends

The deployment of distributed energy resources is transforming the power grid and the electricity market. It poses challenges to the security of the network, but it promotes the creation of new services and the energy transition. The market and the grid must evolve in order to accommodate distributed generation while preventing blackouts and lowering costs.

Smart grid technology allows for the existence of ancillary services like energy storage and demand response. They are usually provided by prosumers, or conscious consumers, and can help the function of the grid. Moreover they can work as Virtual Power Plants when their efforts are coordinated by an aggregator. [51]

Market coupling platforms, such as XBID, allow cross-border trading and capacity allocation, promoting market integration and liquidity. Some possible challenges remain in harmonizing national pricing mechanisms with European market practices. [52]

Italy will phase out coal-powered generation by 2025 and it will reduce its gas dependence. This transition requires regulatory support and a lot of investments, but it is necessary for aligning with EU's decarbonization goals.

Digital technologies and AI-driven demand forecasting have the potential to improve market operations, by increasing the accuracy of demand and supply predictions, and automating grid management. These technologies can help planning production during negotiations in the MGP.

Regulatory frameworks will need to include measures for protecting vulnerable families from energy poverty and market speculation, and ensuring an equitable access to electricity.

4.2 Peer to Peer Market

- The European P2P energy market is growing rapidly, driven by EU directives such as RED II and the Electricity Market Directive, which promote decentralized energy trading and the integration of renewable energy production.
- Blockchain, smart contracts, AI, and IoT are the technologies that will facilitate the adoption of P2P energy trading across Europe.
- Regulation remains a significant barrier, but it is necessary for ensuring grid stability. Different EU member states show varying levels of maturity across the continent.
- Italy, together with other countries, is hosting pilot projects with the potential to introduce this framework to the general population.

Peer-to-peer (P2P) energy trading is a model that enables direct energy exchanges between all actors of the energy market, with limited intervention from a central authority. This paradigm is part of Europe's strategy for the energy transition. Regulations are designing how such markets should behave and interact with the rest of the grid and energy markets. Pilot projects are being deployed for investigating the limits and possibilities of this new approach. [53]

The European regulatory framework for peer-to-peer energy trading is set by the Clean Energy for All Europeans package and the two directives: Renewable Energy Directive (RED II) and the Electricity Market Directive. They define P2P energy trading as the direct exchange of energy between two members of the market via contracts with predetermined conditions and with automated execution and settlement. This EU framework promotes prosumer communities and decentralized production. EU is running many pilot project and financing energy start up in order to explore what it is possible to create under this new regulations.

The adoption of this kind of market varies widely across member states, and it is slowly gathering market participants. More social education is needed in order to change the idea of energy from a passive subscription service to an active and continuous choice.

P2P trading follow different market designs. It can be part of bilateral contracts, auction-based models and cooperative frameworks. Bilateral contracts are signed directly between two participants. They tend to be more long term and may be less transparent than other solutions. Auction-based models use competitive bidding among all members and require regulation in order to prevent manipulation. Cooperative models prioritize the community that hosts the market, but may limit the choices of their members. [54]

The blockchain is one of the main technologies that support P2P trading. It records transactions and supports smart contracts. Physical technologies such as AMI are essential as well. [55]

Blockchain is not the only technology able to keep track of exchanges in a P2P market, but it is a good choice that provides no single point of failure and shared consensus instead of centralized control. Moreover, blockchains are immutable and freely available. If, on one hand, this increases the transparency of the market, on the other, it may also make it more difficult to protect the privacy of the participants. Smart contracts automate energy trading and may be used to process information without disclosing sensitive data.

AI and machine learning can be used in order to create a forecast of the production and the demand. These algorithms work as brokers inside the P2P market.

Since P2P markets are still in their infancy, a lot of work is being done in order to simulate their behavior. Different approaches exists such as game theory and multi agent simulations.

Developing efficient market agents that can represent their users and, possibly, develop trading strategy is another aspect of the research. The most common approach is to use reinforcement leaning.

It is difficult to find P2P project because that definition is not well know by the public, so they often don't use it for describing their product. Some successful examples include Piclo and the the Brooklyn Microgrid. [56]

Piclo operates in USA, Europe and Australia. It is a P2P platform that connect flexibility seller to buyer. Its clients include Octupus Energy, Enel X, E-Distribuzione and others.

The Brooklyn Microgrid is a P2P platform in New York. It connects prosumer and consumers in a microgrid ecosystem. It is able to interface with EV too, and lets them buy and sell electricity as long as they are connected to the grid. The DSO can manage the grid using price adjustments and other operations like demand response.

Chapter 5

Simulation

- P2P trading allows prosumer to exchange electricity with each others without the a centralized authority and, possibly, in rest of the power grid.
- However problems like over voltage or line congestion need coordination in order to be solved. In traditional markets, a single operator has responsibility over grid security.
- This chapter proposes a policy that allows prosumers to self regulate their behavior and manage the network in a decentralized way while maximizing their profits.
- A multi-agent simulation provides the framework for researching the limits and the possibilities of such regulation.

The global energy landscape is undergoing a shift towards decentralization, driven by the proliferation of DERs and the emergence of prosumers communities. This transition introduces both opportunities and challenges. P2P energy trading systems allow prosumers to interact with the grid in new ways, for example by trading directly with other peers. P2P reduces the reliance on the main grid and increases local energy consumption. However, the inherent unpredictability and variability of renewable energy generation can destabilize the grid, particularly because of issues such as over voltage. The lack of a centralize control in pure p2p systems may make it harder to mitigate these problems. Traditional centralized control mechanisms follow a top-down framework for grid management, they are a robust system for ensuring grid stability, but they struggle to integrate individual prosumer choices in their system.

This thesis proposes a simulation that models the behavior of a prosumer community through a multi agent simulation (MAS). MASs are a powerful tool for modeling complex system. They work thanks to the interaction on autonomous agents. In this simulation, each agent represents a prosumers with their own priorities and decision-making algorithm. They are able to meet their energy needs while dynamically adjusting their behavior following grid conditions and market signals.

The objectives of the simulation are:

- To model a decentralized P2P energy market in an isolated prosumer community.
- To implement a voluntary self regulating pricing mechanism that automatically adjust the buy/sell prices of prosumers based on the probability to cause grid instability (e.g., over voltage risks).
- To analyze the impact of different percentages of self regulated prosumers on the grid (i.e. over voltage occurrences) while comparing their trading success with not self regulated prosumers.

5.1 Framework

The following framework defines the roles of the simulation and their interactions:

- Prosumers: Autonomous entities that both consume and produce energy (e.g., with solar panels). They participate in the P2P market by submitting buy/sell orders and dynamically adjusting their prices according to the grid condition. Their primary objective is profit maximization, but they may also prioritize grid stability if incentivized. Prosumers act as rational, utility-maximizing agents. Their electricity behavior is defined by generation, consumption and self consumption.
- Market Operator: This entity aggregates the offers sent by the prosumers and adjusts their prices according to their preferences. Its responsibility is to ensure market transparency and fairness. Its role is necessary in order to protect the privacy of prosumers and the confidentiality of grid data. In a scenario where prosumers have direct access to all grid data, then they will not need the MO as a role.
- Distribution System Operator: The DSO has the responsibility of maintaining grid stability. It exchanges information with the market operator, which, from the point of view of the DSO, becomes a load aggregator. It doesn't control market prices directly, but it sends feedbacks and signal to the market operator that indicate when certain trades have the risk to cause issues in the distribution grid

The interactions between roles are illustrated in Figure 5.1, which shows the flow of information (price signals, grid status) between the different actors.

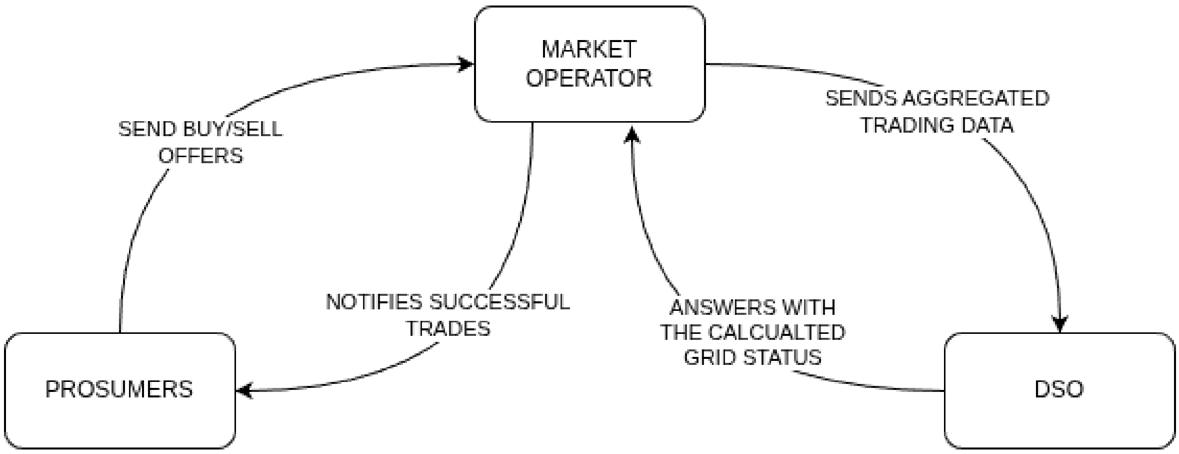

Figure 5.1: Simulation Framework

5.2 Multi Agent System

The simulation employs a MAS system to model the prosumer community, where each agent represents a prosumer. An agent is defined by the following attributes:

- Net power to be exchanged: This parameter represents the difference between generated power and consumed power. It is assumed that prosumers will always choose to self consume electricity when they have the possibility. If it is positive, then the agent is acting as a seller, otherwise it is acting as a buyer. This value is set to a random variable with a gaussian p.d.f. and mean zero. Its standard deviation remain constant during the entire simulation. At each time step the agent will start with a new value for this parameter.

- Trading Strategy: Rules for increasing or decreasing its buy and sell price according to the success of previous trades. The strategy depends on a power threshold parameter P_{thres}.

- Self regulation status: At the start of the simulation a certain percentage of prosumers will be set to follow the self regulation algorithm. The community will be divided into SRPs (self regulating prosumers) and NSRPs (not self regulating prosumers).

Optimization model 5.1 describes the global behavior of the prosumer community. It accounts for the offer matching made by the market operator and the self regulation algorithm (or lack of) adopted by the prosumers.

$$
\begin{aligned}
\max \quad & \sum_{i=1}^{N}\sum_{j=1}^{N} P_{i,j} \\
\text{s.t.} \quad & Q_{i,j}^{sell} \leq Q_{i,j}^{buy} && \forall_{i,j} \\
& Q_{i,j}^{sell} = K_i^{sell} P_{i,j} + R_i V_{i,j} && \forall_{i,j} \\
& Q_{i,j}^{buy} = K_j^{buy} P_{i,j} - R_j V_{i,j} && \forall_{i,j}
\end{aligned}
\tag{5.1}
$$

$P_{i,j}$ is the amount of power sold by prosumer i to prosumer j. $Q_{i,j}^{sell}$ is the minimum price that prosumer i is willing to accept from j for $P_{i,j}$, $Q_{i,j}^{buy}$ is the maximum price that prosumer j is willing to pay to j for $P_{i,j}$. K_i^{sell} is the base unit sell price for i, K_j^{buy} is the base unit buy price for j. $V_{i,j}$ is the signal used by the market operator to indicate that the exchange characterized by $P_{i,j}$ has a risk of causing grid instability. R_i can assume values 1 or 0, depending on whether the prosumer adjusting the price for the exchange $P_{i,j}$ or not.

Algorithm 1 describes how offers between agents are matched in the simulation.

Algorithm 1 Algorithm for offers matching

Require: $P \leftarrow$ Net power vector to be exchanged
Require: $K_{sell} \leftarrow$ Unit sell price vector
Require: $K_{buy} \leftarrow$ Unit buy price vector
Require: $R \leftarrow$ Self regulation status vector
while It is still possible to make exchanges **do**
  $i \leftarrow$ A randomly selected agent
  $N \leftarrow$ Neighborhood of i
  $V_{i,N} \leftarrow$ Signal indicating risk of over voltage per each exchange
  $P_{i,N} \leftarrow min(|P_i|,|P_N|)$
  if i is a seller **then**
    $Q_{i,N}^{sell} \leftarrow K_i^{sell} P_{i,N}$
    $Q_{i,N}^{buy} \leftarrow K_N^{buy} P_{i,N} - R_i V_{N,i}$
    $j \leftarrow$ Neighbor with highest $Q_{i,j}^{buy} \geq Q_{i,j}^{sell}$
    Accept exchange (i, j)
  else
    $Q_{N,i}^{sell} \leftarrow K_N^{sell} P_{N,i} + R_i V_{i,N}$
    $Q_{N,i}^{buy} \leftarrow K_i^{buy} P_{N,i}$
    $j \leftarrow$ Neighbor with lowest $Q_{j,i}^{sell} \leq Q_{j,i}^{buy}$
    Accept exchange (j, i)
  end if
  Update P
end while

Parameter R is 1 or 0 depending on whether the neighboring agent is a SRP or a

NSRP. The algorithm shows that only agents that are sending an offer adjust their limit price.

The Algorithm 2 describes how prosumers update their unit prices after each time step

Algorithm 2 Pseudo code for adjusting prices

Require: $P \leftarrow$Desired net power injection vector
Require: $N \leftarrow$ Net power injection vector from market clearing
$M \leftarrow (P - N)/P$
$C \leftarrow G(M - P_{thres})/(1 - P_{thres})$
$K_S^{sell} \leftarrow K_S^{sell} + C_S$
$K_B^{buy} \leftarrow K_B^{buy} - C_B$

C is a vector of realizations of a gaussian random variable multiplied by a factor that is zero when $M = P_{thres}$, positive when $M > P_{thres}$ and negative when $M < P_{thres}$. P_{thres} is the percentage power that each prosumer want to match as a minimum in the market phase.

5.3 Self Regulation Algorithm

Algorithm 1 showed a high level description of the Self Regulation Algorithm during a market time step. Algorithm 3 goes into more details about how the self regulation algorithm works while the agents decides who to exchange with:

Algorithm 3 Self regulation algorithm

Require: $i \leftarrow$ agent that is looking for an exchange
Require: $N \leftarrow$ Vector of offers from the neighbor of i
Require: $Q \leftarrow$ Vector of unit prices of i (initially all set to the same value)
Require: $P \leftarrow$ Net power vector to be exchanged with the neighbors
$j \leftarrow$ index of offer with most convenient unit price in N
while N_j is acceptable **do**
    if offer N_j was already evaluated by the market operator **then**
        Choose offer N_j and exit
    else
        Ask the market operator to evaluate the possible exchange N_j
        $V \leftarrow$ Signal received from market operator
        Receive updated N_j according to V
    end if
    $j \leftarrow$ index of offer with most convenient unit price in N
end while

5.4 Simulation Environment

The simulation models an isolated prosumer community spanning 14 buses. It consists in 100 prosumers distributed over 13 buses, the 14th one is the reference bus. The goal of the simulation is to test the algorithm for a self sufficient community in islanding conditions. No power is inject or retrieved from the reference bus.

Each prosumer is equipped with a photovoltaic panel and they participate in an auction market similar to the Infra-day market. They send buy/sell offers to the market operator according to their current needs and possibilities.

The distribution network is simulated with a statistical model. Each power flow calculation return an over voltage at one or more buses half of the times. The amplitude of the violations is set to a gaussian random variable with a given standard deviation. A synthetic network may make the simulation less realistic. However, by doing so, it removes any topological effect that the real network could have had on the simulation itself. Additionally a statistical model is way faster to run than computing the full power flow of a power grid. In a real-life feasibility evaluation, true network data should be used.

Generation and consumption data is synthetically realized before each time step from a random variable, as explained in the previous chapter. Time steps start with the definition of offers. Afterwards the market operator will aggregate and match them. At the end of the timestep prosumers will adjust their prices according to the results from the market. Offers will be valid for the duration of a single timestep.

Before starting each following timestep, relevant measurements are collected for generating the metrics explained in the next chapter.

5.5 Supplementary work

In order to archive a sufficient result for the simulation, different paths have been explored.

Power Flow Calculations Regarding the power flow calculations, an initial surrogate model has been developed in order to predict the p.f. results within an acceptable error. The surrogate model calculates the value of the voltages at each bus by taking the weighted mean of the power flows results from the closest k known grid configuration. Distance between grid configurations is defined as the MSE between their power injections. The inverse of the distance is used as a weight.

A dataset of grid configuration and p.f. results have been produced by running p.f. calculations with synthetic data within the minimum and maximum power injections that each bus can experience during the simulation. It was divided into a training set and a test set in order to test the model.

This surrogate model has been rejected because it wasn't running fast enough for an acceptable simulation time.

Self Regulation algorithm with memory A more advanced SR algorithm was initially designed. The adjustment of the price followed the formula:

$$Q = KP \pm R(V + M)$$

where M was a malus valued stored in the memory of the agent. After a voltage violation causing exchange, the two agents that agreed on it would have received a malus value from the other SRPs proportional to the amount of violation. The malus were cumulative, and at each time step they would slowly decreasing until zero.

This strategy was thought for a more distributed regulation which was able to account for all exchanges within the grid, not only the current ones.

Unfortunately this control mechanism wasn't able to produce any measurable difference from its absence, so it was removed from the simulation.

Visualization dashboard While the simulation is written is Julia, a, interactive dashboard written in Python was used for visualizing the results. It was a convenience tool able to use the results of the simulation an provide insights into which regulations were working or not, and for fine tuning the parameters.

Chapter 6

Case Studies

Two main case studies have been analyzed. The difference between them is the standard deviation of the gaussian random variable used for generating the net power injection of each prosumer.

Figure 6.1 shows the production curve of photovoltaic systems and the load curve of the power grid for the 17th of August 2024, in the entire country of Italy. The production curve is bell shaped and it follows the cyclical amount of light received from the sun. The load curve has a minimum around 5:00 in the morning and a maximum around 20:00 in the evening. This difference of shape generates two different scenarios, one where the consumed power is similar to the produced power (CS1), and one where it is higher (CS2).

The two case studies (which model the two scenarios described above) consist in a sequence of statistically independent time steps with synthetic generation and consumption data. This choice removes any individuality from prosumers. Moreover it is assumed that most of the energy trading is being done in the Day-ahead market, thus the trading in the

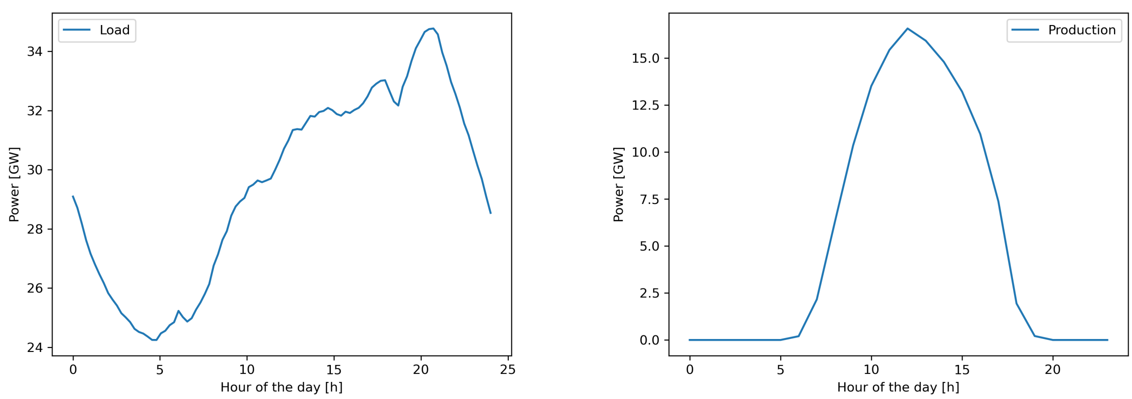

Figure 6.1: Load and Production curves. Data from Terna (17/08/24)

Infra-day market can be accounted as a small gaussian disturbance from the forecasted load and generation.

The results shown are the average of 30 simulations, run for 600 steps. Each curve is smoothed by using a rolling average with a window of 10 steps. Averaging across different simulations removes the peculiarities of a single run and shows general trends. For each case study, the proportion of self-regulating prosumers varies in percentage (25%, 50%, 75% and 85%). The community is isolated with no external grid interaction, thus forcing the prosumers to rely on self-produced electricity only. In a more realistic scenario, it is expected that they will try to meet their power demands by first exchanging with their neighbors, and only then by exchanging with the main grid. This assumption is supported by the fact that usually the cost of electricity produced by a photovoltaic panel is lower than the cost from a non renewable source (without considering the initial investment).

Lines labeled as ”Baseline” indicate the behavior of the system run with no SRPs. When comparing profits between the two groups, the baseline is calculated by dividing prosumers into two groups randomly. In this case, the baseline will indicate the natural fluctuation caused by noise. This indicator is useful in order to understand the impact of the regulation.

Comparison between the ability of prosumers to meet their energy needs is not shown because it is not affected by the regulation. Prosumers are always able to meet their desired energy demand (up to an acceptable threshold), the only factor limiting them is when there is not enough supply in the grid for everyone, such as in CS2. Even in that case study, the self regulating policy doesn't affect the result.

6.1 Voltage Regulation

Figure 6.2 shows the total voltage violation (in percentage) in the grid. The graphs clearly show that by increasing the number of self regulated prosumers, the risk of voltage violation decreases, compared to the baseline level without the regulation.

The results are not meant to represent real world voltage violations, but only a quantitative indication of the effect of the policy.

The relationship between the percentage of SRPs and the voltage violation is a direct one with indications of being linear.

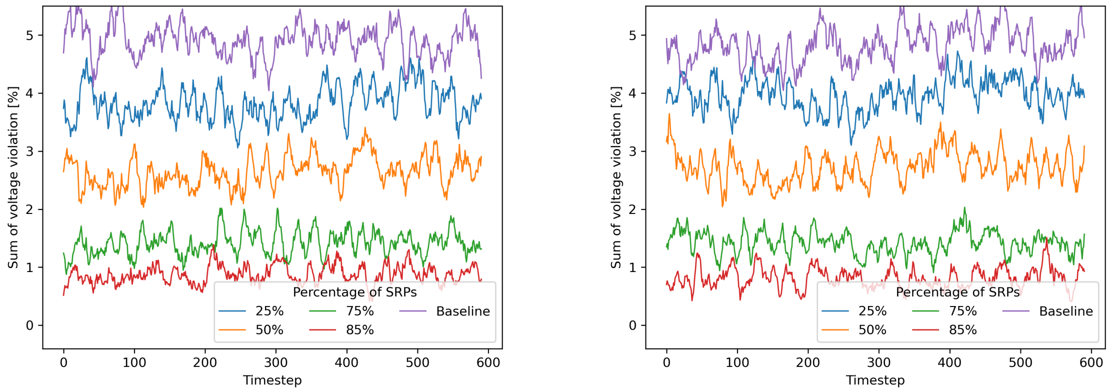

Figure 6.2: Comparison of total voltage violation. CS1 on the left, CS2 on the right

6.2 Revenue difference

Two different metrics have been used to understand the economic success of the two groups of prosumers. They are simply called Revenue Difference (1) and Revenue Difference (2) and are shown respectively in Figure 6.3 and Figure 6.4. They both show how much a SRP is expected to earn more than a NSRP, per unit of power. However they calculate the profit of prosumers in two different ways.

Revenue Difference (1) calculates total profits by summing the profit of each time step, defined as the difference between the mean unit sell price (K_t^{sell}) and the mean unit buy price (K_t^{buy}) of all prosumers at that time step.

$$RD_1 = \sum_t (K_t^{sell} - K_t^{buy})$$

Revenue Difference (2) calculates profits as the mean across prosumers of the difference between the mean unit sell price and the mean unit buy price, calculated from timestep 0 to timestep t, multiplied by t.

$$RD_2 = mean(K_{[0,t]}^{sell} - K_{[0,t]}^{buy})t$$

RD1 shows that in CS1, the less SRP there are, the more they are able to profit. While in CS2, their behavior is quite erratic (especially for the 85% case) and it doesn't deviate enough from the baseline.

RD2 shows that in CS1 it is always convenient to be a SRP, regardless of the level of penetration in the community. In CS2 the profit is again similar to the baseline, except for the 85% case which gets worse.

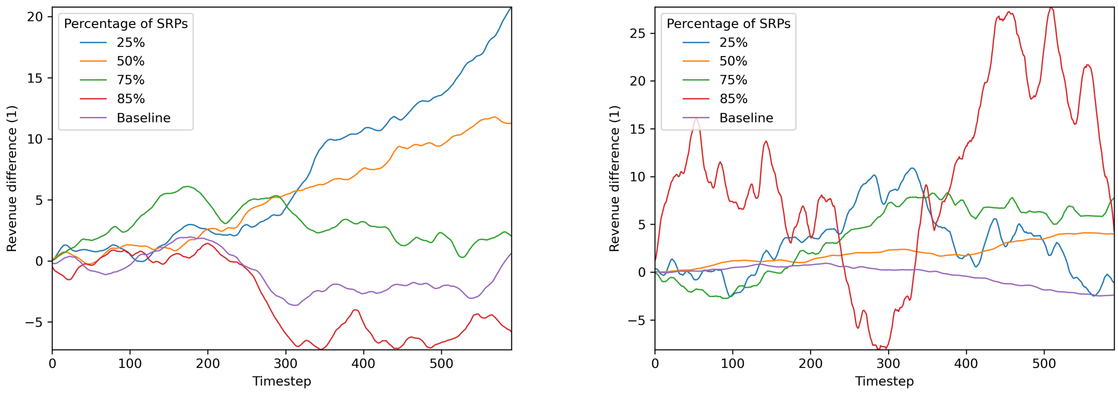

Figure 6.3: Comparison of revenue difference (1). CS1 on the left, CS2 on the right

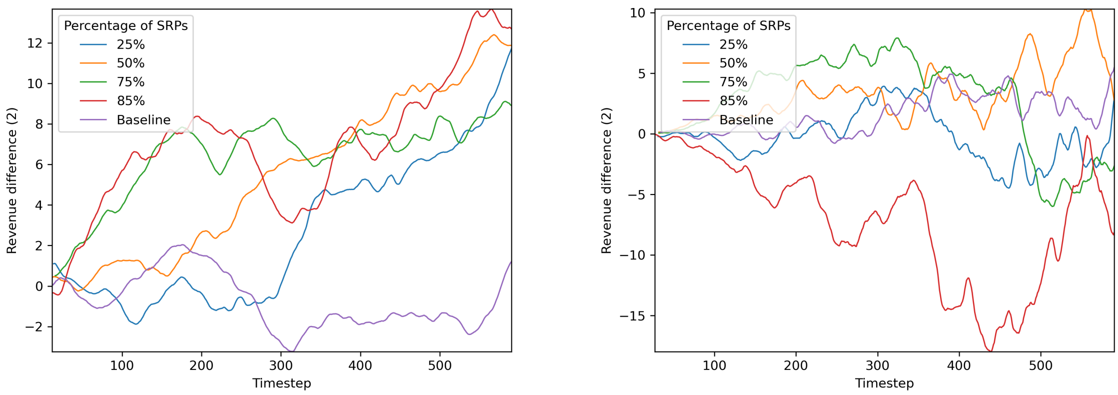

Figure 6.4: Comparison of revenue difference (2). CS1 on the left, CS2 on the right

Chapter 7

Conclusions

The results of the simulation clearly show that the self regulation policy is able to improve grid security and lower the level of voltage violation.

The reduction in voltage violations with increasing self-regulating prosumers can be attributed to their dynamic pricing strategies, which avoid trades that would stress the grid and cause overvoltage. By internalizing grid stability risks into their trading decisions, these prosumers effectively act as system operators, ensuring grid security.

However the ability of Self Regulating Prosumers to profit more than their counterpart is not that clear. Even if the results suggest the possibility to earn more by self regulating, data collected from all the runs shows a high standard deviation (which wasn't drawn in order to limit the number of lines on the graph). The best results have been selected for this thesis, but running the simulation with different seeds sometimes shows an opposite behavior regarding RD1 and RD2.

Overall, the results indicate that it may be possible to let prosumer community regulate themselves, and proving an economic incentives may guarantee their compliance.

However the simulations static synthetic generation and consumption data limits the generalizability of results in real-world scenarios which are more dynamic and may have unpredictable imbalances. The absence of external grid interactions and the simplified modeling of grid physics also affect the realism of the simulation.

The ambiguity in profit results reflects the complexity of prosumer behavior and market interactions, suggesting that while self-regulation generally improves economic outcomes, results of individual prosumers may vary widely.

More research is needed in order to test the algorithm with more realistic data and with a better algorithm which may take past behavior into consideration as well.

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