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Pricing Policies for Cooperation in the Smart-Grid

Tesi di Laurea Magistrale in
Nuclear Engineering - Ingegneria Nucleare

Author: **Gabriele Fadanelli**

Student ID: 842824
Advisor: Prof. Enrico Zio
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To my parents,
because without them
nothing would have been possible
nothing would have had sense

Посвящается Евгении
за то, что она никогда
не теряла надежды
на наше будущее

Abstract

In this thesis work it will be investigated the possibility to adopt pricing policies in order to drive the energy consumption towards optimization limiting at the same time the carbon emissions of the "players" in the electric Smart Grid.

The thesis proceeds in the following way.
In the first chapter the concept of "cooperation" is presented: even if it is often considered more a sociological than mathematical concept, Game Theory and Evolutionary Game Theory offer a frame in which it can be given a precise definition. Hence some concepts of the game-theoretical "language" will be given, together with a first theoretical attempt to provide a solution to the Energy Dispatch problem with a proper pricing policy.
The second chapter provides an overview of the electric grid from the technical point of view, showing how some disrupting technologies developed in the last decade are rapidly changing it.
In the third chapter, the electric grid will be described from the point of view of the energy market, describing how it actually works, who are the actors in it and why it is also rapidly changing in a more "prosumer" focused direction.
The fourth and fifth chapters instead are devoted to the description of two computational models for the Smart-Grid. At first it will be considered the possibility to develop a model for the integration of nuclear power with renewable technologies aiming at underlining their complementarity : based on given electricity and water demand and on given wind and solar profiles, a Genetic Algorithm will be used for the optimization of electricity production, with the possibility to connect the nuclear plant to a desalination Plant to cover the water demand.
In the following chapter instead, it will be considered how a central entity might drive the electricity demand through different price signals and the use of smart appliances, preserving at the same time consumers' privacy.
The sixth chapter aims at revealing the more common policies publicly adopted for climate change, with a special focus on the European Union and its pivotal ETS. Sadly, none of these policies has obtained relevant goals up to now, so it will be given another point of view to tackle the climate change problem.

In the seventh chapter, a last computational model will provide a solution to the energy dispatch problem from a local point of view: it will be shown that with the help of Blockchain and an Ethereum Smart Contract, both energy consumption and GHG emissions might be optimized, finding in the cooperation between the players in a MicroGrid a local solution to a global problem.

Last, a conclusion to join together all these concepts will discuss the obtained results and the feasibility of the proposed models.

Keywords: Smart-Grid, Pricing Policy, Game Theory

Parole chiave: Smart-Grid, Pricing Policy, Game Theory

Contents

Introduction

The Paris Agreement, signed by 194 states and the European Union (November 2021 update) was the last international treaty, adopted in 2015, trying to seal a pact on climate change mitigation.

After discussion, countries agreed upon reaching a long-term temperature goal to restrict the rise in mean global temperature to well below 2 °C above pre-industrial levels, and preferably limit the increase to 1.5 °C, recognizing that this would substantially reduce the effects of climate change [44].

The Agreement provided that each country must determine an emissions target plan and supply regularly reports on the effectiveness of such a plan.

While Paris Agreement was praised by world leaders at the time of ratification, it has been later on criticised as scarcely binding by some environmentalists, writers, analysts and academics and there is still an ongoing debate about its true effectiveness, supported by data that show how the global warming trend has not been slowed down.

What has been mostly criticized can be encompassed within the words *"If you can't measure it, you can't improve it"*, a concept which underlines how achievement of the goals of the United Nations Framework Convention on Climate Change (UNFCCC) is vulnerably dependent on the ability of the international community (and of every signatory country) to accurately measure greenhouse gas emission trends and revert them accordingly [63].

All eyes have been focused on the energy sector, since it is responsible for over two thirds of the greenhouse gases emission and as a consequence, multiple countries have started offering incentives to the renewable energy sector at multiple levels or have taken different kinds of measures to limit high-carbon technologies.

Nuclear power technology, historically at the center of a large public debate (especially in Italy) because of misperceptions of the risks associated to it, has always been accounted for being a low-carbon technology, but the lack of financial support or better, the oversupply of incentives to renewable technology has in some cases plunged its competitiveness in the energy market, with the result of its phase-out in favour of higher carbon intensive technologies such as coal or gas [64].

In fact, when we consider the Levelized Cost Of Electricity as a measure to evaluate the competitiveness among different sources and excluding the financial supports for renewable, most statistics consider nuclear power as one of the cheapest on the market, even without considering the trend in extending the life of the plants.

Recently, in European Union the role of Nuclear has been reassessed, both for its capability of lowering carbon emissions at times when intermittent renewable are out of power and for its strategic role as a future energy source, independent from fossil fuel extraction. It's in fact always worth remembering how an uranium fuel pellet of 1 cm height and diameter contains the energy equivalent of 1000 kg of coal or 0.7 m^3 of oil and not considering this basic factor in a serious discussion about the development of nuclear sector must be considered as the real *"cost of a lie"* [70].

A concrete step towards its public recognition as a strategic energy source for meeting the goals of Paris Agreement has been including nuclear research and safety (sadly, together with energy from gas plants) in the EU taxonomy for sustainable activities: a classification system established to clarify which investments are environmentally sustainable in the context of the European Green Deal, whose aim is to prevent green-washing and to help investors in making greener choices.
In addition, nuclear technology has historically been used for co-generation or water desalination and for that reason it can contribute in mitigating the consequences of global warming even further, filling the water demand of countries with higher risk of desertification and higher needs in terms of either district heating or drinkable water.

The existence of power at accessible cost is what leads to countries wealth: energy at high costs, apart from generating anxiety in the members of a population, can lead to more serious complications, such as an indiscriminate surge of inflation, with the consequent shutdown of industries or power plants and the risk to plunge the country into into a stagflation spiral.
The rising prices of fossil fuels and its economic consequences during 2022 or other periods such as the 1970s Oil Crisis are all examples of how the whole structure of the energy market should be restructured, also because, not always owning energy sources is a synonym of wealth: sometimes the possibility to exploit an oil field looks more like being seated on a time-bomb than on a golden mine.

Even if public opinion is more and more concerned about the nefarious consequences of global warming, as testifies the growing popularity of green parties in many occidental countries, many people need to face daily with the problems of a high residential price of electricity, so that it is arguable that citizens would allow a concrete shift towards (more expensive) low-carbon sources when given the alternative of a higher electricity bill at the

end of the month. This statement can be certainly debated, and many study focus on the predominance of social fairness over self interest [29]: nevertheless in the following, self-interest will be considered as the driving absolute force.
If this is the case, the short-term profit is preferred to the long-term avoidance of a catastrophe for our planet especially for those populations which are already lacking food and water. To bring those divergent interests together, an optimal compromise solution must be found, because only with a highly coordinated cooperation among players in the grid, countries could meet their GHG reduction goals without the cost of such a change discharged onto consumers' bills.

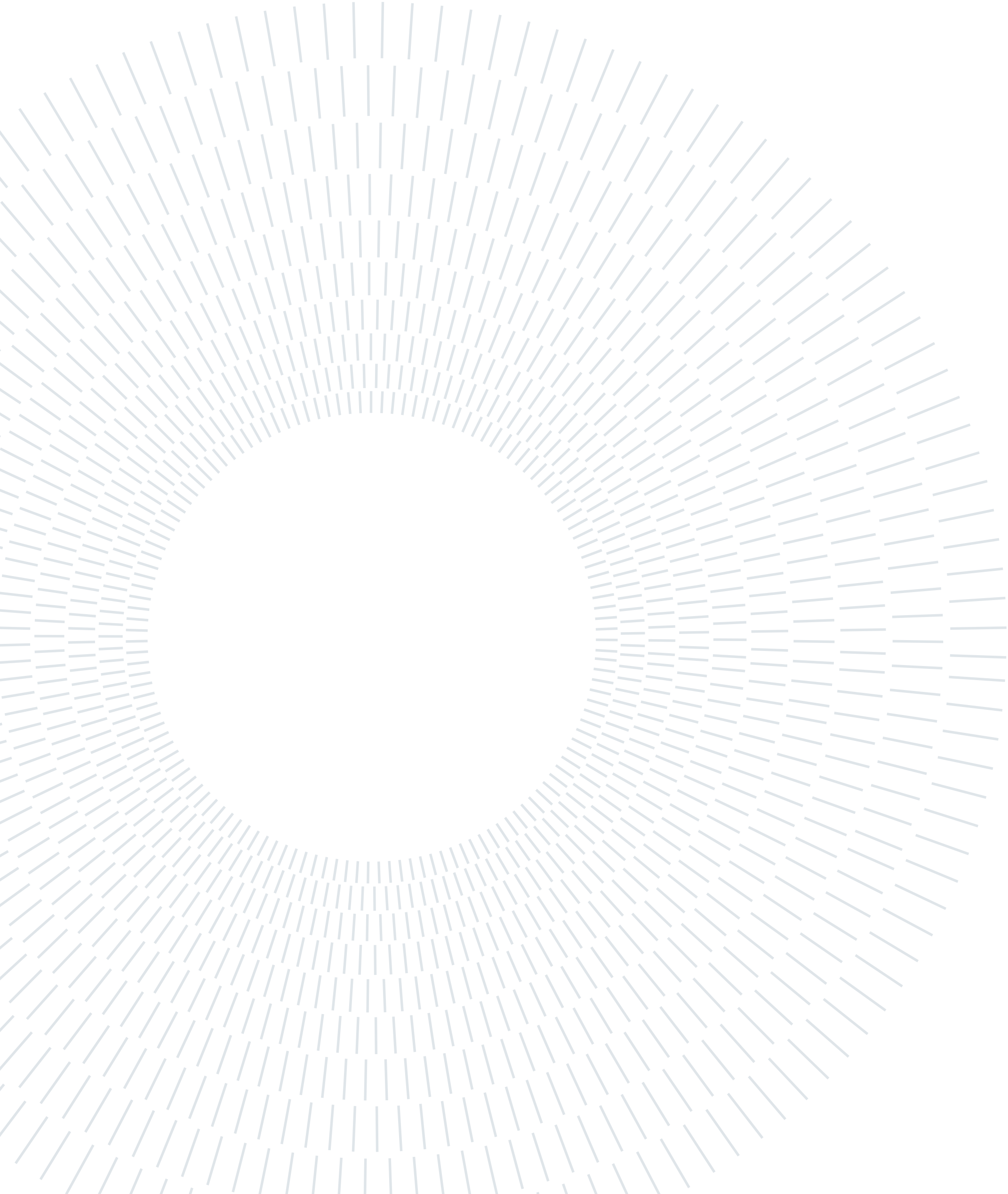
In this thesis, the challenge of finding an optimal solution takes on the form of the evolution of cooperation among players in a Smart Grid, analyzed with theoretical and computational models at different levels.
Due to the vastness of the subject and under the hypothesis that all the participants in the grid try to increase their own income, such models take the form of pricing policies, also because that is the main way through which governments all around the world try to promote the use of renewable technologies or try to limit energy waste .
After a short historical introduction about the growth of collaboration in a community, cooperation will be analyzed within the frame of Game Theory, finding a viable, optimal theoretical solution to the energy dispatch problem.
After that, the role of nuclear power in the Smart Grid will be discussed: small modular reactors represent nowadays a feasible solution for countries or communities with limited investment funds and moreover can easily be connected (the literature in this sense is immense) to a desalination plant for water production. The optimization of a simple model (built with *Python*) to integrate renewable (solar and wind) production, battery storage and water/electricity production from a cluster of SMRs connected to a desalination plant will be described.
To assess the roles of consumers in an integrated grid and how cooperation should be enforced among large electricity providers (plants, or other actors in the grid) and small or medium consumers, after a short presentation of nowadays electricity market, it will be presented a model of demand-management through a pricing policy.
In such a model (still simulated with *Python*) the large energy producers play an active role, sending pricing signals (real-time pricing) to which the households demands respond accordingly. Demand-flexibility will be possible in the near future with a large development of smart appliances in the grid, which will generate deep change in the grid management. Including electric vehicles for households, the analysis evaluates also the

viability of a *vehicle-to-grid* [22] system.
Following, it will be described the role of subsidies to renewables, carbon taxes or other financial instruments to the market, assessing their success/failure in meeting their goals. In comparison, a personal solution will be proposed, which should transfer the responsibility of carbon emissions directly to the consumers, instead of on the producers.
Even if it might seem an unviable solution in the near future, this approach could let the consumers know exactly how much GHG were produced based on its consumption. In this way, we should reach two important goals: from one side the consumer will be motivated to optimize its electricity consumption, from the other side (especially in the case where this emission could have a monetary intrinsic value) it will be motivated to actively act in favour of low-carbon policies, among which, nuclear could certainly play a central role.

Finally, it will be shown the importance of cooperation among prosumers and consumers in a Microgrid: with a mixed model based on cooperative and non-cooperative games, it is possible to find an optimization price for the exchange of energy among households, even if every household is assumed to use its own storage for the personal interest. To facilitate the energy exchanges in the Microgrid, as suggested in other academical studies, a smart-contract for energy exchange on the Ethereum Blockchain will be described, together with the advantages, disadvantages and the gaps to cover in order to allow a full development. The smart contract includes the trace of carbon production together with electricity exchanges, so that it would be even ossible to keep track or to exchange carbon emissions as an asset in the Ethereum Blockchain.

In synthesis, the thesis work relates to how cooperation to fight climate change must be integrated from the highest to the lowest level of the grid, for more concrete results to be attained. If the paradigm of the neoliberism ideology has been that one of creating a free-trade-market to cap emissions and encourage investments in the renewables, the evident failure of such policies should put in discussions the same basis that produced the situation where we are now.

"Monetizing" carbon consumption with a Smart-Contract could be an interesting solution, and what is most interesting in that is the fact that with this option people will be directly considered responsible and the "value" of such "coin" would be given by people taking part in the market. Because if we keep looking at global problems with the logics of convenience, instead of what is wrong or what is fair, the single can save himself in the short-term, the world we live in becomes different. If we prioritize self-convenience above cooperation, without a collective responsibility, than not only climate change, but also freedom and injustices become a limit to the interest of the self: but it's not obvious that such a world will be the one we'd like to live in.



1 | Cooperation: from a Local Perspective to a Decentralized Smart Grid

In a certain way, it's hard to define cooperation: it's a concept that governs our daily lives social behaviour, but it has also a specific definition when viewed from the point of view of theories such as Evolutionary Game Theory. Most importantly, it's not always easy to grasp the reason of the birth of cooperation among rational individuals, when it is not reduced to a mere mutuality: nevertheless we have many examples of the growth of a collaborative behaviour both in the living and in the physical world.
This introductory chapter is supposed just to show how cooperation among agents, often offers an optimal solution from the point of view of the social welfare. In view of the challenges posed by operations and management in a Smart Grid, cooperative and non-cooperative game theoretical models can help in providing suitable solutions, even in the presence of conflicting interests.

1.1. A Story of Successful Cooperation

> *"Nasce modesta e senza pretese, ma sembra animata a fare però sul serio quel poco che farà. Auguro sia scintilla di maggiori incendi"*
>
> Don Lorenzo Guetti

A brief introduction, which shows how cooperation stems from crisis, blossoming in a local environment.

At the end of 19th Century, Trentino was a small underdeveloped region in the North of Italy, whose economy was still dominated by a subsistence agriculture in which most of the population was employed.
Its land morphology nevertheless was not favourable to the development of agriculture,

since most part of the territory was above 700 meters in altitude and the land was divided among many small parcels, shrinking generation after generation.

One of the only products which could be sold on the market was grapes, which could grant an annual income to many families and was often bought from Austrian or South-Tirolean winemakers to produce wine.

That was the economical situation up to the half of nineteenth Century, when a collection of multiple events created a demographic and economical earthquake which devastated the territory: the infamous Phylloxera, potatoes illnesses and two well-known floods (1882, 1885) frustrated the harvests, a situation that was common in many parts of Europe during the period that is widely known today as the Long European Depression [45].

To counteract this situation, many people decided to emigrate from Trentino to richer countries, mainly northern Europe and North or South America, but for those who were unwilling to leave or who couldn't even afford the ticket for the journey, the redemption had to start from the bottom: the cooperation was the tool.

A local priest, Don Lorenzo Guetti was the promoter of the idea of cooperation in Trentino in many sectors: from the financial one, in order to give credit access to farmers and organizations, up to the agricultural productive one, where people could literally "share their efforts" to solve their primary need which was the alimentary one.

1892 was the date in which the first "Cassa Rurale" (agricultural credit union) was founded, in Bleggio Superiore.

Figure 1.1: First "Cooperative Family" at Santa Croce, Giudicarie Valleys, 1890

The goal was clear: to pursue the social and economic development of marginal realities compensating for the distance from large markets. The tool was simple: merge the forces and make a qualitative leap in production and marketing methods. The strategy was precise: compensate for local weaknesses by creating a structured movement and capable of unitary representation.
From that moment, the creation of new similar entities spread among all the region. After that, and along the following decades, cooperatives started to aggregate in larger and larger consortia and what was born as mutual assistance entity, began to stratify and organize its own structure [49].

Today, after more than 100 years, Trentino is one of the European regions with the highest density of cooperative enterprises, some of which have been active since the end of the nineteenth century. Out of a population of 500,000 inhabitants, the members of cooperatives are 270,000.
Trentino itself is one of the regions with the greatest variety of economic sectors organized in a cooperative form. Over the years, the cooperative experience has expanded from the traditional areas of credit, agriculture and consumption, up to personal services, environmental management, energy production, culture and education.
Trentino represents a case study, as it constitutes one sort of enclave that has gone through 120 years of history without ever knowing fatal crises or events that have substantially altered its nature and values. This was certainly, but not only guaranteed, by the intrinsic resilience of a cooperative system deeply rooted in the territory and among the population.

Historians agree that although the birth of the cooperative movement in Trentino was born in a period of deep crisis, nevertheless cooperation helped to give answers to need more elevated than the material ones.
It had the ambition to be an advanced system of change and improvement and Don Lorenzo Guetti compared its modernity impact to that of the telegraph and electricity or as a "new way" to overcome the conflict between consumers and producers.

Joining together with rules, rights and duties greatly developed people sociability: the first cooperatives were real forges to regain trust and esteem in oneself and in others (the community) and to rebuild the meaning of existence in a world that was changing extremely rapidly. Cooperation was therefore the catalyst for resources that risked being fragmented and irreparably dispersed.
It therefore became one of the most effective responses to mastering that great change that upset the world and the relations of production and exchange in the second half of the 1800s

We live in a time where reflection on cooperation and its models can bring fresh ideas on how to deal with the effects of the global crisis. In reality, however, the cooperative model does not exist in an absolute form, but it is the result of events and conditions that have determined its specific path, in a plurality of variants and paths.

With this caution, from the development of cooperation in Trentino, it is possible to draw some elements to reflect on, even in different geographical contexts.

A first element concerns the cooperative experience as a reaction to a context with social and economic difficulties, at risk of underdevelopment, that the approaches based on the market or public intervention alone cannot cope. Cooperation is born in response to situations of crisis and fragility, and is successful because it manages to mobilize energies and resources otherwise dispersed or fragmented.

A second element concerns the advantage deriving from a systemic approach, because in Trentino cooperation has never been just a sectoral phenomenon: one of its strengths has always been the variety of fields of application and the ability to propose a unitary and integrated approach.

The third element of reflection,is that of a high degree of autonomy. The same democratic organizations that made it possible to manage internal differences without exasperating them, have resulted in greater resistance to adversity and to attacks from outside. In the Trentino case, as mentioned, the autonomy of the cooperative system was a founding element which lead to the autonomy of public institutions.

Figure 1.2: Don L. Guetti, promoter of the Cooperative Movement in Trentino

A fourth element, which has played a decisive role in the history of Trentino, is the relationship between the autonomy gained within the cooperative movement and the public institutional dimension. The high institutional autonomy of the Province of Trento should be read in direct relationship with the history of a community whose development has based on a strong sense of social cohesion, whose governance models have been based on the democratic principle of the extended participation of citizens.

Without autonomy the history of cooperation would have been different and probably more fragile. As well as without the dimension derived from the culture of cooperation political autonomy would not have developed as we know it today.

Finally, the experience of Trentino shows that one of the elements that makes the cooperative model so attractive is its intrinsic relationship with local development. Cooperative enterprises are rooted in a specific territory, as they are connected directly to the needs of a community.

The relocation of a cooperative is in fact prevented by the fact that these are organizations whose ownership coincides with the beneficiaries (producers or consumers), which certainly cannot simply be relocated. This aspect in turn indicates that the link between these companies and the local area is not purely economic in nature.

Cooperative enterprises reflect a dimension manifesting itself in terms of solidarity, collaboration, trust, networks of interpersonal relationships. Instead of relying on financial capital as a leverage main to carry out their business, these enterprises use to a large extent intangible resources that derive from the social reality in which they operate.

This is ultimately the profound reason why cooperation has been in Trentino the principal factor of the transition from a rural and subsistence economy to a dynamic and fully developed economy, in which the most widespread needs are those typical of one welfare society.

Cooperation represented a redemption lever and a development tool from the destiny of geographical and economic isolation, that made possible for Trentino to enter the modern world.

It granted ts emancipation from a past of misery and uncertainty. And after filling the development gaps, this story continues today [34][10].

1.2. Game Theory and the Building of Cooperation

1.2.1. Game Theory: a Review

Game theory is a theoretical framework for conceiving social hypothetical situations among competing players.

Generally speaking, game theory investigates conflict situations, the interaction between the agents and their decisions. To some extent, game theory is the science of strategy, or better, the optimal decision-making of independent and competing actors in a strategic setting.

As a subject, it was given its first general mathematical formulation by mathematician John von Neumann and Economist Oskar Morgenstern in 1944 [80]. Later on however, it was mainly thanks to the great work of mathematician John Nash that Game Theory started to be applied to many sectors and branches of economical, biological and social sciences.

A game in the sense of game theory is given by a number of players, who interact according to given rules. Those players might be individuals, groups, companies, associations whose interactions have an impact on each of the players and on the whole group of players.

1.2.1.1. Definitions

Normal Form Games A game in normal form consists of:

1. A finite number of players $\mathcal{P} = \{p_1, ..., p_n\}$
2. A strategy set S_i assigned to each player $p_i \in \mathcal{P}$
3. A utility function $\mathcal{U}_i : S_i \longrightarrow \mathbb{R}$, which assigns a certain payoff to each player depending on his strategy and the strategy of the other players

If the number of players is limited to two and if their sets of strategies consist of only a few elements, the outcome of the payoff function can be represented in the so-called payoff matrix, which shows the two players, their strategies and their payoffs.

Player2 **Player1**	**c**	**d**
a	1,3	2,4
b	1,0	3,3

Table 1.1: Normal Form Game

The elements of the matrix are the utilities for the two players for playing certain strategies, i.e. supposing, player 1 chooses strategy a and player 2 chooses strategy c, the payoff for player 1 is 1 and for player 2 is 3.

Extensive Form Games

As opposed to the normal game representation, an extensive form game is described such that the agents of the game execute their moves consecutively.

The classical representation is that of a tree, where each node represents every possible stage of the game as it is played. There is a unique node called the initial node that represents the start of the game.
Any node that has only one edge connected to it, is a terminal node and represents the end of the game (hence a strategy profile). Every non-terminal node represents a stage in the game and every edge represents a possible action that can be taken. Every terminal node has a payoff for every player associated with it which is the result of the combination of actions required to reach that terminal node.

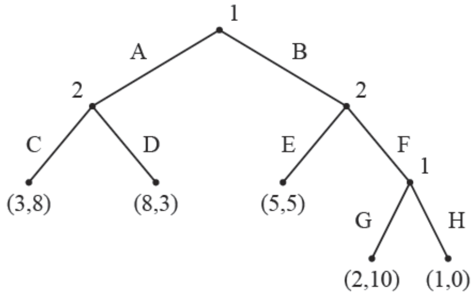


Figure 1.3: Extensive Form Game

Nash Equilibrium

Nash equilibrium (named after John Nash, who first described it [56] is a solution concept for a game involving two or more players, where no player has anything to gain by changing only his own strategy.
If each player has chosen a strategy and no player can benefit by changing his strategy while the other players keep theirs unchanged, then the current set of strategy choices and the corresponding payoffs constitute a Nash equilibrium. Mathematically, a combinations of strategies $s^* \in S$ is called a Nash Equilibrium if:

- $\forall p_i \in \mathcal{P}, \quad \forall s_i \in S_i \quad :$
- $\mathcal{U}_i(s^*) = \mathcal{U}_i(s_i^*, s_{-i}^*) \quad \geq \quad \mathcal{U}_i(s_i, s_{-i}^*)$

As demonstrated by Nash in 1950, every game with a finite number of players and finite number of strategies has at least one mixed strategy Nash equilibrium.

Stackelberg Equilibrium

Stackelberg Games are a form of consecutive game where one party has the advantage of being the "first-mover", i.e. introducing a hierarchy in the game itself. This is especially the case when a service provider can act as a leader in an extensive form game.

The Stackelberg equilibrium is hence found as a sub-game perfect equilibrium. If we divide the set of players among leaders $\mathcal{L}$ with strategies l_i and followers $\mathcal{F}$ with strategies f_i, a Stackelberg equilibrium $\boldsymbol{l}^*$ satisfies the condition:

$$\mathcal{U}_i(\boldsymbol{l_i^*}, \boldsymbol{l_{-i}^*}, \boldsymbol{f}^*(\boldsymbol{l}^*)) \geq \mathcal{U}_i(\boldsymbol{l_i}, \boldsymbol{l_{-i}^*}, \boldsymbol{f}^*(\boldsymbol{l_i}; \boldsymbol{l_{-i}^*})) \quad \forall \boldsymbol{l}_i \in \mathcal{L} \tag{1.1}$$

with $\boldsymbol{f}^*(\boldsymbol{l}^*)$ defining the optimal followers' response to the leaders' decisions.

Non-Cooperative Games

Non-cooperative games describe situations where played do not cooperate among each other. They individually optimize their strategies according to their own interest with the purpose of optimizing their own utility, without joining into coalitions. A Nash equilibrium is reached when all players decide a strategy that is the best response to other players'. The degree of information exchange among players is usually a factor that must be taken into account in the development of non-cooperative games.

Cooperative Games

Cooperative (or coalitional) games are studied when there exist the possibility among agents to form coalitions, even with a rational selfish behaviour.
Coalitions are formed in matching games in order to optimize the utility function of the coalition itself. In these kind of games, a common solution concept makes reference to the Shapley Value, which represents the unique distribution of the total payoff over the members of the coalition.
Therefore in a cooperative game with sets N of n players and for each of their subsets $M, v(M)$ gives the payoff of the subset. In this sense the Shapley value, which defines the payoff for the single player p_i is defined as:

$$\mathcal{U}_i(p_i, v) = \phi_i(v) = \sum_{M \subseteq N \setminus \{i\}} \frac{|M|!(|N| - |M| - 1)!}{|N|!}(v(M \cup \{i\}) - v(M)) \tag{1.2}$$

Nash model fits within the cooperative framework in that it does not delineate a specific timeline of offers and counteroffers, but rather focuses solely on the outcome of the bargaining process.

Iterated Games

Iterated or repeated games are extensive form games that consists of a number of repetitions of some base game (called a stage game) used to capture the idea that a player will have to take into account the impact of his or her current action on the future actions of other players; this impact is sometimes called his or her reputation.
In this kind of games, a special parameter to be considered is the time horizon H_i of the game: players in an infinite repeating game might prefer to choose a strategy that has a lesser payoff in the near future than a strategy with a higher payoff in the distant future. One way of modeling this on future utility is through the incorporation of a progressive discount δ.

1.2.1.2. Interesting Games

Prisoner's Dilemma

This vastly studied game, is a two players game modeling the situation where the Nash equilibrium doesn't represent the whole optimum of the game. Each player has two strategies, called "cooperate" (C) and "defect" (D). The players are considered to be rational and prior communications are avoided. In the next table we give a representation in a normal form:

Player2 **Player1**	**C**	**D**
C	3,3	0,5
D	5,0	1,1

Table 1.2: Prisoner's Dilemma Game

The dominant strategy is that of defecting, hence gaining a less overall payoff than the two players could gain if cooperating. To reach cooperation, both players should gain enough "trust", coordinating their effort.
This game is the most famous example in Game Theory of how a rational approach might lead people to avoid cooperation. However, different results might be obtained when PD is played in an iterated way, where the number of interactions is an important parameter to define cooperation or defection strategies.

Public Goods Game

The Public Goods Game considers a set of individuals who have to secretly decide if to contribute to the wellness of their own community by offering a token. Cooperators are those that aim to the "common" wellness, while defectors are those that follow a selfish behavior. In addition, being the choice "secret" , prior communications are avoided also in this game. The token provided by cooperators represents a very general form of contribution.

Then, the total amount of tokens is enhanced by a numerical parameter, named synergy factor, that promotes collaborative efforts, and its final value is equally divided among all individuals, no matter their action. Therefore, defectors, i.e., those whose contribution is null, can be considered as free riders. At the same time, since both defectors and cooperators receive an equal fraction of the total pot the most rational strategy is defection and constitutes the Nash equilibrium. A mathematical formulation of the payoffs is:

$$\begin{cases} \mathcal{U}_c = r\dfrac{P_c}{P} - c \\ \mathcal{U}_d = r\dfrac{P_c}{P} \end{cases} \tag{1.3}$$

where P_c indicates the number of cooperators among the P players involved in the game, r indicates the synergy factor, and c represents the players' contribution. This time, more than the number of repeated interactions, is the topology structure (dependent on P) which could determine a different outcome in an iterated game.

Iterated PD & PG Games

From the analysis of the previous games it is clear that Nash equilibrium cannot always indicate the best outcome of a game: in the case of PD game, it would end with both players being sentenced (in the original proposal of the game) and PG defection strategy would imply a "tragedy of the commons", with no tokens distributed among the population.

For this reason, both of these game have been intensively studied in the iterated form and many strategies have been applied to determine how it is possible to reach cooperation in a community, even in the presence of "rational" defectors.

One simple, and famous (but not, contrary to widespread myth, necessarily optimal) strategy for preserving cooperation in repeated PD games is called "tit-for-tat", a strategy which tells each player to behave as follows:

- Always cooperate in the first round.
- Thereafter, take whatever action your opponent took in the previous round.

A group of players all playing tit-for-tat will never see any defections. Since, in a population where others play tit-for-tat, tit-for-tat is the rational response for each player, everyone playing tit-for-tat is a Nash equilibrium.

There are two complications, though. First, the players must not be uncertain as to when their interaction ends, second, players' ability to distinguish defection from cooperation must not be imperfect. Because in a "tit-for-tat" population at equilibrium, one defection, or one misjudged cooperation can be enough for triggering a chain-reaction of defections, thereby resulting in what resembles a population of defectors.

It is also possible to define new strategies: more or less forgiving, risking defection after n cooperate moves, or being completely irrational; in the literature there are many examples of these proposed strategies [52] [17] [59].

However it has been demonstrated that not always a complex behaviour would result in a player with a high payoff: that is because if their behaviour during interactions is more difficult for other players to infer, that would add a level of miscommunication, which in turn is what causes repeated-game cooperative equilibria to unravel in the first place.

Iterated Prisoner's Dilemma game have been largely investigated in a monumental works about Game Theory by R. Axelrod, *"The Evolution of Cooperation"* [18], where the scientist experimented various tournaments at different levels, to determine which could be the real reasons behind coalitional behaviours in Game Theory.

In a simulation environment [9] in *Python*, it is possible to play repeated games modifying parameters such as length of the tournament, number of repetitions of the tournaments, probability of ending the tournament unexpectedly, probability of random players and so on.

For a classical repeated PD game with just cooperators, defectors and tit-for-that players, playing a game with 10% probability of unexpected termination, gives the following violin-plot results for the utilities:

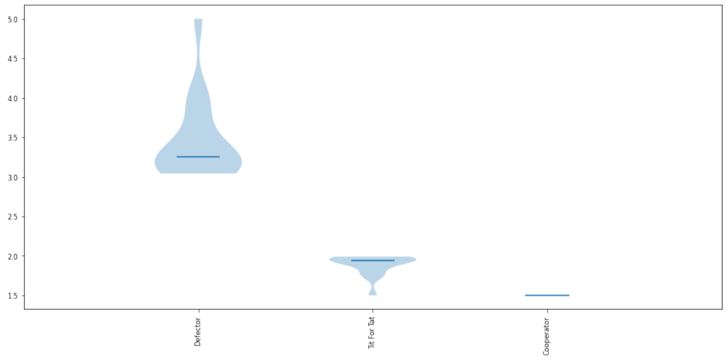


Figure 1.4: Payoffs plot for a 100 steps tournament, 50 repetitions with 10% end probability

If however it's included a concept of evolution of population following a certain mechanism, i.e. for instance eliminating the lowest scores players and reproducing the highest scores one at the end of every tournament, it's possible to find out whether the population is evolving through a cooperation or a defection model.
With the same parameters as the previous experiment we find for example (in blue is represented the fraction of *Cooperators*, in orange the fraction of *Tit-for-Tats*, in green the fraction of *Defectors*):

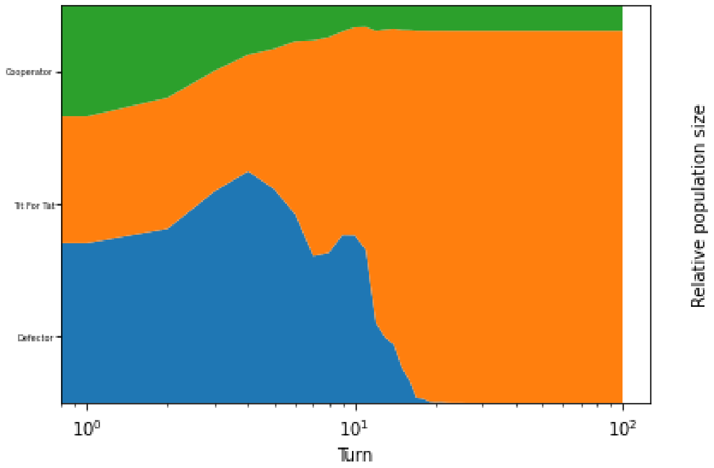


Figure 1.5: Population Evolution removing/reproducing the 5 worst/best players

But if we just increase the termination probability of a 20%, we get a different result:

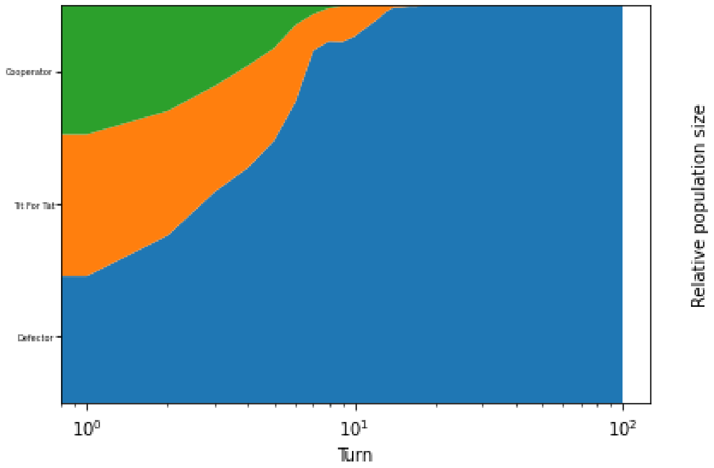


Figure 1.6: Population Evolution removing/reproducing the 5 worst/best players

Similarly we can simulate the population evolution for a situation like the one represented by a Public Goods Game, considering this time that it would be more appropriate to investigate also the space structure of the game, representing the number of players that interact at every step in the game. In fact, at every step it is possible to consider a maximum number of players that interact together. For the simulation we considered, apart from cooperator and defectors, even a group of *Loners* who do not take advantage of the game, but have a constant payoff along the game. Even in this case, setting different parameters such as synergy factor, contributors and number of players interacting at every step, led to different evolution structures (l represents loners payoff). In the pixel plot, white pixels represent *Cooperators*, black pixels *Defectors*, grey pixels *Loners*.

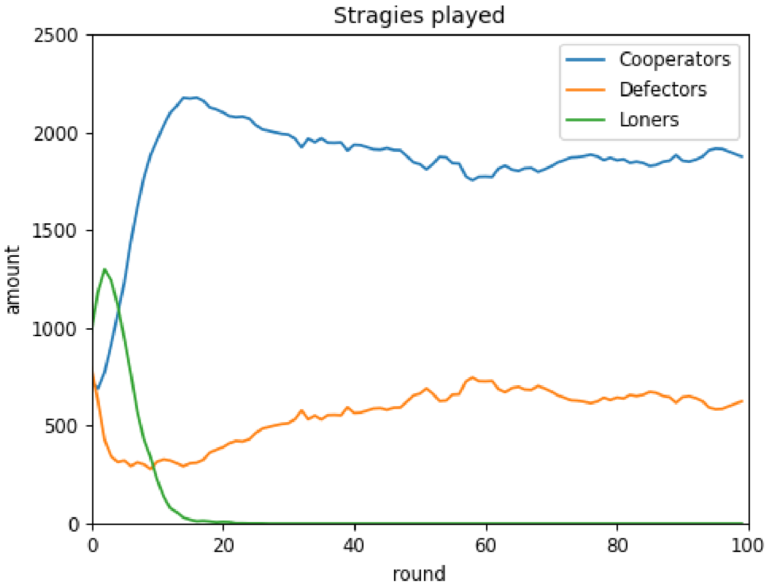


Figure 1.7: Population Evolution in PGG, c=1, r=8, l=4, 10 interacting players

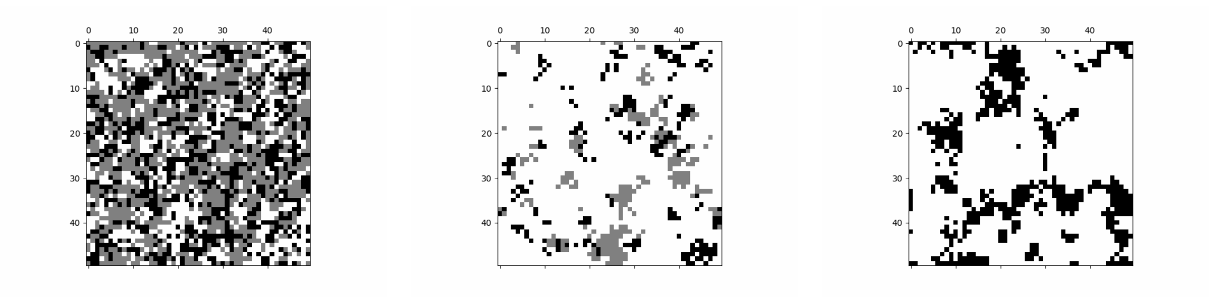


Figure 1.8: Evolution of Population towards Cooperation in PGG, ex. 1

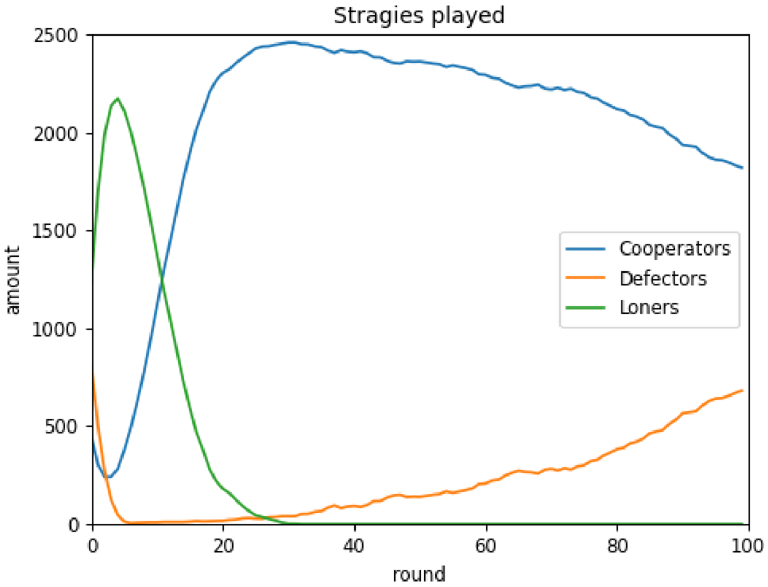


Figure 1.9: Population Evolution in PGG, c=1, r=5, l=3, 20 interacting players

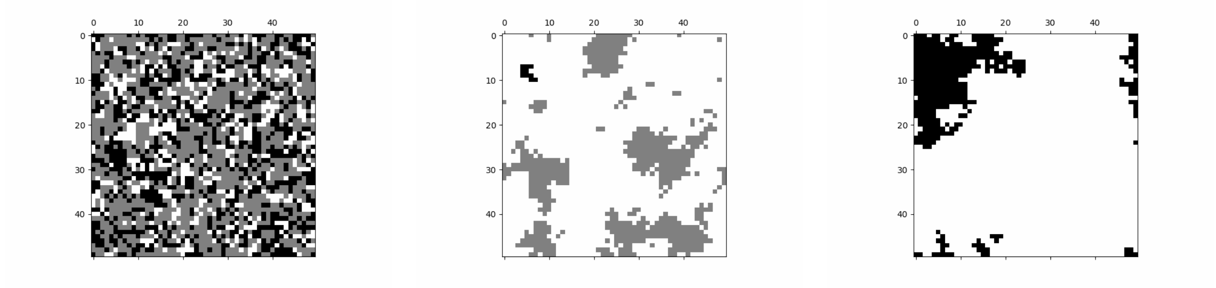


Figure 1.10: Evolution of Population to Coop. with Defector Cluster in PGG, ex. 2

Many other simulations can be performed equivalently, but it s important for the following part of the Thesis to remark how Cooperation appears to emerge among clusters resistant to the attack of the defectors, evidencing a situation of equilibrium in time opposed to the Nash equilibria of the games.

1.2.2. Evolutionary Games and the Evolution of Cooperation

1.2.2.1. Introduction to Evolutionary Game Theory

Evolutionary Game Theory (EGT) [71] is a scientific interdisciplinary area employed for the study of complex phenomena, which combines the principles of Game Theory with those of the theory of evolution.

In this sense, while Game Theory is employed in problems aimed at finding the optimal strategy in a competition the evolutionary part of the game combines this competitive aspect with the possibility of optimization of the information transmitted among competitors. EGT constitutes therefore a powerful framework for modeling several scenarios, spanning from social systems to biological phenomena, and representing specific mechanisms (e.g., reproduction, imitation), interaction patterns, and behaviors [13].
While the mathematical foundations of Game Theory have solid roots, there are cases in which the Nash Equilibrium does not represent the optimal solution or simply is not reached in reality.
Therefore one of the goals of EGT is to find out the motivations, and the mechanisms, that can lead to the phenomena we observe and that cannot be predicted using only the Game Theory.

A fundamental key point of EGT is given by the adaptive behavior introduced in the dynamics of a population. Notably, this behavior is driven by "rational behaviour" obtained by implementing agents that take actions for optimizing their own gain, with the possibility of replication of successful strategies.
What in Game Theory has been described with the term “payoff”, in Evolutionary Game Theory finds its parallel with the concept of fitness.

First of all, the focus is to understand the mechanisms that lead to cooperation in dilemma games, with particular emphasis for those dilemmas whose Nash equilibrium is defection. The underlying motivation, as already discussed, is born from observations on the real world where, fortunately, it is possible to find clear examples of cooperation.
To assess that, it is needed to move from the dynamics of a single game, to analyze the global level of an agent population where players’ interactions take the form of a game, and, being the system adaptive, study the evolution of strategies over time.
Within this approach it is even possible to consider a "thermodynamic" view of our population and, driven by the statistical physics approach, study the local mechanisms that lead toward a particular equilibrium (or steady state), i.e., a particular distribution of strategies.
As result, being particularly interested in games whose Nash equilibrium is defection, a special attention s payed to those mechanisms/conditions that allow to reach a state of full cooperation.

Agent populations playing evolutionary games show critical behaviors, e.g., order-disorder phase transitions (well known in Statistical Physics); hence the reason to try to approach to such problems with methods and tools of Statistical Physics, such as as the Ising model [48].

The "evolution" character of the games lies in the adaptability of the players' strategies according to a particular rule,usually "rationality", goes under the name of "strategy revision phase".

Analytically , the evolution of a population takes therefore usually the form of an ODE, or better a dynamical equation, whose strategy revision can be assessed in multiple ways, employing different revision protocols.

Classical example in this cases are: "Smith dynamics", "Brown-von Neumann-Nash dynamics", "logit dynamics", "replicator dynamics" [76].

The latter, for instance is based on the following conditions: given a strategy i, used with a frequency x_i (in a population), the frequency rate reads

$$\dot{x}_i = (f_i - \phi)x \tag{1.4}$$

with f_i the expected payoff associated to the strategy i and ϕ the average payoff as a whole.

As introduced in the repeated PG game however, when considering agent populations, a further relevant aspect in EGT is given by the geometrical space, since the latter is directly related to the interaction topology. For instance, we can consider continuous spaces, where agents randomly move and play with their neighbors, and discrete spaces that usually are represented as graphs.

If the players are connected in a topological network where they can have multiple interactions over time, they are facilitated in developing cooperative behaviors, thanks to the effect defined "network reciprocity" [60] [59].

Accordingly, in the case of the PGG, other authors [75] computed the critical threshold of the synergy factor for achieving cooperation. In particular, they found the minimum value of this parameter to ensure the survival and success of cooperators, when payers are arranged on regular square lattices.

Other studies instead, [36] [54] show how heterogeneous networks do not promote cooperation when humans play the PD, [66] demonstrating that the cooperation increases as the heterogeneity of the network structure.

1.2.2.2. Statistical Physics and EGT

Let us now go back to the process before introducing the evolution of an agent population, the "strategy revision phase": this can be implemented according to different methods, usually related to the analysis of the payoff of the involved agent.

In general, methods based on the payoff analysis can be divided in the following categories:

- Comparison
- Self-evaluation
- Imitation

The first one, is often implemented as a stochastic rule by a Fermi-like function. The latter allows to compute the probability an agent y takes the strategy of an agent x and reads

$$W(s_y \longleftarrow s_x) = \frac{1}{1+e^{\frac{\pi_y - \pi_x}{K_y}}} \tag{1.5}$$

where π_x and π_y correspond to the payoffs of two agents, s_x and s_y indicate their strategy. $K_y > 0$ is an agent-dependent parameter whose role is the same as the temperature T in Fermi-Dirac Distribution.

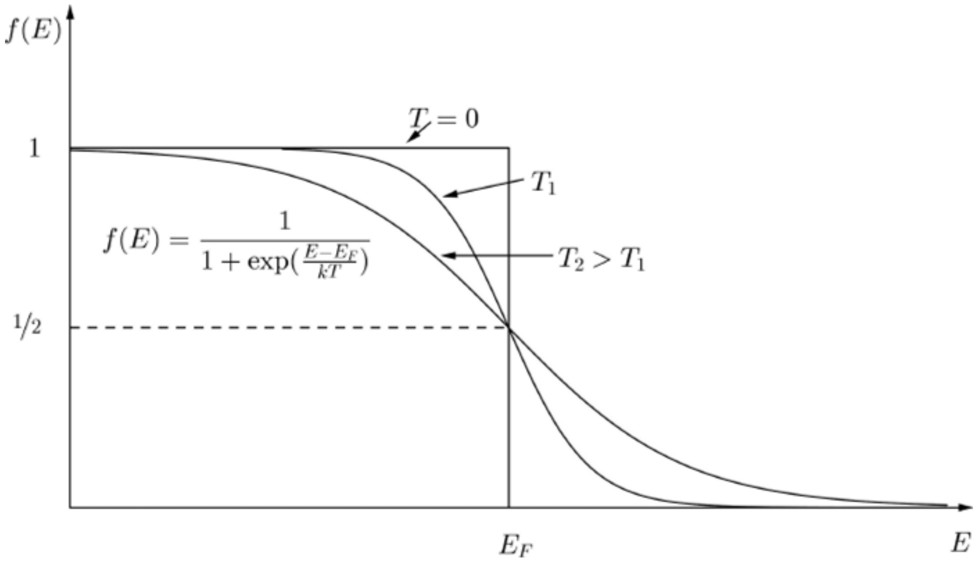


Figure 1.11: Fermi-like function in Statistical Physics

Notably, its "stochastic" behavior comes from the opportunity to use it as a weighted distribution, where even inconvenient choices can be performed (low, but still present, probability of imitating a poorer agent), while its "rationality" is represented by the temperature T (reads K_y). It is the temperature parameter, using this approach that therefore determines the appearance of cooperation, defection or cooperative clusters in a population.

The second category in the list, self-evaluation methods, entails agents decide to change their strategy whether the current payoff is smaller than the previous one. This approach can be viewed as a kind of evaluation on the own performance and entails that agents have some memory (against the common approach where the agent payoff is reset after each iteration).
Last, methods based on imitative mechanisms (considering the payoff as reference) usually lead agents to imitate a richer opponent in their neighborhood.

Statistical Physics aims to connect the macroscopic behavior of a system with the local mechanisms of its constituents.
As a result, this approach becomes strongly valuable when dealing with complex systems, also in those cases where the subject of investigation is a nonphysical system.
To see an example of its possible application in EGT, we start considering a classical population dynamics model: the Lotka-Volterra [53].
Population dynamics are classical dynamics models introduced by Malthus,Lotka–Volterra, Verhulst, Ginzburg and many more, for studying the behavior and the dynamics of a population.
The Lotka-Volterra or predator-prey model is used in analyzing the behavior of a system with two competing populations/species. Obviously, in order to model this occurrence, we have to know the rules underlying the interactions between individuals of the two species.
The mathematical definition of this model reads:

$$\begin{cases} \dfrac{dA}{dt} = \alpha AB - \beta A \\ \dfrac{dB}{dt} = \gamma A - \delta AB \end{cases} \tag{1.6}$$

with α and γ representing internal processes within the single species (e.g., growth) and β and δ parameters quantifying the interactions between the two species.
The values of these parameters can be modified for considering different scenarios.

In the classical case individuals may belong only to one species, so a competition process can lead to the extinction of a species, without affecting the amount of individuals belonging to the winning species.
In EGT instead, individuals might change their group of belonging, while the total size of the population is conserved over time. Here, the benefits deriving from interactions can be interpreted as fitness and what determines reproductions/extinctions is not the individuals but their strategies.

The equivalence payoff-fitness, and the relation between the payoff of an individual and its strategy (and those of its neighbors), allows to introduce an analytical description of the system.
For instance, in two-strategy games, i.e., with individuals that can adopt the strategy C (cooperators) and the strategy D (defectors), we can write:

$$\begin{cases} \dfrac{dC}{dt} = C(\pi_C - \phi) \\ \dfrac{dD}{dt} = D(\pi_D - \phi) \end{cases} \tag{1.7}$$

with $\phi = C\pi_C + D\pi_D$ and $C + D = 1$.

The solution of this system can lead to different equilibria, as the extinction of a strategy, as well as the coexistence of both.
This is the approach related to the so-called replicator dynamics.

To give an example of how a Statistical Physics approach can improve the situation, given the aforementioned assumptions, we try to interpret the situation with a model which is classically used to describe the ferromagnetic transition in solids: the Ising Model.
Of course, the atoms and spin values can have different meanings in accordance to the phenomenon under analysis and a number of problems can be successfully faced by using this very simple modelization.
The Ising model considers a lattice of dimension D composed of N cells, each one provided with a spin $\sigma = \pm 1$. Then, in the defined lattice, a pair of cells forms a bond J, which represents their interaction.
The whole set of bonds can be denoted as B, and for each element of the set, we have an energy of value $-J\sigma_i\sigma_j$, so the interaction energy is equal to $-J$ for bonds with the same spins and to J in the opposite case. When spins are aligned, the energy s smaller and the configuration is more stable.
In addition, some sites of the lattice can have an own energy of value $-h\sigma_i$ (here h may represent an external field), so the Hamiltonian of the Ising model reads:

$$H = -J \sum_{i,j \in B} \sigma_i \sigma_j - h \sum_{i=1}^{N} \sigma_i \tag{1.8}$$

which is necessary to compute the expected values of a macroscopical physical quantity, by using the Gibbs-Boltzmann distribution.
The parameter called magnetization $\mu = \frac{1}{N}\left(\sum_{i=1}^{N} \sigma_i\right)$ is often particularly useful, allowing to have a high level overview of the system.

Notably, it vanishes when the amount of positive spins is equal to that of negative ones, (full disorder) and it is maximized when all spins are aligned in the same direction.

It is then interesting to evaluate how the temperature affects the state of order of a system: at low temperatures low-energy configurations have a probability higher than high-energy configurations and in absence of external fields low-energy states of the Ising model have all spins pointing in the same direction, so that the magnetization μ has a (absolute) value close to 1.

Increasing the temperature, spin configurations with various energies emerge with equal probabilities.

Accordingly, the macroscopic state of the Ising model becomes disordered, and its magnetization goes to zero.

Hence, it is possible to identify a relation between μ and T and, most importantly, a critical temperature T_c below which the magnetization is greater than zero and above which the magnetization reduces until its value goes to zero.

The phenomenon described is known as "order-disorder phase transition," and it has a deep relevance both in Physics and in the related applications to complex systems.

From this simple example, is possible to draw more complex situation, and founding the power of EGT with Statistical Physics it is possible to reach important results about the emergence of cooperative behaviours inside a population.

As discussed before, the dynamics of the games are affected by a number of parameters and processes, namely, the topology of interactions among the agents, the synergy factor, and the strategy revision phase.

Notably, the latter can be simulated with the Fermi-like function we have described above, revealing a high dependence on the development of the game from the temperature parameter.

As it is possible to see performing a Montecarlo simulation which goes under the name of Metropolis Algorithm, even in the simple Ising Model we assist at the emergence of cluster of cooperators with a dependence on temperature, as shown in the following pictures.

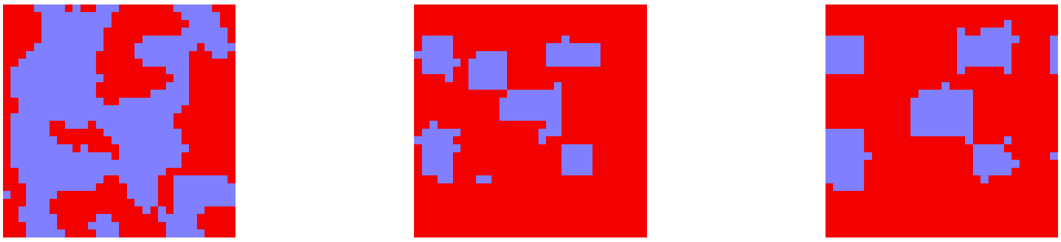


Figure 1.12: Cluster cooperators (light bue) at low temperature in the Ising Model

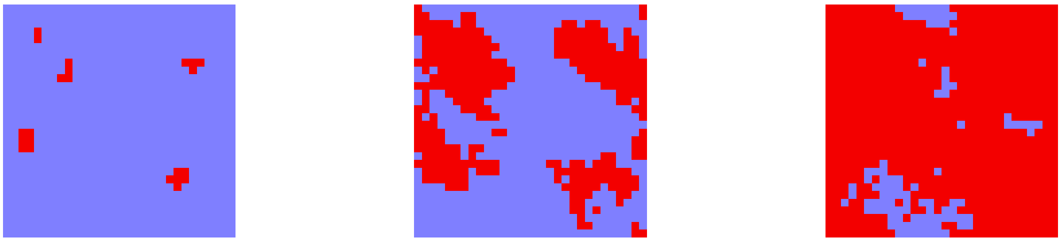


Figure 1.13: (Red)Defectors' takeover at a higher temperature in Ising Model

Encouraged by these results, we will go on with the core of the work, where we will try somehow to answer this questions:

- How is it possible to coordinate a Smart Grid in which the agents are intrinsically selfish (sort of PD)?
- How is it possible to avoid the "tragedy of the commons" in the public game where the total payoff is the benefit from GHG reduction and the "tragedy" is the irreversible impact of global warming?

Or better, encouraged by theoretical results which shows an equilibrium towards cooperation when some specific rapports of contribution/cost are employed, is it possible to find a way that the contribution to pay (i.e. the bill, for the consumers) for GHG reduction would be so low that the grid would automatically, go towards the goal?

We therefore propose some solutions to tackle the problem, based on different pricing policies which represents, in many ways, the concrete payoff of all the players in a game. Eventually, some optimization techniques derived by EGT will help in finding a "perfect" (but unfortunately scarcely applicable in reality) result.
Encouraged by theoretical results, the final scope will be to underline and model the characteristics of a new Cooperative Smart Grid through pricing policies.

1.3. A Decentralized Cooperative Smart Grid

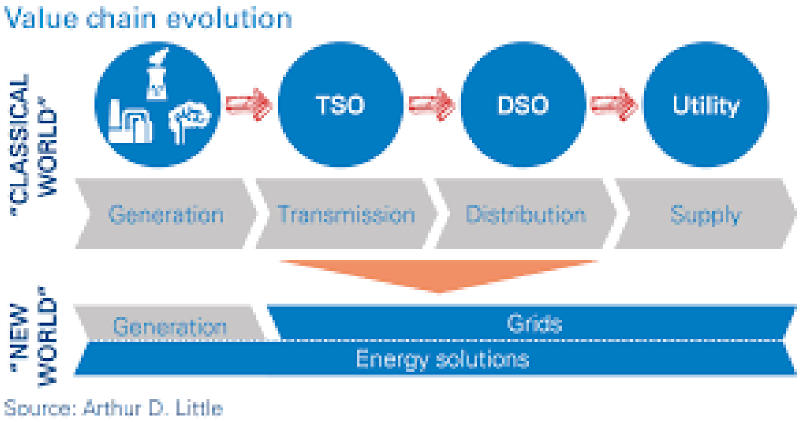
Power grids as we have been known up to now will probably face strong modifications in the near future.
Renewables and the increasing use of distributed generation sources are stretching the traditional energy grids, which were built to accommodate large central generation units, single transmission system operators (TSO) and one-way distribution system operator (DSO) networks.
Current prosumers reality has inverted the system, new actors have emerged, geographies

are increasingly interconnected, and all ecosystem stakeholders are rethinking their strategies.

Specifically, a whole range of "energy solutions" are emerging along the value chain, forcing energy industry participants to rethink their traditional business models. In addition, central generation is transforming, with offshore wind and PV parks that mandate new transmission solutions.

As a result, the traditional "linear" grid structure is evolving towards a "meshed" structure, and both TSOs and DSOs need to deal with new flexibility requirements and constraints.

On the one hand, this challenges traditional network operator models, but on the other, it offers opportunities to existing and new players [19].



Source: Arthur D. Little

Figure 1.14: Evolution of the Power Grid [19]

Although the electricity system will continue to require a central transmission backbone network (central generation, whether it is conventional or renewable, is forecasted to remain predominant in the generation mix for the foreseeable future), the rise of intermittent, decentralized generation and micro-grids could lead to a decrease in reliance on transmission networks.

This pose certainly a large number of challenges, but one big reason to ease this transition would be to completely eliminate the high degree of centralization of the grid, ultimately the cause of its lack of reliability.

In a centralized paradigm, when the central power-plant (or central TSO) fails, the whole grid can fail with it. Moreover, costs of transmission from centralized production to more distant areas represent a substantial part of O&M costs and are thought to be increased with the expansion of the grid.

Hence a decision must be taken: optimizing the reliability of the single power-plant, or distribute the grid.

The first solution requires central high investments in Power Plants O&M, while the second one faces the requirements of a higher degree of distribution capabilities.

A higher penetration of distributed energy resources implies that the production responsibility is distributed among various smaller-scale energy harvesters: its natural evolution is towards self-sustainable and semi-isolated communities with energy-trading platforms, achieved through decentralized home storage solutions and advanced metering infrastructures (smart-meters).

The combined arguments of increased reliability with decreased costs per unit of energy forms a strong case against a totally centralized power-grid [61].

Stating these arguments, it is not surprising that the power-grid is already in the process of being more distributed.

From the challenge of promoting coordination and cooperation among large energy suppliers, TSOs, DSOs and consumers, the new cooperation model is shifting towards an integration among all players, were players' roles can change during time, with no static distinctions.

The changes taking place however necessarily require to adapt new pricing models for energy exchanges: a number of academical experiments to shift the market towards real-time pricing policies and demand-side management have therefore been proposed [21] [81] [82], showing how this pricing policy associated to the introduction of smart-meters could both add transparency and efficiency to the grid as a whole.

Reflecting the real balance between demand and offer, a real-time pricing model gives a more accurate situation of the imbalance in the grid, hence giving the possibility of an "auto-balance".

If from many sides this can be viewed as optimal from the side of an elastic consumer, it is not always the case for large producers which account their investments on a fixed yearly-based income, such as nuclear plants, among the others.

There will be certainly difficulty for large suppliers to adapt to this new market, but poses also challenges which can lead to new degrees of efficiency and optimization determined by a cooperative interaction between large suppliers and small consumers/prosumers.

1.3.1. Challenges introduced by decentralization

With decentralization come challenges because a substantial part of grid-control is lifted out of the hands of the nation-wide macro-grid.

In centralized grids, power-plants can supply according demand and are very quick to

ramp up- or down-production when needed. In a decentralized paradigm, dependency and control within a micro-grid shifts to the distributed agents which, in contrast, produce power that is highly variable and intermittent. A micro-grid community needs an effective and fair way to distribute the available energy among its households, reducing community-wide deficits and dependency on the macro-grid.
At the same time, it is arguable that a micro-grid could provide for all its own needs, considering that not all the demand is provided by households (26.3% in EU), but also industries and agriculture participate to the market. Hence, a high interconnection among small consumers/prosumers and large energy supplier is to be looked for.

Parallel to dependency for energy distribution, households currently depend on the service of a tertiary intermediate to facilitate payments.
However, with recent technological advances and widespread adoption by society, a blockchain database might provide for the need of a decentralized transaction method, completing the decentralized cycle between energy and payment.

Considering the power-grid of today, there is no widespread mechanism for trading a surplus of energy without a central authority or a group of retailers. Decentralization is therefore to be promoted not only because of its efficiency and increase in reliability, but also because in the decentralized paradigm, we can reject the dependency on retailers.
The current mechanism for price reimbursement to surplus supplying prosumers varies from State to State, but the most frequent solution is to offer a fixed price reimbursement in a range from 7 to 11 cents/kWh [61], or, for large "green" prosumers, feed-in tariffs for long-term contracts. However, these fixed prices are often below par with dynamic market prices for energy
Hence the adoption of an independent, real-time energy-trading system could help in regaining autonomy over their energy. In a global perspective, the impact of an autonomous decentralized community is even more noticeable.
In countries affected by inefficiency and corruption, communities that are self-sufficient and independent from corrupted central institutions still have a chance to thrive.

In an optimistic perspective, with the help of blockchain technology, it would be even possible to directly subsidize those communities which, in turn, could also gain authority and take decisions on energy development projects, promoting their chosen energy policies.

1.4. Cooperation through pricing policy: a theoretical result

The promotion of cooperative behaviours in a Microgrid is strictly dependent on providing a clear and competitive pricing policy among users which allows a fair allocation of the energy.
In this section, the results of EGT will be applied to a population in order to obtain a correct pricing for a mixed population with different electricity demands. The results, though merely academical and scarcely applicable to the real world, retrace the study by [20].

1.4.1. A Demand-Response optimal solution with EGT & VCG

As an example of the effectiveness of the Evolutionary Game Theory techniques, we try to model a daily electricity allocation problem among selfish agents who want to maximize their own welfare and must decide how to distribute the electricity usage during the day. This case is treated in the literature within the realm of Game Theory [5], although Nash Equilibrium is a sub-optimal solution: the aggregate demands of the participants have a direct influence on the price and without coordination it's impossible to reach the optimal solution. In order to maximize the aggregated profit of the population it is necessary to introduce a properly designed incentive schemes which doesn't need private information from the agents and can coordinate the distributed demand. Each agent can afterwards implement an evolution dynamic to find the best distribution of resources.

It has been demonstrated [20] that it is possible to achieve an optimal equilibrium for such a strategic environment with a Vickrey-Clarke-Groves mechanism with Clarke Pivot rule [58] where the central utility determines the aggregate demand of the agents and calculates the incentives, receiving as information the aggregated consumption from each user, preserving privacy among one another.

Modelling a population $\mathcal{P} = \{1, ..., N\}$ of agents i having at each time interval $t = \{1, ..., T\}$ a q_i^t electricity consumption , the aggregate demand (representing the strategy) is defined by the vector $\boldsymbol{q^t} = \{q_1^t, ..., q_N^t\}$ and to each agent is assigned a logarithmic valuation function $v_i(q_i^t)$ at each time instant, representing the welfare received from the electricity supply.
If we assume that the electricity cost is the same for all t and the unitary price is p, we

can express the utility function of each agent as:

$$\mathcal{U}_i(q_i, \boldsymbol{q}_{-i}) = v_i(q_i) - q_i p(\|\boldsymbol{q}^t\|) + I_i(\boldsymbol{q}) \tag{1.9}$$

With $\|\boldsymbol{q^t}\| = \sum_{j=1}^N q_j^t$ the aggregation consumption at a given time, $p(\|\boldsymbol{q}^t\|)$ the price function (calculated as the cost function divided by the whole consumption at each time) and $I_i(\boldsymbol{q})$ the incentive of the appropriate form required by VCG mechanism with Clarke Pivot Rule, which assigns incentives according to the contributions made by an agent to the society:

$$I_i(\boldsymbol{q}^t) = \|\boldsymbol{q}_{-i}^t\|(h_i(\|\boldsymbol{q}_{-i}^t\|) - p(\|\boldsymbol{q}^t\|)) \tag{1.10}$$

h_i representing the externality of each consumers and given by:

$$h_i\|\boldsymbol{q}_{-i}^t\| = p(\|\boldsymbol{q}_{-i}^t\|)\frac{N}{N-1}. \tag{1.11}$$

The objective function of the population is obviously the maximization of the total welfare function $\mathcal{U}(\boldsymbol{q}) = \sum_{i=1}^N \mathcal{U}_i(q_i)$.

Defined the valuation and cost functions as:

$$v(\boldsymbol{q}^t, \alpha_i^t) = \alpha_i^t \ln(1 + q_i^t) \tag{1.12}$$

$$\tag{1.13}$$

$$C(\|\boldsymbol{q}\|) = \beta\|\boldsymbol{q}\|^2 + b\|\boldsymbol{q}\| \tag{1.14}$$

it is possible to define the fitness function of the population evolution as the derivative of the valuation minus the cost, which per each player becomes:

$$F_i^t(q^t) = \frac{\alpha_i^t}{1 + q_i^t} - 2\beta\|\boldsymbol{q}\| \tag{1.15}$$

Hence we evaluate the evolution of the population using two different dynamical models: the aforementioned replicator dynamics, together with a generalization of the Fermi model to a population of more than two individuals, which goes under the name of *Logit dynamics.*

In this way it is possible to obtain the convergence of the incentives, electricity production and power demand to a stable value, which gives a hint on the real possibility of finding a suitable pricing policy for a population of users to rech an optimal welfare utility.

Unfortunately, for large populations such policy is not often adaptable: especially for what concerns electricity consumption, users have different behaviours and interests; demands are usually unpredictable and are not only influenced by incentives, but by necessities which go beyond the results of EGT.
Moreover, the constant price hypothesis is never found in reality, the power consumption profiles varies much more than what has been included in the simulation (whch can create some deviation from equilibrium for the evolution dynamics) and the evaluation of the incentive policy is just made *a posteriori* in the simulation.
However,the results provide a demonstration of the power of EGT which, determining its effectiveness in finding how the evolution toward a situation of social welfare is in fact possible.
In the next chapters therefore with the aid of computational agent-based models we will try to evaluate different possible solution to the energy dispatch problem from different points of view, taking into account the limits of a real electric grid.

The next figures explain the results obtained in the simulation of a population of 5 users with similar (and adaptable) energy consumption profiles.

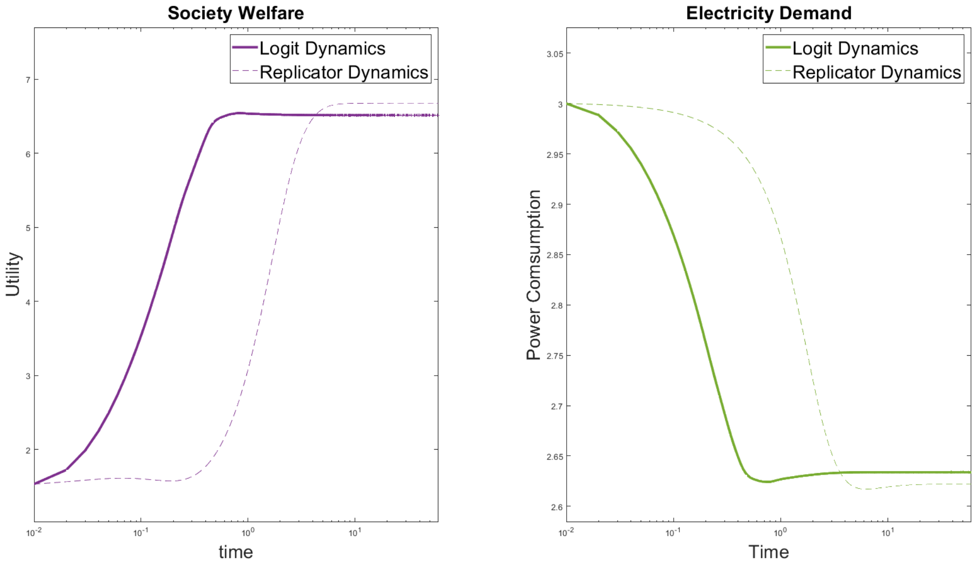


Figure 1.15: Welfare and Demand Evolution

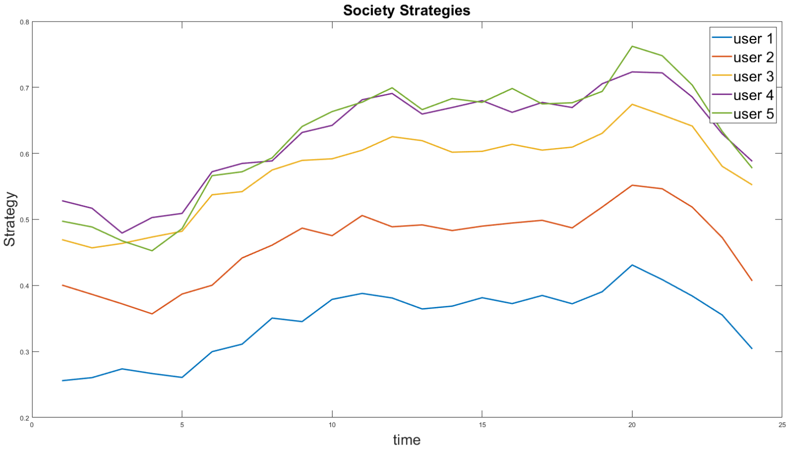


Figure 1.16: Population Strategies

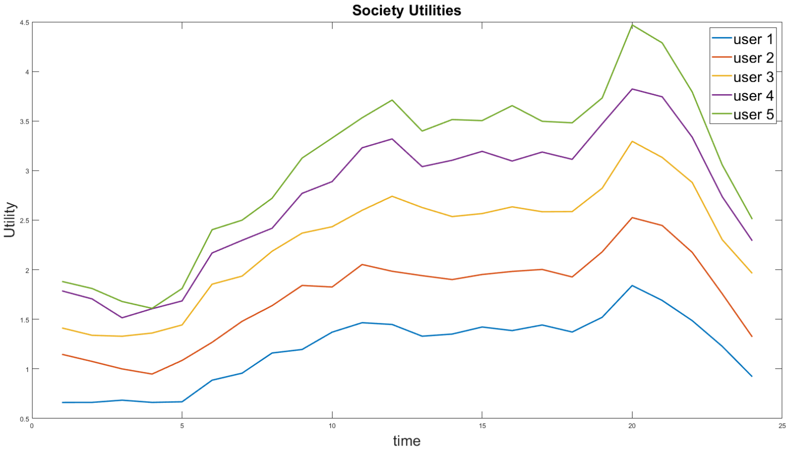


Figure 1.17: Population Utilities

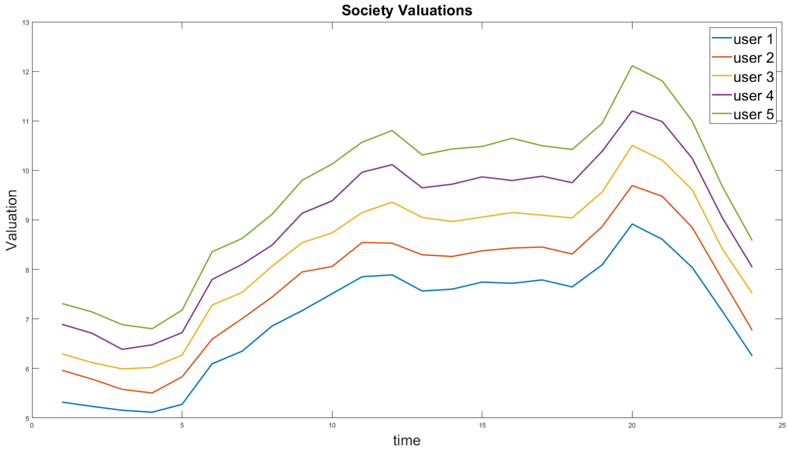


Figure 1.18: Population valuations (assumed proportional to desired demands)

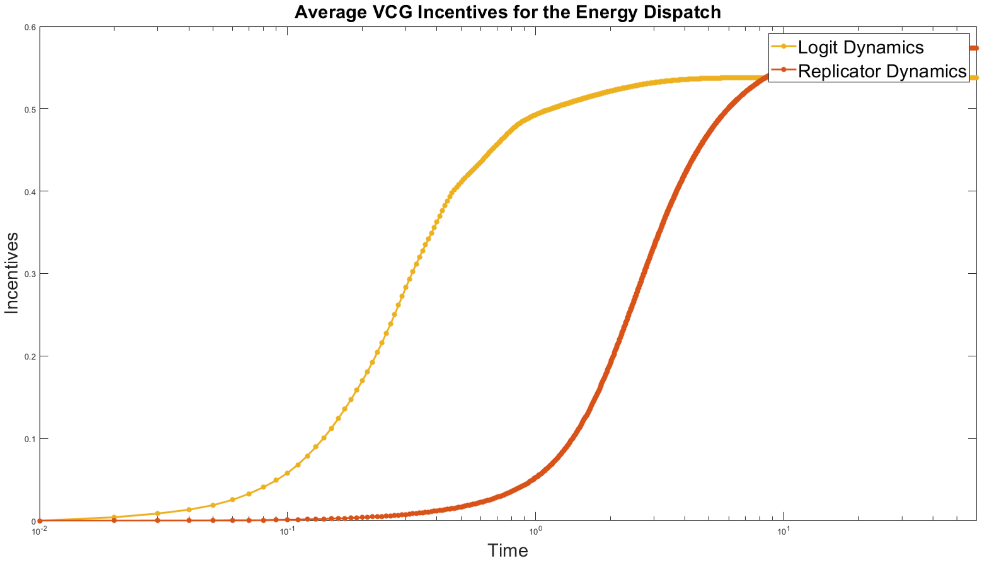


Figure 1.19: Incentives Evolution in the Simulation

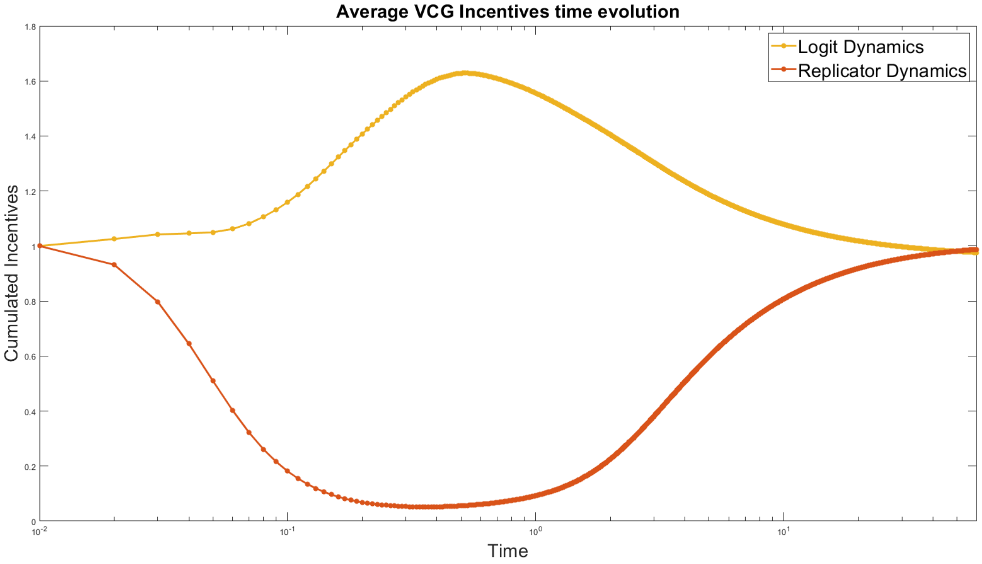
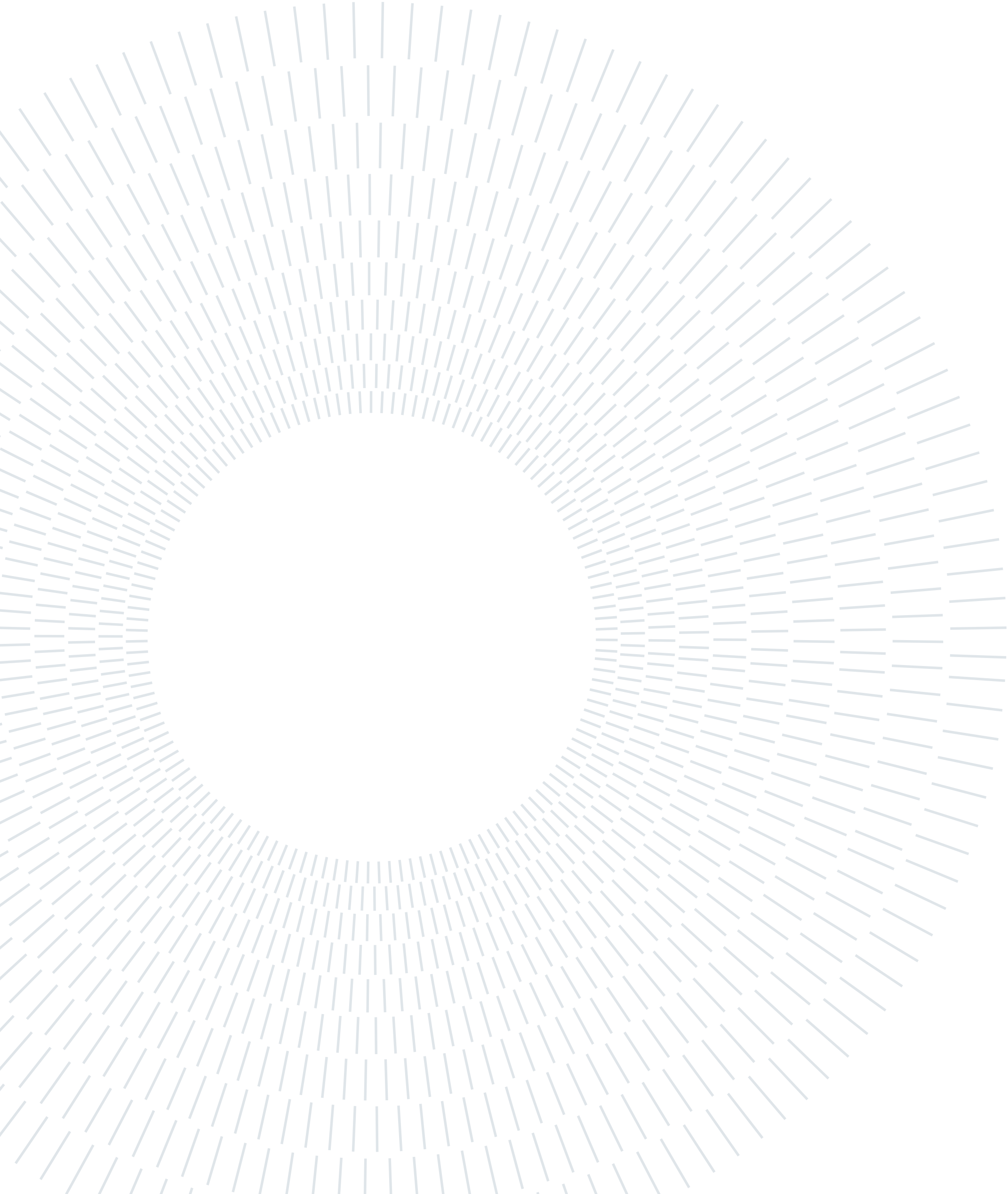


Figure 1.20: Cumulated Incentives Evoluion in the Simulation



2 | The Electrical Power System

> *"Every age thinks it's the modern age, but this one really is. Electricity is going to change everything. Everything!"*
>
> Tom Stoppard

A description of electricity grid infrastructure and its future evolution.

2.1. The Traditional Electrical Power System

The traditional electricity system consists of the physical infrastructure for electricity generation, transport and use on the one hand, and an organised electricity market on the other.

The physical grid, that is, the flow of electricity, consists of electricity generators and electricity-transport systems, which are usually subdivided into systems for transmission over long distances and systems for distribution to residential and industrial consumers of electricity. The electricity market, that is the flow of money, consists of:

- electricity suppliers, who buy electricity from generators and sell it to consumers;
- consumers, who use electricity and pay suppliers via their bills;
- transmission system operators (TSO), who are paid for the long-distance transport of electricity and for ensuring system stability;
- distribution network operators (DSO), who are paid for delivering electricity to consumers;
- regulators, who set rules and oversee the functioning of the market.

2.1.1. The Electric Grid

The electric grid concept is surely one of the greatest engineering achievement of the 20th century: a network connecting electricity generators and consumers via the transmission

and distribution networks.
The electric grid has two fundamental technical properties, which also have an impact on electricity markets:

- Supply and demand of electricity in the grid must always be balanced, otherwise failures (blackouts) will occur.
- The flow of electricity in the grid cannot be controlled. It simply follows the path of least resistance, so that consumers receive electricity from mixed sources.

Therefore, when considering electricity in economic terms as a commodity, it should become clear that these peculiarities are reflected in the electricity market, whose features will be outlined in the next chapter.

2.1.2. Electricity Supply

Electricity generators come in various sizes, starting from rooftop solar panels or small waterwheels (with a generation capacity starting from around 1 kW) to large hydro-electric dams, nuclear or coal power stations (with capacities of several GW).
Generators are rated by their generation capacity, that is, the maximum power they can produce. Firm-capacity generators can be switched on or off on demand, variable-capacity generators instead are dependent on factors like wind or sunshine and are therefore only able to generate certain amounts at certain times.
Generators also differ with respect to the flexibility with which they can be operated. Some generation technologies, such as nuclear, are well-suited for producing a stable amount of electricity over longer periods, while others can change production more rapidly to adapt to fluctuations in electricity demand and in production from variable sources.
Hydro-power is the most flexible (only a few seconds to switch on or off), gas and (to a lesser extent) coal offer some flexibility (minutes to hours, depending on technology and operation), while nuclear is the least flexible form of generation technology, even if in countries where its penetration is extensive (i.e. France) they can be used with a higher level of elasticity.

2.1.3. Electricity Transmission and Distribution

Transmission and distribution are ancillary services needed to support the supply-demand balance of electric power from the generators to the consumers at the distribution grids, to guarantee the continuity, quality and security of the supply. In the traditional grid, transmission and distribution services are provisioned by two different actors: transmission system operators (TSOs) and distribution system operators (DSOs).

2.1.3.1. Transmission Networks

Transmission networks are networked grids of long-distance power lines. High voltages, between 220 kV and 1000 kV are used for reducing transmission losses. Traditionally, transmission networks use alternating current (AC), but high-voltage direct current (HVDC) is emerging as an effective alternative.

Transmission grids are operated on a sub-national or national level by transmission-system operators (TSO) who have the responsibility to secure system stability.

To fulfil this obligation, the TSO uses data on current and projected power generation, the status of the network infrastructure, the capacity that is internationally traded, potential congestion and the flexibility potential that can be offered by power plants and large electricity consumers.

The TSO must guarantee the security of supply by ensuring that the grid always remains stable, which entails meeting the demand for transmission to maintain generation and consumption levels balanced to keep the system's nominal frequency between its nominal limits, which is based on non-local resources such as inertia and automatic and manually activated reserves .

To acquire the flexibility needed, other systems are also put in place to help the TSO to balance the grid: balancing markets, redispatch and the curtailment of renewables.

Redispatch allows the TSO to demand a modification of the intended schedule of power plants (via trading) to secure grid stability. One power plant that is located in front of the congested network line reduces power generation and another power plant behind the congestion increases generation.Therefore, redispatch results in additional costs that are covered by the network charges.

Curtailment, on the other hand, reduces the feed-in from renewable generators and the generators are paid a full compensation fee.

2.1.3.2. Distribution Networks

Distribution networks take electricity from the transmission networks and distribute it to consumers.

They are managed by distribution-system operators (DSO), who connect consumers, install electricity meters and communicate the consumption to the energy suppliers.

Electricity from smaller renewable sources, such as solar and wind, is generally fed into this distribution network.

The distribution system operator (DSO) is responsible for operating, ensuring the maintenance and, if necessary, developing the distribution system in a given area. Where applicable, it is also responsible for its interconnections with other systems and for ensuring the long term ability of the system to meet reasonable demands for the distribution of electricity [77].

More precisely, the DSO is responsible for the operation (and sometimes owner) of the electricity distribution network, from high-voltage grids through primary substations (HV/MV) to the final consumers and for ensuring the agreed power flow between distribution and transmission grids operating at low-voltage, medium-voltage and, in some cases, high-voltage distribution networks.

DSOs technical challenges are mostly local, such as branch congestions, under and overvoltages and network service restoration after local outages by reconfiguring the network or, in the cases of longer interruptions, through emergency generation groups.

The local nature of distribution network problems requires finding feasible solutions within an enclosed geographical area. To do so, DSOs need to foster, as market facilitators, the participation of all types of potential market actors in a non-discriminatory and transparent way [69].

2.1.4. Frequency Control

The transmission system operator (TSO), must comply with the physical grid requirements and coordinate the dispatch of generating units to meet the expected demand of the system across the transmission grid. If there is a mismatch between supply and demand the generators speed up or slow down causing the system frequency (either 50 or 60 hertz) to increase or decrease. If the frequency falls outside a predetermined range the system operator will act to add or remove either generation or load.

In order to keep the expected operating conditions and supply energy to all the users (loads) connected, it is important to control the grid frequency within predefined limits, to avoid unexpected disturbances that can create problems to the connected loads or even cause the system to fail.

Frequency variations in a power system occur because of an imbalance between generation and load; when the frequency value of a power system reaches the emergency condition, the control strategy is initiated.

Frequency control is divided in three levels: primary, secondary and tertiary controls. Each frequency control has specific features and purposes.

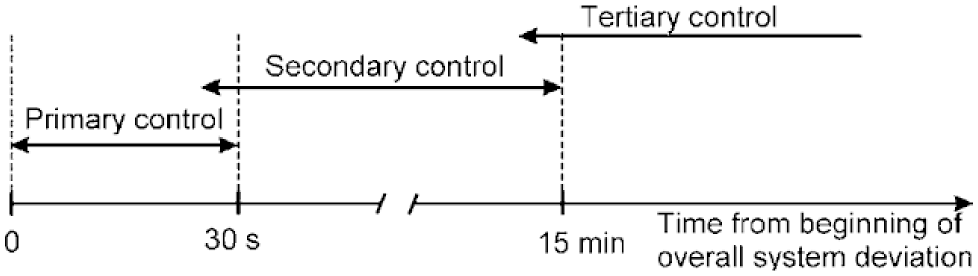


Figure 2.1: Timing of Frequency Control

2.1.4.1. Primary Control

The primary control is an automatic function and it is the fastest among the three levels, as its response period is a few seconds. It consists of changing a generating unit's power versus the frequency, according to its static generation characteristic as determined by the speed governor settings.

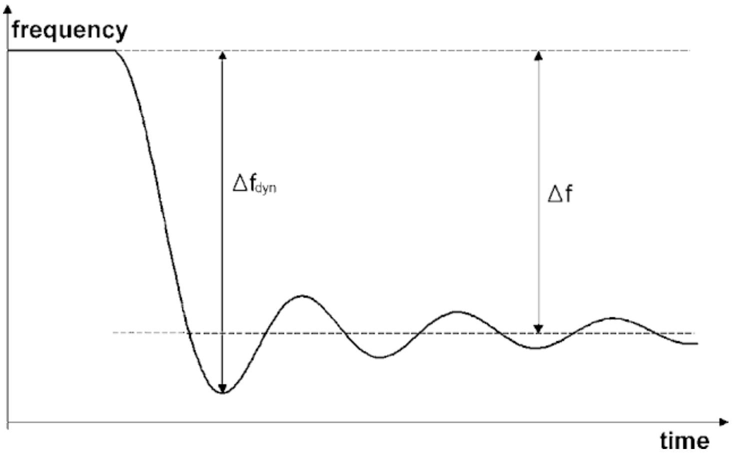


Figure 2.2: dynamic Δf_{dyn} and quasi-steady-state frequency Δf deviation

The objective of primary control is to re-establish a balance between generation and demand within the synchronous area at a frequency different from the nominal value. This is done at the expense of the kinetic energy of rotating masses of generating sets and connected motors.

For example, with a load increase, the generated power doesn't immediately change, so the energy to compensate for this load increase arrives from the kinetic energy of the rotating generators that start decreasing the velocity (inertial response). After this moment, the speed controller of each generator acts to increase the generation power in order to recover this speed decreasing and try to clear the imbalance.

Under normal conditions the system operates at nominal frequency, maintaining the condition of equality of generated power and demand. Each disturbance of this balance causes a change in frequency and when this attains the maximum deviation of dynamic frequency deviation Δf_{dyn} the primary controllers of all generators subject to primary control act to respond within a few seconds.
The controllers alter the power delivered by the generators until a balance between the power output and consumption is re-established and when the balance is reestablished, the system frequency stabilizes remaining at a quasi-steady-state value, which differs from the frequency set point.
Generally, in about 30 seconds, each generation unit shall be able to generate the required additional power and then keep it for at least 15 minutes (this timing depends on the requirements of the TSO).
All the generation plants connected in the HV power system are called to supply this service, except the renewable energy source (RES) not schedulable, so, for this reason each generation unit shall have a dedicated and proper "reserve" power in order to accomplish this regulation when active.
The service is mandatory for all the generators entitled to provide it and not remunerated.

2.1.4.2. Secondary Control

Once the primary regulation accomplished its target, the frequency value is different from the nominal one, the reserve margins of each generator have been used and also the power exchange between the interconnected power systems is different from the predefined one. So, it's necessary to restore the nominal value of the frequency, the reserve of each generator previously used, and the power exchange among the power systems: this is the purpose of the secondary control.
In practice, the demand varies continuously, even without having forecast errors, so that secondary control on a real-time basis is required on a continuous basis.
In order to perform this task, there are some generators entitled to perform the secondary control, through a dedicated reserve power. This reserve depends on the requirement of each TSO and usually, it's a percentage of the maximum power available, with a predefined minimum value to guarantee, independently from the maximum power of each generator.
If the frequency value is less than the nominal one, additional generation capacity needs to be started, while if the frequency value is higher than the nominal one, some generation capacity must be stopped, or the load has to increase.

Whereas during primary control all systems provide mutual support, only the system in

which the unbalance occurred is required to undertake secondary control action. The controller of this system activates appropriate secondary control power restoring the nominal frequency and scheduled power exchanges.
In order to provide effective secondary control, the generating units that contribute to this control process must have sufficient power reserve to be able to respond to the regulator signal with both the required change in generated power and the required rate of change. The rate of change in the power output at the generator terminals significantly depends on the generation technique.
Typically, for oil or gas-fired power stations this rate is about 8% per min, for lignite-fired and hard-coal-fired power stations it is up to 2% and 5% per min, respectively, and for nuclear power stations this rate is up to 5% per min.

The secondary control is usually performed in an automatic way, by all the generators that participate to this regulation, through specific "set-point" sent by a central controller. This service is usually remunerated according to the negotiation condition in each energy service market

2.1.4.3. Tertiary Control

Tertiary control is any automatic or manual change in the working points of the generating units participating, in order to restore an adequate secondary control reserve or to provide desired (in terms of economic considerations) allocation of this reserve within the set of generating units in service.
Tertiary control acts similarly to secondary control, and as this one, it is a remunerated service in the grid. In general, it may be achieved by means of:

1. changing the set operating points of thermal power plant generation sets, around which the primary and secondary control acts;
2. connection/disconnection of pump storage hydro power stations or gas turbines operated at an intervention mode;
3. altering the power interchange program;
4. load control (centralized telecontrol or controlled load shedding).

Where the frequency variation exceeds the permissible range, due to a significant loss of generation or consumed power, the system conditions are deemed impaired (emergency) conditions.
In such circumstances supplementary actions are needed in order to re-establish the active power balance. These include:

1. Emergency load tripping (system load shedding) in case of a major frequency drop;
2. Emergency disconnection of generators in case of a large frequency increase.

The following non-usable capacity must be taken into account in the calculation of capacity needed to meet power requirements in view of tertiary control capability:

1. units subject to long-term shutdown;
2. units shut down for repair and maintenance;
3. limits on capacity associated with restrictions in fuel supplies (e.g. restrictions on gas supplies during the peak winter months);
4. limits on capacity associated with environmental restrictions
5. limits on the capacity of hydroelectric plants associated with hydraulic and environmental constraints
6. reserves to cover variations in production and consumption (secondary and tertiary reserves).

2.2. Towards the Next Generation Electricity System

After Paris Agreement (2015) many countries are in the process of transforming their economies with the aim of reducing GHG emissions: electricity is expected to play a key role in this low-carbon transformation.
First, more efficient electricity use and a growing share of electricity from renewable sources will help reduce GHG emissions from electricity generation.
Second, the share of electricity in total energy use is expected to grow, especially in the transport sector (electric vehicles) and in heating and cooling (electric heat pumps). Making all of these changes happen requires significant investments in electricity generation, transport, distribution and in electrical consumer goods.
In addition, investments and innovation are needed to ensure the stability of the electricity supply in the face of higher demand and an increasingly variable supply from renewable sources that depends on unpredictable sunlight, wind and rainfall. The challenge is how to enable these investments while keeping electricity reliable and affordable for both households and energy-intensive industries.

To face all these challenges together, the electricity grid as we know today, needs to be remodelled and this should be done through the following series of measures:

- encouraging investments in flexible low-carbon electricity generation;

- encouraging investments in a stable and adaptable grid that is fit for a growing share of renewables;
- incentivising the use of energy-efficient equipment and consumer goods;
- providing affordable and reliable energy for industry and households.

This calls for significant changes with respect to the transmission and distribution networks as well as the rules governing electricity markets, which were designed at a time when electricity generation was concentrated at comparatively few and dispatchable conventional power plants with large generating capacities.
The trend goes towards prioritizing intermittent RES (which can operate at almost zero marginal cost) at the expenses of fossil fuel or nuclear plants when possible, and at the same time keep in reserve power plants that are only used in cases of peak demand, making it more and more difficult for conventional electricity generators to earn money with plants that operate only some of the time and at higher wear and tear rates.

While the phase-out of high-carbon plants should be welcomed with praise, however it is largely unlikely that the grid of the future will be self-sustainable by virtue only of renewable sources: hence, a higher degree of interconnection is advisable, supporting the development of power plants which can allow the same reliability of the grid at a low carbon impact.

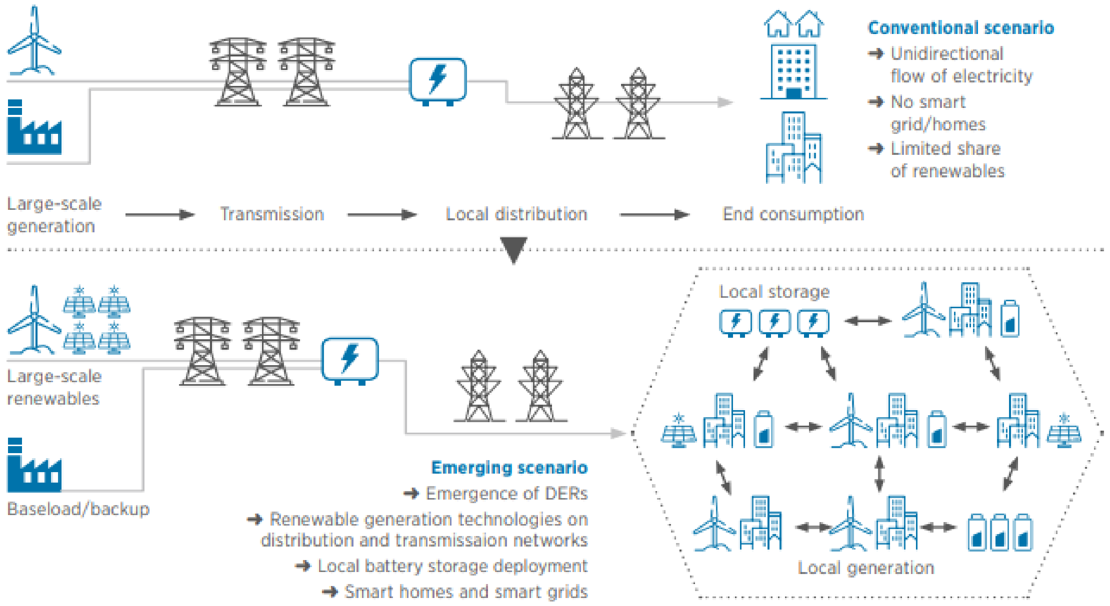


Figure 2.3: Conventional scenario versus emerging scenario in the power system due to the emergence of distributed energy resources

2.2.1. Grid Technologies

In the past decades disruptive technologies have paved the way towards the promises of a next generation grid.

First, the improvement of transformers and power electronics has enabled an efficient conversion between different power voltage levels also for Direct Current (DC). This provides the basis for the development of the HVDC transmission technology, which allows to cover longer transmission distances compared to AC.

This allows respectively for an easier integration and interaction of distributed energy resources like photovoltaics or batteries and therefore an increased efficiency at the low-voltage level.

Second, high-temperature superconductors have emerged: materials which thanks to their low impedance might be able to significantly enhance grid capacities in the future, enabling longer HVDC connections with high current carrying capacities.

2.2.2. Electricity Transmission and Distribution

The relationship between transmission system operators (TSO) and distribution network operators (DSO) is changing.

The increase of non-dispatchable and less predictable distributed generation and the progressive decrease of conventional dispatchable generation is making the balance between supply and demand harder to achieve, which emphasizes the relevance of balancing ancillary services, either mandatory or remunerated.

At the same time, this is also transforming the distribution grids from passive to active grids by accommodating many of the new power system resources and increasing the operational complexity and responsibilities of distribution system operators.

Examples of these trends are the electrification of energy consumption and the increasing volume of distributed generation being connected to the distribution grid.

To achieve a closer interaction between TSOs and DSO grid monitoring has to be implemented, communication between TSO and DSO has to be established and means of communication between the DSO and its flexible customers have to be available. DSOs should also be able to perform (quasi) real time network simulations with input from measurements on the grid.

Such technical requirements should not be underestimated regarding implementation and operational cost, complexity and skills required.

Nonetheless, only the distribution grid operator has information about the actual grid configuration and grid loading. This means that even when other entities take up certain

roles, the distribution network operator will always be responsible for monitoring the grid and will need to implement communication solutions to one entity or another.
With the current status of technology, technical requirements for an evolved interaction between TSOs and DSOs can be met. However, several non-technical issues, or points of discussion, have still to be clarified.

Flexible demand and generation can be used to support grid operation and avoid or redirect infrastructure investments; however the flexibility available by curtailing renewable energy sources needs to be limited to avoid a high loss of renewable energy.
The question about introducing markets among local operators or using appropriate bilateral contracts is still open such as the possibility to create a regulatory framework or contracts between flexible customers and network operators, facilitating the use of flexible generation and demand for grid operation purposes.
Even in this case, when the combined flexibility of customers on the distribution and transmission grid is used, favoring one set of customers at the cost of the other should be avoided.
Although most of these technical aspects remain open and are regulated different among countries or even among regions in the same country, a clear policy framework is to be reached and it will, in every case, push forward investments in Smart Grid solutions to deal with the challenges that grid operators are facing.

2.2.3. Electricity Supply

As it has been considered at the beginning of the chapter, the peculiarity of electricity lies in that it is by nature difficult to store and has to be available on demand. Consequently, unlike other products, it is not possible, under normal operating conditions, to keep it in stock, ration it or have customers queue for it. Furthermore, demand and supply vary continuously.
Traditionally, non-flexible generators have been used for serving the base load (the normal level of electricity use), while flexible generators have been used for meeting peaks in demand. With the increased share of variable capacity, such as wind and solar, more flexible generation capacity is needed to satisfy demand when production from variable generators is low.

To ensure security of electricity supply however, enough generation capacity must be available to meet demand at all times and the supply-demand balance, as just described, is traditionally done in the short term with the scheme of primary reserves (activated within seconds), secondary reserves (activated within a few minutes) and tertiary reserves (activated within 15 minutes).

The continuous growth of RES and the reduction of thermo-electric plants in operation, creates therefore new challenges in performing this frequency regulation, because apart from the intermittent nature of RES, there will be a decreasing inertia in the whole grid with a higher risk of sudden shutdowns.

Moreover, if RES generators should be able to adapt and modulate their power at will, this could be feasible in case of over-frequency, which requires power decrease; however it could be really complex in case of under-frequency, which would require a power increase, not always possible (even with a reserve power) due to the volatility of the primary resource itself.

Luckily there are already different solutions under analysis and some of them already in place in several power systems (battery energy storage systems are among the most promising).

2.2.3.1. Electricity storage technologies

Energy storage allows to partially loosen a tight constraint posed by the use of electricity as energy carrier and increases the elasticity in balancing supply and demand because it allows to shifts the delivery time of electricity.

However, storage is expensive and losses of energy occur in the process.

More recently, energy storage has gained increasing attention, due to advances in storage technologies like batteries, pumped hydropower, compressed air, flywheels, superconducting magnets, or supercapacitors.

Each of these technologies has advantages either regarding the capability to absorb, respectively to provide power or the ability to store energy.

Hydro technologies that have gained special importance are pumped storage facilities or hydroelectric reservoirs, as they may provide electricity storage in addition to generating electricity. However, pumped hydro-storage also has some drawbacks with respect to start-up and ramping constraints, leading to efficiency losses compared to, e.g., battery solutions.

Battery solutions, or electrochemical storage in general, are likely to grow in capacity in the near future.

Concerning different battery technologies, there are different advantages and disadvantages: redox flow batteries allow flexible layouts and long lifetimes, while charging and discharging rates cannot yet compete with lithium-ion batteries, which display a high round-trip efficiency, as they exhibit little self-discharge.

Overall, battery systems are still very expensive, but are expected to become less expensive in the future. The overall high efficiency constitutes a major argument in favor of electrochemical storage solutions.

Pumped heat storage is an established concept, which allows to store heat as molten salt; compressed air technologies are quite mature, but still exhibit significant start-up costs as well as a low efficiency in reconverting electricity. Supercapacitors exhibit quick response and long lifetimes, but are limited in their storage time.

Flywheels possess quick response times and are frequently employed as primary reserves; besides, they allow the grid to gain a portion of the inertia lost with the phase-out of large fossil fuel plants.

Granting the possibility to cover gaps in the supply-demand, storage technologies become a fundamental block in the next generation grid, providing flexibility not only on the supply side, but also on the demand side, since they can locally accommodate the consumers' demand. Because of that reason, they will be taken into account in the following, where demand-side flexibilities will be discussed in light of technological developments.

2.2.4. Electricity Demand

In the past, electricity demand was mainly inflexible. As there has not been a regular, intensive information exchange between electricity suppliers and consumers (often only once a year for billing), the electricity generation has been congruent to standard load profiles, which described the consumption behavior of different electricity consumer groups during a day.

Introducing the concept of demand-side management, research made first efforts to make electricity demand flexible in the late 1970s [33].

The underlying technology was however fairly simple, requiring a one-way communication and more similar to an incentive policy rather than to a real-time price policy.

The liberalization of the electricity markets in many countries offered the opportunity to provide and actively market demand-side flexibilities.

Even if it were theoretically possible for electricity consumers on electricity markets to benefit from price fluctuations, today it is predominantly large consumers that react to market prices.

Demand flexibility comes at certain costs and is characterized by different restrictions: for instance, certain home appliances or industrial core processes may not be interrupted or delayed without significant losses in utility or product quality.

Focusing on industrial demand flexibility, a temporal shift of production processes may cause rescheduling costs as well as production inefficiencies which may translate into higher costs for fuel, labor or maintenance.

To exploit demand-side flexibilities also on a smaller scale and to better integrate the demand side into the future electricity system, the introduction of smart meters, but also other smart devices, is an important step for enabling intelligent technologies for electricity demand.

2.2.5. Information Technologies

In addition to engineering-driven changes, energy systems are also affected by recent advances with respect to digital technologies, being enabled by developments in both hardware and software components.

More precisely, improvements in hardware lead to an increase in data transmission and processing speed, while sophisticated software applications further support automated and autonomous decision making by software agents as well as resilience, security, and enhanced encryption technologies.

First of all, information technologies help collecting information about the electricity system in order to gain insight into its current state. Thereby information technologies increase the transparency about the state of the grid, the electricity market and all other components of the electricity system.

For example, sensor technologies allow to collect raw data on the temperature of transmission lines, which network operators can use to determine network utilization more precisely.

Market players can use data transmission technologies to transmit the data from the place of collection in near real-time. They can then use the data to evaluate the state of the system and make decisions accordingly.

Employing cloud- and high-performance computing and data analytics makes it possible to convert raw data into information, again increasing the transparency of the system since this supports an interpretation of the current state based on processed data.

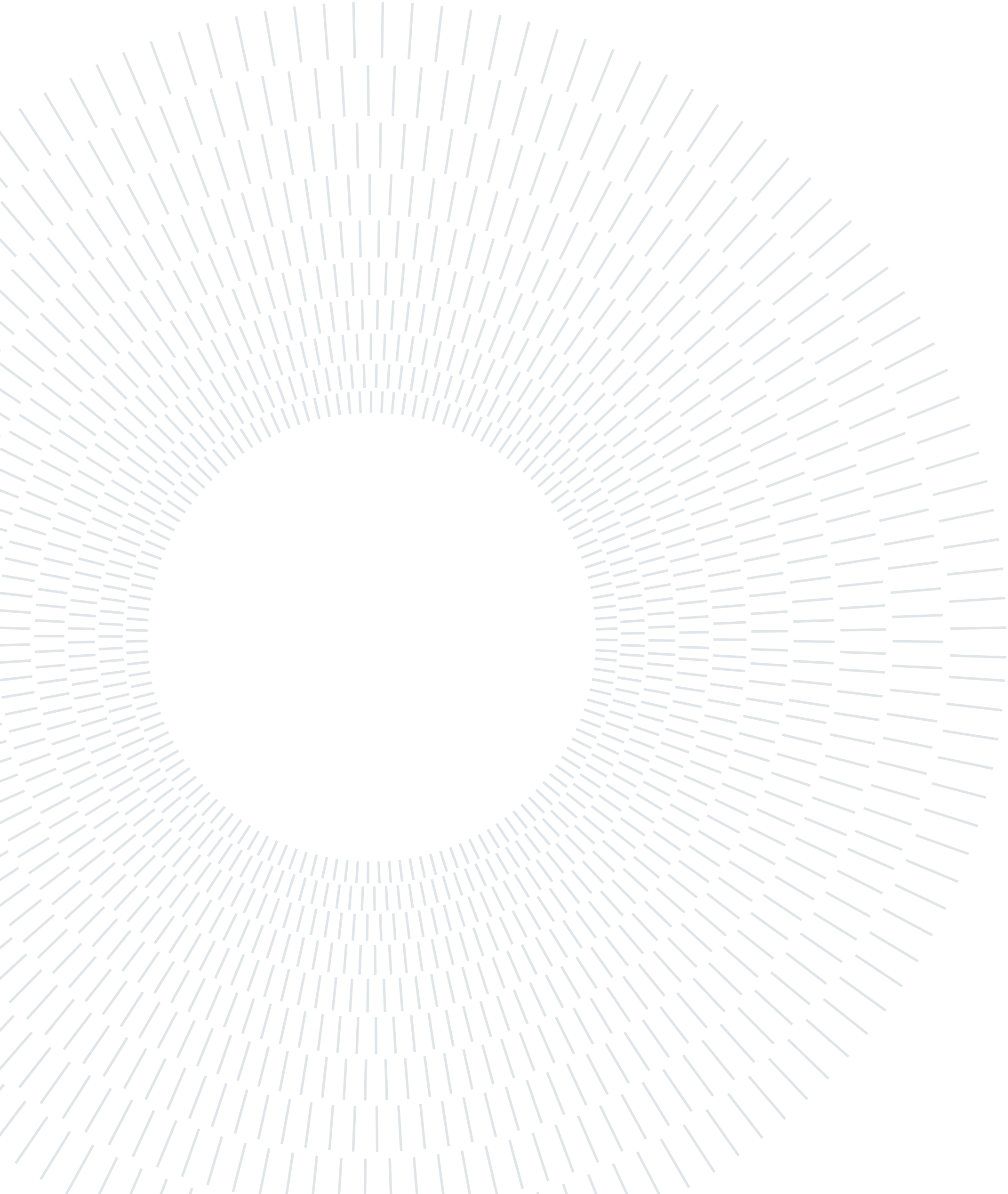
Secondly, information technologies help participants in the electricity system to create knowledge faster and to share it easier. Technologies like Artificial Intelligence can therefore take an important role in the generation of knowledge out of the ever-increasing amount of data and information generated, transmitted, and processed by sensor, transmission, computing and analytics technologies.

Examples for the generation of knowledge by the use of AI in the electricity system are the design of pricing mechanisms and incentive schemes for demand response as well as the customer segmentation in the electricity system depending on the specific loads of the individual consumers.

More recently, blockchain has been tested in the energy sector for sharing information and knowledge among parties that do not necessarily know each other trustworthy.
Although in principle blockchain may generally consume more electricity than centralized database technologies, the electricity consumption of blockchain is by far not as high as often claimed.
Blockchain helps digitizing processes that centralized database technologies cannot digitize. This may even save more electricity than blockchain consumes [68].

Moreover information technologies allow an increased automation of electricity systems, leading to, e.g., automated decision-making and trading on electricity or flexibility markets.
With respect to algorithms used for market clearing, advances in optimization approaches and equilibrium algorithms have been particularly relevant in the past and will continue to be at the core of market clearing in the future.
Regarding the automated exchange of information, digital platforms, in combination with other information technologies such as data transmission and database technologies, may also play a key role.
For instance, market players may use platform technologies to automatically trade electricity and, thereby, match based on supply and demand information.
Taken together, the increasing automation of electricity systems calls for adjustments to market design, as a set of new players like automated software agents, become active on electricity markets.
Automated trading in turn allows to carry out market interactions at an increasing speed, allowing for shorter bidding intervals or real-time continuous trading.

It's mainly thanks to these disruptive innovations in IT field, that many of the inefficiencies present in today's grid can be tackled without loss of transparency, with benefits for all the players, from the small consumers to the large suppliers: to encourage the transition it's however necessary to rebuild the energy market, which is the topic of the next chapter.



3 | The Market of Electricity

> *"High energy prices will have a large negative effect on the California economy and could possibly drag the rest of nation into a recession"*
>
> Doug Ose

A description of the complexity of Energy Market, from wholesale to retail, focusing the attention on the consequences for consumers' bills and how real-time pricing could improve transparency and energy dispatch efficiency

Even if it presents peculiar characteristics, in economic terms electricity is just a commodity capable of being bought, sold, and traded. An electricity market, or power exchange, is an organized and regulated system enabling purchases (through bids) and sale (through offers).

Bids and offers use supply and demand principles to set the price. Long-term contracts are similar to power purchase agreements and cane be generally considered as private bi-lateral transactions between counterparties.

Prior to the 1990s, most investor-owned electric utilities were regulated and vertically integrated, which means the utilities owned electricity generators and power lines (distribution and transmission lines). Today, only one third of U.S. electricity demand is serviced by these integrated utility markets because many states have abandoned this system in favor of deregulation. After the 1990s, most occidental countries have lived a wave of liberalization of energy markets, in order to avoid monopolistic and oligopolistic behaviours from the retailers, promote competitiveness among energy suppliers and to protect consumer rights.

This transition, known as restructuring, required electric utilities to sell their generating assets and led to the creation of independent energy suppliers that owned generators. Because each new independent energy supplier could not cost-effectively create their own power line infrastructure, electric utilities held onto these assets and became transmission and distribution utilities, which continue to be regulated.

In different deregulation processes the institutions and market designs were often very

different but many of the underlying concepts were the same, i.e. separate the potentially competitive functions of generation and retail from the natural monopoly functions of transmission and distribution and establish a wholesale electricity market and a retail electricity market.
The biggest impacts resulting from deregulation were changes to retail and wholesale electricity sales, with the creation of retail customer choice and wholesale markets, together with ancillary services markets for transmission and distribution.

As of today, in the path towards a full decentralization and coordination of the grid, electricity market needs to undergo major restructuring because of increased difficulties in scheduling the dispatch and the feasible technical possibility to introduce demand-side flexibility.

3.1. Energy Markets

Energy markets are organized as auctions that are used to coordinate the production of electricity on a day-to-day basis.
In an energy market, electric suppliers offer to sell the electricity that their power plants generate for a particular bid price, while load-serving entities bid for that electricity to meet their customers' energy demand.
Supply side quantities and bids are ordered in ascending order of offer price; the market "clears" when the amount of electricity offered matches the amount demanded, and generators receive this market price per megawatt hour of power generated at the market clearing price.

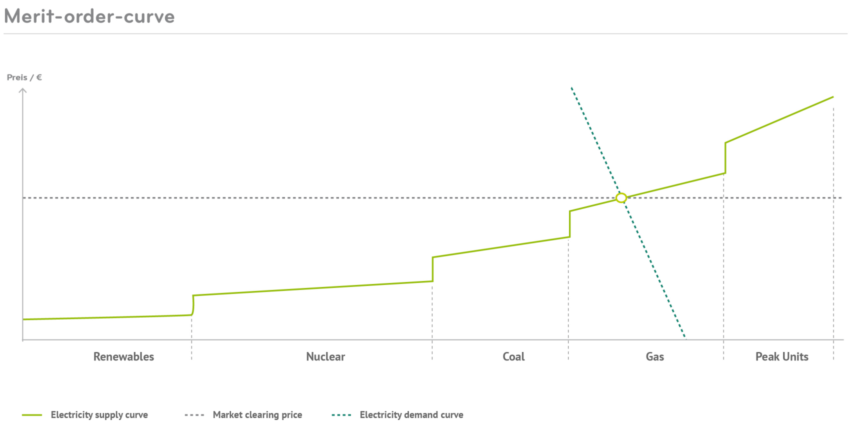


Figure 3.1: Intersection point corresponding to the Market Clearing Price in Electricity Market

In particular, the notion of electricity markets usually refers to a multitude of sequential markets, eventually determining the actual dispatch.
Aside from these markets, several short-term corrective measures have evolved in order to ensure constant balance of supply and demand.

In the first place, electricity market can be divided between wholesale market (between suppliers and retailers) and retail market (between the retailers and final consumers). Wholesale market is usually structured on auction and bilateral contracts, while retail market refers to the contracts stipulated between retailers and consumers with the definition of the final tariffs.

3.1.1. Wholesale Electricity Market

A wholesale electricity market exists when competing generators offer their electricity output to retailers. The retailers then re-price the electricity and take it to market.

Wholesale markets are usually integrated on a transnational regional level and its participants are generators, electricity suppliers and large consumers.
Being related to a particular commodity like electricity, the wholesale power market can be distinguished based on the way the deals are reached, i.e.via a power exchange for free-trade, through an over-the-counter (OTC) deal, or with an organized OTC market which is cleared continuously. Wholesale market differ among countries, but they share a common structure which is similar for liberalized energy markets. In the following, when not explicitly stated, E.U. market will be taken as representative.

With respect to the time sequence of power markets, the futures and forward markets are the first to mention.
They offer market participants the opportunity to optimize their portfolios in the medium to long term and to financially hedge future delivery transactions.
Futures can be traded on the power exchange using standardised products, while forward contracts are usually bilaterally agreed in OTC deals.

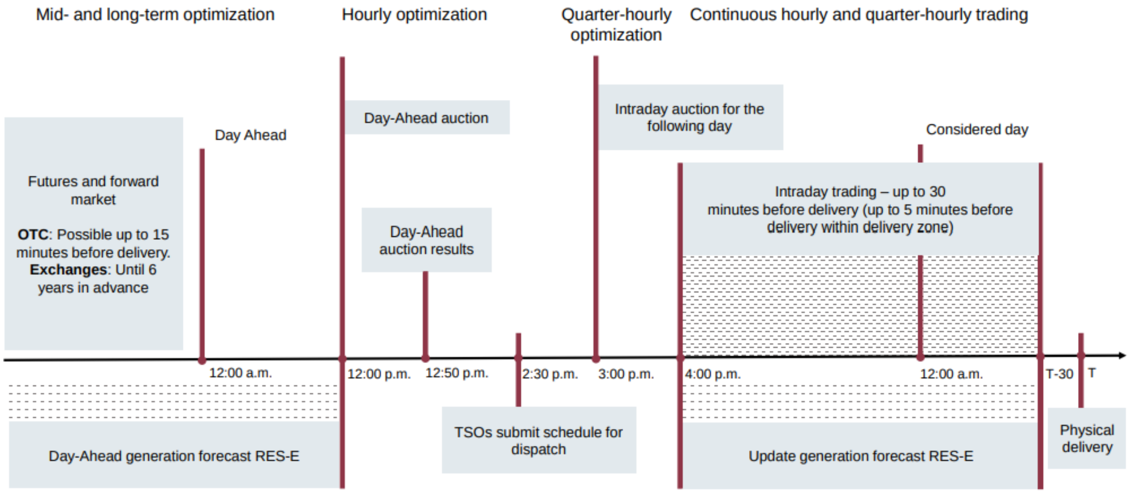


Figure 3.2: electricity market timescale [23]

In the day-ahead auction, bids for the following day can be submitted by 12 P.M. on any day of the year.
The auction results are published at 12:40 P.M. and the price of the last accepted bid determines the single market clearing price.
The price (in E.U.) is limited to the range between -500 EUR/MWh and 3000 EUR/MWh.

The intraday market stands out between the intraday auction and continuous trading on the intraday continuous market. The auction enables market participants to optimize on a quarter-hourly basis following the hourly optimization on the day-ahead market.
The auction design is similar to the day-ahead auction, with prices ranging from -3000 EUR/MWh to 3000 EUR/MWh.

Following the intraday auction, continuous intraday trading for hourly contracts and blocks of combined hours will start at 3 P.M. and enables the continuous adjustment of trading volumes to intra-hour changes in production and consumption.
Continuous trading is based on a "pay-as-bid" auction format, which means that there are no uniform prices for the products, but rather different prices for the same product depending on the supply and demand at the time of the trade. Moreover, intraday trading is seen a key component for direct marketing of power produced by renewable energies when quickly-changing weather forecasts result in an unplanned shortfall or surplus of power from solar or wind power plants.

A consequence of the complexity of a wholesale electricity market can be extremely high price volatility at times of peak demand and supply shortages.

The particular characteristics of this price risk are highly dependent on the physical fundamentals of the market such as the mix of types of generation plant and relationship between demand and weather patterns. Such price risks can be highlighted by price "spikes" that are hard to predict.
Volume risk is often used to denote the phenomenon whereby electricity market participants have uncertain volumes or quantities of consumption or production. For example, a retailer is unable to accurately predict consumer demand for any particular hour more than a few days into the future and a producer is unable to predict the precise time that they will have plant outage or shortages of fuel.
Electricity retailers, who in aggregate buy from the wholesale market, and generators who in aggregate sell to the wholesale market, are exposed to these price and volume effects, so to hedge the risk they make extensive use of forward and futures ensuring a more stabile "strike" price.

While wholesale pricing used to be the exclusive domain of large retail suppliers, increasingly markets are beginning to open up to end-users. Large end-users seeking to cut out unnecessary overhead in their energy costs are beginning to recognize the advantages of such a purchasing move.
This opportunity goes hand-in-hand with the introduction of substantial amounts of intermittent RES, so that participation in intraday market for small prosumers could represent an ulterior opportunity to manage flexibility.

Advances in computational power and optimization algorithms may allow for even finer time granularity that may even get close to real-time, hence price signals may reflect flexibility almost immediately and thereby incentivize efficient short-term flexibility offers and long-term investments in flexible production technologies.

Buying wholesale electricity is certainly not without drawbacks (market uncertainty, membership costs, set up fees, collateral investment, and organization costs). However, the larger the end user's electrical load, the greater the benefit and incentive to make the switch, so that if end-users could associate in "microgrid" communities and buy electricity together on the wholesale market, they could profit from the participation in such a market instead of the retail one.

3.1.2. Retail Electricity Market

A retail electricity market exists when end-use customers can choose their supplier from competing electricity retailers.
Suppliers buy electricity from generators, sell it to consumers and send invoices featuring

the price charged for the electrical energy delivered, transmission and distribution, as well as taxes that are sometimes used to support production of renewable energies.
Competitive retail needs open access to distribution and transmission wires. This in turn requires that prices must be set for both these services. They must also provide appropriate returns to the owners of the wires and encourage efficient location of power plants.

In deregulated areas, electricity customers have the option of selecting an electric supplier rather than being required to purchase electricity from their local electric utility.
This introduces competition for retail electricity prices because many electricity suppliers can exist within a region offering competitive prices.

For consumers, there are both advantages and disadvantages in selecting a supplier other than their local utility company. Retail competition in fact can help to lower a customer's electric bill and tailor their energy use to their preferences, such as by selecting a "clean energy" supplier.
However, independent companies often require customers to sign contracts, which can lock them into a set electricity price for multiple years.
While fixed rates could be beneficial for some customers, they could also negatively impact others if the rate they agree to ends up being more expensive than the rate set by the local utility. Moreover, if payments are not based on the real-time price, there is no incentive to reduce demand at times of high (wholesale) prices or to shift their demand to other periods.

In order to reduce peak demand, a retail market incorporating demand-response mechanisms would be beneficial to the grid.
New technologies are now available which may be better suited to real-time market pricing.
The real-time market price and control system for instance could turn home electricity customers into active participants, actively managing the power grid and their monthly utility bills. [78]
Customers would be allowed to set limits on how much they would pay for electricity to run an appliance and electricity providers willing to transmit power at that price would be alerted over the grid to sell electricity accordingly. Further, the electricity suppliers could perform real-time market analysis to determine return-on-investment for optimizing profitability or reducing end-user cost of goods.
The effects of such a competitive event-driven retail electricity market are difficult to forecast, but generally [28] appear to lower prices in contexts with high participation and raise prices in contexts that have little customer participation.

3.2. Balancing Markets

Balancing markets consist of balancing capacity markets and balancing energy markets. After trading in the intraday market closes, the balancing mechanism is put in place to ensure that supply equals demand in real-time.
In electricity networks in fact it is crucial to maintain the frequency at a constant level, therefore, supply and demand have to be balanced at every point in time and at every node of the network. To achieve that, the TSOs are legally obliged to guarantee system stability by providing system services.
To do so, each TSO organises balancing markets where it caters the resources needed to balance the system.

Electricity retailers are required by the TSOs to support enough generating capacity to meet the forecasted load plus a reserve margin to maintain grid reliability. In order to meet these requirements, TSOs run a capacity auction to provide retailers with a way to procure their capacity requirements while also enabling generators to recover fixed costs, i.e. costs that do not vary with electricity production and that may not be covered in the energy markets alone.
The capacity market auction works as follows: generators set their bid price at an amount equal to the cost of keeping their plant available to operate if needed.
Similar to the energy market, these bids are arranged from lowest to highest. Once the bids reach the required quantity that all the retailers collectively must acquire to meet expected peak demand plus a reserve margin, the market "clears" when supply meets demand.

As described in the previous chapter, the TSOs tender volumes for three types of balancing energy at the balancing capacity markets. Primary balance is a symmetrical product, as participating units have to provide both positive and negative balancing energy: the TSO acquires capacities according to the merit order of capacity prices and no further remuneration is paid.
Secondary and Tertiary balances are similar and differ in relation to the activation time. Secondary balance is activated automatically, whereas tertiary is controlled remotely by the TSO. Capacities for both are activated based on a merit order of capacity prices as well. However, the retrieval of energy is activated according to the merit order of bids submitted at a second energy market.
Consequently, the generators contracted in the balancing capacity market offer their bal-

ancing energy in the balancing energy markets, with the volume of activated energy depending on real-time imbalances.

Payments to generators in the capacity market are essentially a reward for that generator being available to operate and provide electricity if needed. Were it not the case, retailers would be incentivized to trying in getting more allocated energy than needed. Consequently, if generators are unavailable to operate during a time when they are called upon, they may face fees under capacity performance requirements, as well as retailers, costs.

In contrast with the actual design, to outline an electricity market more and more closed to real-pricing, there is a debate as to whether capacity markets are still necessary or whether an energy-only market with time-variant pricing can provide sufficient incentives for the provision of spare capacity.

3.3. Redispatch Markets

Network congestion is mainly addressed by redispatch and feed-in management.
Redispatch refers to the intervention ordered by the TSOs in the originally dispatched flow of conventionally generated electricity to shift the feed-in to either prevent or remedy grid congestion and violations from operational limits.
The prediction of congestion occurs mainly after the day-ahead auction.
Based on this prediction it is necessary to reduce the power feed-in of conventional power plants "before" the congested transmission lines and to increase it "behind" the bottleneck.
The two main redispatch approaches involve cost-based and market-based redispatch.
In the first case, generators forced to redispatch will be reimbursed for the incurred costs; in the second case instead, the compensation for affected generators is according to their bids.

In case of remaining congested transmission lines, Distribution System Operators (DSOs) can use feed-in management almost as a matter of last resort to reduce the in-feed of electricity generated by RES as well as combined heat and power generators.
Therefore, feed-in management only applies when it is imperative due to system security.
Aa a consequence of the increased installed capacities of renewable energy without expanding grid capacities or without adopting an appropriated demand-response mechanism the incidents and volumes of feed-in management are likely to increase, as well as redispatch measures.

3.4. A Successful Electricity Market Design

The advent of liberalization of the electricity market introduced many advantages to the grid and benefits for consumers in terms of reliability, transparency and resources allocations, which almost always translated into an optimal choice for the governments which implemented it.
However, even if deregulation was well received in most of countries, it certainly brought some drawbacks when it was not well designed for the market it was introduced.

The most iconic example regards California, where in 2001 a flawed regulation of retail competition led to the California electricity crisis and left incumbent retailers subject to high spot prices but without the ability to hedge against these [72]. An 800% surge in spot prices on the wholesale market lead to multiple blackouts and multiple retailers bankruptcies, accounting for a loss of between 40 and 45 million dollars. In UK, as well, a retailer (Independent Energy) with a large customer base went bankrupt when it could not collect the money due from customers.

Those example show unmistakably how a not properly designed market can lead to heavy losses; hence, in virtue of the challenges posed by decentralization and the energy market of the future, in the next sections some of these challenges will be underlined, together with the possible optimal design solutions.

3.4.1. An Imperfect Electricity Market

As an example of deviation from an optimal market design, with a focus on the pricing policy, it is presented an electricity market with strategic opportunities for the suppliers, that can be encouraged to bid differently from the theoretical optimal marginal cost as described in [27].

Marginal cost bidding theory expects that power suppliers bid on the market according to its production cost, including all costs that are production dependent: this fact however does not necessarily reflect the way electricity producers bid in the market in reality.
In practice, during scarcity hours for instance, prices tend to go higher than the production costs of any production unit, simply because these instants are the only ones at which peaking plants can recover their fixed costs. Especially in the case where energy supply is provided by few entities, bidding strategies may surge as a strategic movement.

In perfect competition, no market participant is able to affect the market price and after

bids, the MCP is set at the intersection of the supply and demand curves and cannot be affected by buyers, nor sellers. Bidding any price higher than marginal costs would eliminate profitable sales without any corresponding gain from the higher price.
In such a market, there is no incentive to issue a bid above marginal costs, as the probability of the bid being executed is significantly reduced when considering an infinite number of sellers.
In reality however there is limited number of market participants with different technologies, each with a different cost structure. Furthermore, a supplier can be the owner of several multiple generator units, even of different technologies. In this case, a successful use of the strategic bidding can increase a supplier profit without lowering its production costs.

When not properly designed, modern electricity markets show these imperfections and, therefore, enable the use of strategic bidding for exercising market power. Thereby, different strategies are possible for the market makers, whose goal is to put a bid above marginal to gain an additional net profit, despite a possible reduction in volume.

1. *Fixed cost bidding*, adding a mark-up motivated by fixed cost;

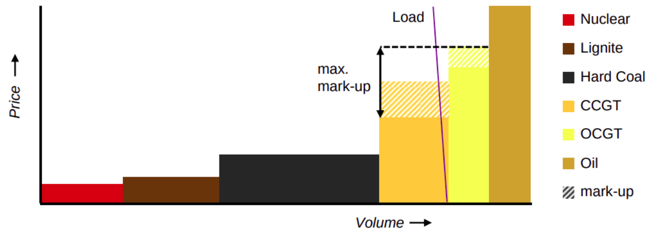


Figure 3.3: fixed cost bidding strategy [27]

2. *Capacity retention bidding*, voluntarily withholding capacity to increase the MCP;

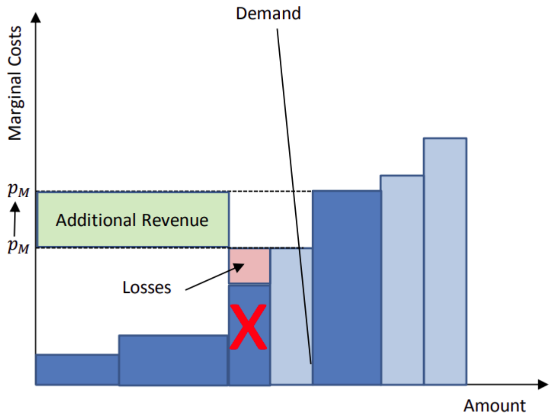


Figure 3.4: capacity retention strategy [27]

3. *Next cluster bidding*, increasing the mark-up stepwise up to next technology MC;

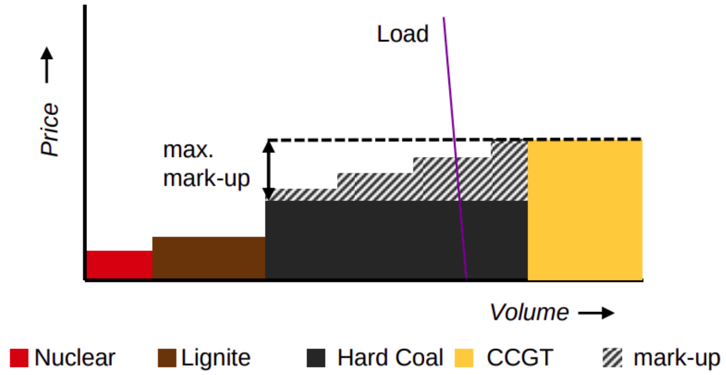


Figure 3.5: next cluster bidding strategy [27]

4. *Oligopoly bidding*, adding a mark-up based on the supplier technologies portfolio.

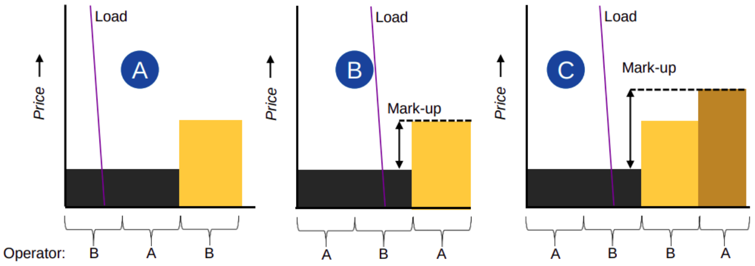


Figure 3.6: oligopoly bidding strategy [27]

3.4.2. Design & Challenges

The electricity system is facing several current and future challenges, driven by the ongoing shift towards a variable renewable dominated electricity generation, the increase of distributed RES, as well as new and active types of electricity prosumers, electric vehicles, and heat pumps. In particular, information technologies are seen as the enablers of the shift towards such an electricity system.
Moreover, recently, the following major trends have had an impact on electricity markets:

- further electrification of the economy with rising electricity demand and increase in transmission capacity;
- the share of distributed and variable RES is increasing in order to reduce CO_2 emissions;

- RES incentives have increased electricity prices, but generation from RES can lead to very low prices in the wholesale market;
- a growing number of prosumers, with decreased revenues for grid operators and higher network charges for consumers;
- technological developments (smart-meters, smart appliances, electric vehicles and digitalization) can enable innovation;
- scarcity pricing incentivizes lower load at peak demand, and store electricity when supply from RES is abundant.

A first but fundamental challenge is the capability of matching supply and demand in the most economical efficient way, while respecting security constraints, which has been recently stressed under the wide development of RES and the reduction of dispatchable power plants.
Secondly, related to that, the electricity system needs to avoid the violation of network constraints, that is, the limits of the power lines to transmit and distribute electricity. This stringency in particular, is becoming more and more binding and costly with the increasing decentralization of the grid.
Third, a current challenge is the efficient utilization of cross-border interconnection capacity and its trade-off with network congestions which strongly affects he resulting dispatch.
Fourth, it should be found a solution to improve competitiveness and welfare in the market, since the lower presence of large suppliers could leave those remaining in a privileged position in regard to market power.
Fifth, the scale of investments in renewable technologies, actually limited due to the uncertainty on contracting and financing provisions, should be rendered more stable in the long-term to account for large investments.
Last, the use of renewables must go hand-in-hand with grid optimization and carbon emissions reductions, i.e. incentives must be well designed in order to avoid feed-in curtailments as much as possible.

In the design of a new electricity market, all these sometimes competitive features must be taken into account.

In addition to the generation side, the market design should address relevant aspects of the demand side so that a flexible demand-side management (encouraged by IT technologies) could become part and parcel of the grid. Flexibility could include shiftable volumes, shiftable profiles or adjustable loads. The charging process for electric vehicles might be an example for a shiftable volume.

Monetary incentives together with a short-time pricing mechanisms are proposals that could enhance network congestion management locally.
Cost-based redispatch, critically relying on the cost transparency of large power plants, will be challenging to implement with increasing numbers of opportunity-cost based consumption and storage options. Hence, information technologies may help to increase the cost transparency of assets in the energy system.
Market-based redispatch instead suffers from the infamous *inc-dec gaming* [43], i.e., incentives for participants to change their consumption and generation behavior to aggravate congestion and to profit from price differences between consecutive energy markets.

Suitable information technology concepts and standards are needed for a successful application of IT technologies to electricity systems, because it not only creates new opportunities in terms of analyzing and forecasting, but also raise concerns regarding security and privacy.
The short-term uncertainty due to intermittency should promote a wider use of continuous intraday pricing, extended to a larger audience, in order to link the pricing mechanism to real-time grid conditions and promote its optimization. For a well-suited design however it will be necessary to find a good time granularity in the auctions: the current proposals on how to integrate auctions in intraday markets range from one auction to high-frequency auctions. If one auction is probably not sufficient, the performance of high-frequency auctions might be questionable, too.
Moreover today's market design adjustments need to consider future technological developments, anticipating both possible collusive behavior of market participants, strategic bidding opportunities as well as enabling TSOs to analyze and prevent such behaviours, increasingly using AI and machine learning techniques.

To synthesize,the design of the future Electricity Market, must include a variety of economic, technological, and strategic aspects of electricity systems to integrate an increasing share of RES.
New storage distributed capabilities and demand flexibilities are to be considered, linked to a growing intermittent and decentralized electricity generation, with corresponding uncertainties regarding returns on investment, as well as the need of longer transmission distances between generation and demand centers.
More specifically, recent developments in energy technologies may enable a better use of demand-side flexibilities in industrial production processes and residential consumption or a better integration of small and medium prosumers into the electricity system.

On the side of new information technologies, overall market efficiency may increase through additional transparency as well as newly gained information and knowledge. In turns, automated electricity trading may become soon feasible and allow market participants to react to changing market conditions almost in real time.

To fully exploit the potential of both new information and energy technologies, however, the adoption of a reformed and optimal pricing mechanism is fundamental, both in the day-ahead and intraday markets, that successfully accounts for recent technological developments and new market players (prosumers or automated software agents).

3.4.3. Pricing Mechanism Design

A breakthrough in electricity pricing theory occurred in 1988 when four professors at MIT and Boston University published a book entitled, "Spot Pricing of Electricity" [67]. In this seminal work it was presented the idea that prices at each location on a transmission system should reflect the marginal cost of serving one additional unit of demand at that location.
It then proposed quantifying these prices by solving a system-wide cost minimization problem while complying with all of the system's operational constraints, such as generator capacity limits, locational loads, line flow limits, using linear programming software.
The pricing so described can be applied in principle to day-ahead and intraday auctions or continuous trade, with specific differences for every case.

First of all, a distinction must be introduced between the market pricing, which, in the case of electricity can be disxtinguished between "pay-as-bid" and "pay-as-clear". In the first case, the price corresponds to the bid in the market, while in the second case it correspomds to the market clearing, i.e. the price at the junction point between demand and offer.

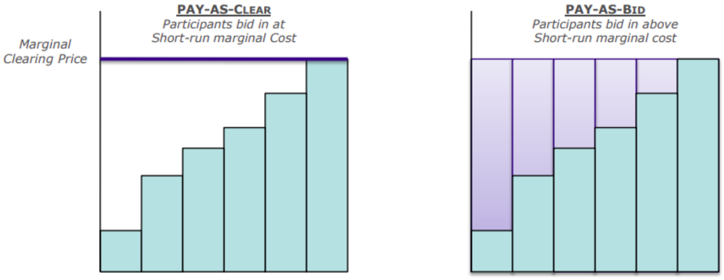


Figure 3.7: pay-as-clear vs. pay-as-bid

Most economists will agree that at least in the case of a liquid market for a homogeneous commodity, a uniform clearing price auction is superior to a pay-as-bid rule.

Other considerations however, make the uniform price more attractive.
In uniform price auctions bidders have an incentive to reveal their true cost and therefore, the dispatch will be efficient.
On the other hand, one must recognize that if demand is uncertain a uniform clearing price will reflect that entire uncertainty and will be more volatile then the average price in a pay-as-bid auction.
Furthermore, one may argue that suppressing price volatility is undesirable since it may also suppress demand response when possible. Nevertheless reduced price volatility is one of the arguments used to advertise a pay-as-bid settlement rule.

It is worth stating that in electricity markets the products are not completely homogeneous and the markets are not complete. Consequently winner determination is often based on attributes such as location, ramp-rate, reactive power capability etc. that are not explicitly priced in the auction.
Designing such auctions so as to take into consideration the interchangeability among the different products is therefore challenging.
Furthermore, such fragmentation reduces the liquidity in each of the separate auctions to the point where some of the underlying assumptions favoring the uniform clearing price approach may no longer be valid.
For these reasons, in situations where the non-homogeneous nature of the product and market incompleteness necessitate a high degree of product fragmentation, a pay as bid settlement approach with optimized assignment may be promising, which is the trend experimented in intraday market, at the moment.

Intraday auctions increase the volume of bids and offers, because market participants can offer all available capacity at its marginal costs, as all accepted bids will be remunerated based on the marginal price.
While in marginal clearing auctions market participants can bid their marginal cost, in continuous trading market participants need to mark up their bids in order to recover opportunity costs, as each bid is cleared at the offer price. The appropriate mark-up depends on the demand and supply balance and therefore needs to be continuously updated to maximize revenue.
Due to the flexibility demand, such as the many limitation of a decentralized grid, to effectively allow participation of players of all scale and technologies, it is stated that a pay-as-bid mechanism, with a fine time granularity, might suit better the goal.

3.4.3.1. Pricing Schemes and Allocation

Another feature of a pricing scheme mechanism is influenced by transmission constraints or better if such costs must be internalized or not. This has lead to the models like the zonal pricing (most used across Europe) and locational marginal pricing (LMP, most common in U.S.).

There are inherent trade-offs between LMPs and zonal pricing models.
First of all, it is important to consider the degree to which the pricing model affects the ability to cope with the increasing complexities emerging in electricity markets, such as an increasing feed-in of decentralized RES, making it difficult to schedule energy flows and forecast available network capacities.
In LMP systems the scarcity of network capacities is reflected in the price itself, as the TSO determines the intersection between demand and supply of electricity under consideration of network capacities. Therefore, beneficial behavior regarding the utilization of grid capacities is incentivized by the pricing scheme. [?]
Moreover, since a shortage of generation capacities leads to higher prices in the respective node, LMPs provide a long-term price incentive for the allocation of planned generation plants, if they are stable and robust.
In theory, LMPs therefore inherently incentivize market participants to efficiently dispatch in the short run and invest in the long run, which reduces the need for expanding grid capacities.
In contrast, uniform pricing schemes do not reflect physical constraints of the transmission network in wholesale market prices within a zone. The same is true for zonal pricing schemes if the zonal configuration does not reflect the existing bottlenecks in the grid. [?]
Thus, market participants do not have a price incentive to consider transmission capacities when offering or demanding electricity. Therefore, congestion of transmission lines needs to be considered by the TSO after markets close and these uniform prices neither reflect scarcity on the local level nor improve the right investments, because the price would be the same in more or less efficient parts of the grid.

A number of theoretical arguments are clearly in favor of LMPs:

1. welfare gain;
2. better regional investment signals in the form of local prices;
3. lower levels of redispatch and feed-in management due to internalization of network constraints;

4. no need for definitions of appropriate and stable price zone.

However, while there are strong arguments for the superiority of nodal pricing to other forms of market organization, in practice there are additional complexities and issues that need to be taken into account when comparing nodal to zonal pricing:

1. lack of price transparency to buyers;
2. high transaction costs for multinodal environments;
3. unnecessary bundle of regulated (transmission) and unregulated (power generation) services;
4. no need for definitions of appropriate and stable price zone [**?**].

If in theory the LMP cannot be subjected to manipulation, in practice system operators have substantial discretion over LMP results through the ability to classify units as running in "out-of-merit dispatch", which are thereby excluded from the LMP calculation.
Another great issue is about the liquidity of LMP market.
In fact the less liquid markets are, the harder it is to compete with existing firms. This issue is closely related to potential problems with market power in nodal systems in situations where transmission capacity is scarce and therefore only a limited number of potential suppliers exist at a given node.
As a result, market power mitigation measures need to be put in place to detect powerful market participants at individual nodes and to avoid monopoly prices in situations of scarce capacities.
Lastly, it is important to note that price signals need to be strong enough in order to efficiently coordinate investment decisions.

At high-voltage levels, the current bidding zone configuration is under pressure. Grid expansion could not keep up with the impressive capacities of renewables installed, and consequently, among other problems, redispatch costs are high and still rising.
At low-voltage levels, distribution networks would need to be expanded in order to deal with the increasing installation of PV panels by consumers, electrification of transport (electric vehicles) and heating (heat pumps).
Flexibility markets can therefore be used to limit costly grid expansions at low-voltage levels. How these new flexibility markets will be integrated into the existing sequence of markets remains an open issue, but the adoption of a LMP might be favorable for the transition.

Irrespective of the discussion on zonal and nodal prices, pricing rules need to address non-convexities in the cost structures of these markets. Those can be described as costs that abruptly grow under certain conditions. The result that in the presence of non-convexities there may be no uniform price supporting a competitive equilibrium is rather general and it is one of the main reasons why different pricing approaches have been suggested in the literature.

In countries that have followed the philosophy of liberalization of energy markets, two are the most adopted pricing schemes:

1. IP Pricing: often regarded as Locational Marginal Pricing in a narrow sense. This scheme assumes that all resources are committed according to the optimal allocation. The locational uniform market price then equals the marginal cost of electricity at a particular location, which may not correspond to the true marginal cost, as the commitment status of generators might change with marginally increasing demand and cause additional non-convex costs. Since the uniform market price might not be high enough to recover the costs of some resources with non-convex costs, so-called make-whole payments are provided as uplifts.

2. CH Pricing: whose purpose is to align incentives with minimum uplift payments. Broadly speaking, the underlying non-convexities of the allocation problem are transformed into convexities, yielding a computationally efficient pricing problem. Under mild conditions, it can be shown that these prices require minimal uplift payments to compensate for lost opportunity costs. However, describing the problem can be a challenging task for real settings [**?**].

3.4.3.2. Strategic Implications in the Electricity Market

Market outcomes are determined by the market's rules as well as the behavior of the market participants.

The market participants' decisions depend on their individual preferences and goals, on the market rules, and also on their expectations about the behaviour of others. Thus, a participant's strategy of how to act in the market is shaped by the market rules and the interdependence with other participants' strategies.

Whether strategic behavior is detrimental or supportive for a given market may depend on the objective of the market designer.

In what follows, ensuring short and long-run economic efficiency as well as system security, while also supporting the expansion of RES, will be assumed as objectives (often in competition).

Undesirable strategic biddings or gamings appear when actors takes advantage of unintended opportunities offered by the market design that counter the market's objectives.

In the short run, generation and grid capacities as well as the technological composition are fixed. In the long run, new capacity can be built, existing plants can be shut down, and new technologies and solutions can be developed. Therefore, an adequate market design needs to set incentives for long-run efficient investment.

Optimal location and technology choice as well as grid adjustments require access to information on local supply and demand. However, multiple reasons might deter price signals from generating optimal investments.

First, optimal investments require firms to predict future prices and profit opportunities correctly, to have confidence in the reliability of regulatory decisions, and to coordinate their investments. Second, efficient locational choices require locally differentiated price signals.

When local price signals are distorted by market power or gaming, investment incentives will also be distorted, leading to over or under-investment.

Misguided locational choices may require high public investments into the power grid to compensate for the inefficient locational distribution of generation.

Nodal prices support the identification of locations for profitable long-run investments by determining prices for every node in a network; zonal prices however enable such identification only if there are no relevant transmission constraints within zones.

An alternative to relying on market price signals to guide investment decisions is a centralized direct stimulation of investments or a regulation of prices and profits by the regulator. However, regulators can improve investment decisions only if they hold information superior to market signals or if market signals are distorted.

Support payments for RES for instance, are designed to influence the quantity, the technology mix, and implicitly the location of renewable energy generation. Again, choosing an appropriate market design that steers the investment decisions in the desired direction is crucial. In Europe, for instance, RES are incentivized based on fixed premiums, sliding premiums or contracts for difference.

Those same incentives however can act in concurrence with a well-designed market, reducing the possibility to adjust operation based on the price signal. [35]

Another strategic behaviour that directly influence efficiency in the market design is the market power, that can be defined as a market participant's ability to influence prices to deviate from competitive prices to their advantage and can arise if an actor dominates the market due to his/her size.

Unfortunately electricity markets – where demand varies unexpectedly, storage is limited, supply faces capacity constraints in the short run, and demand and supply need to be constantly balanced – market power of small actors can easily arise.

Limits to exercise such influence on prices are general or individual offer caps, however, setting exogenous price or bid caps optimally is a challenge.
The need for exogenous caps stems from the decoupling of demand from supply, such that demand cannot react to price signals. Luckily, integrating demand into the market can address this issue and lower the market power of some players.
These behaviours are in general, limited in liquid markets, since they can strengthen competition and reduce incentives for collusive behaviors which, by the way, might be identified or even prevented using new possibilities of information technologies, i.e., by machine learning or cryptographic certification of load profiles.
Market power can also be prevented by inviting participation by more or different firms, because an increased diversity and number of actors reduce a firm's ability to execute market power.
As an example of increasing actor diversity, inviting purely financial traders into the market is considered a means to prevent price differences between day-ahead and intraday markets, so to prevent any arbitrage opportunity and thereby eliminate the plant operators' possibilities to profit from price distortions.

In some cases, market discrimination may act in favour of consumers and can be promoted by the regulators: the privileged treatment of *Bürgerenergie* (citizen energy) in Germany's auctions for RES is an example.
The aim in this case was to improve acceptance of wind energy by facilitating projects operated by local communities. The preferential treatment in the auctions for onshore wind, in particular the reduced requirements for securities and permits, led in this case to a large number of successful projects by local communities.
Such an example demonstrates how a properly designed energy market can not only improve the social welfare of the community and reduce strategic behaviours, but also help the same community to gain autonomy and steer the investments in a cleaner energy or other benefits not strictly related to electricity production.

Ultimately, to give a concrete example of a viable way to face some of the challenges described (namely, define the right dimensions of investments and find a suitable demand-management policy) in the next chapters two agent-based models will be presented, proving the way through which a local community can gain higher reliability of the grid reducing CO2 intensity, electricity prices and social welfare.

4 | Electricity Production Optimization in the Smart Grid

"Only nuclear power can now halt global warming."

James Lovelock

After an introduction of the challenges for Nuclear Power in the future Smart Grid, it will be presented a Smart-Grid simulation model for optimization of energy-management

4.1. Nuclear Power in the Smart Grid

If the Electric Grid is gradually shifting towards a model characterized by higher intermittency and private production, it is also true that to cover peak demands during the day fossil fuel plants are still considered as essential.
Realistically, nobody would prefer to face frequent electric shortages or industrial productions stops or even frequent blackouts, in order to lower carbon emission much faster than at our actual rate; hence without a demand-side management of electricity, the natural consequence is that we witness to peaks and valleys which vary seasonally and within the same day at a level that can reach the double (or half) of the base average demand.
In a future grid where batteries and electric cars are becoming more popular both at a household and at an industrial level, this creates serious challenges for the dispatch management and frequency control of the grid, also because of the not simultaneous coincidence of load and demand peaks.

In the past, most electricity customers were served by a vertically integrated monopolist until the 1990s. Regulatory authorities on the state level set prices, allowing the monopolist to cover its costs including a rate of return on capital.
For large plants where investments covered a large part of the plant costs, that situation could provide a certain income, so that the risks associated with the investment itself were minimized.
After the deregulation of the energy market, that situation radically changed, in such a

way that it is no more possible for large plants to hedge the investment risk with state-set prices. At the beginning of the 1990s (especially in U.S.) this was definitely a big challenge for nuclear power.
However, nuclear power is still one of the energy resources with the lowest LCOE; moreover it is one of the lowest carbon intensive sources and because of that (but not only) can play certainly a central role in the grid of the future.

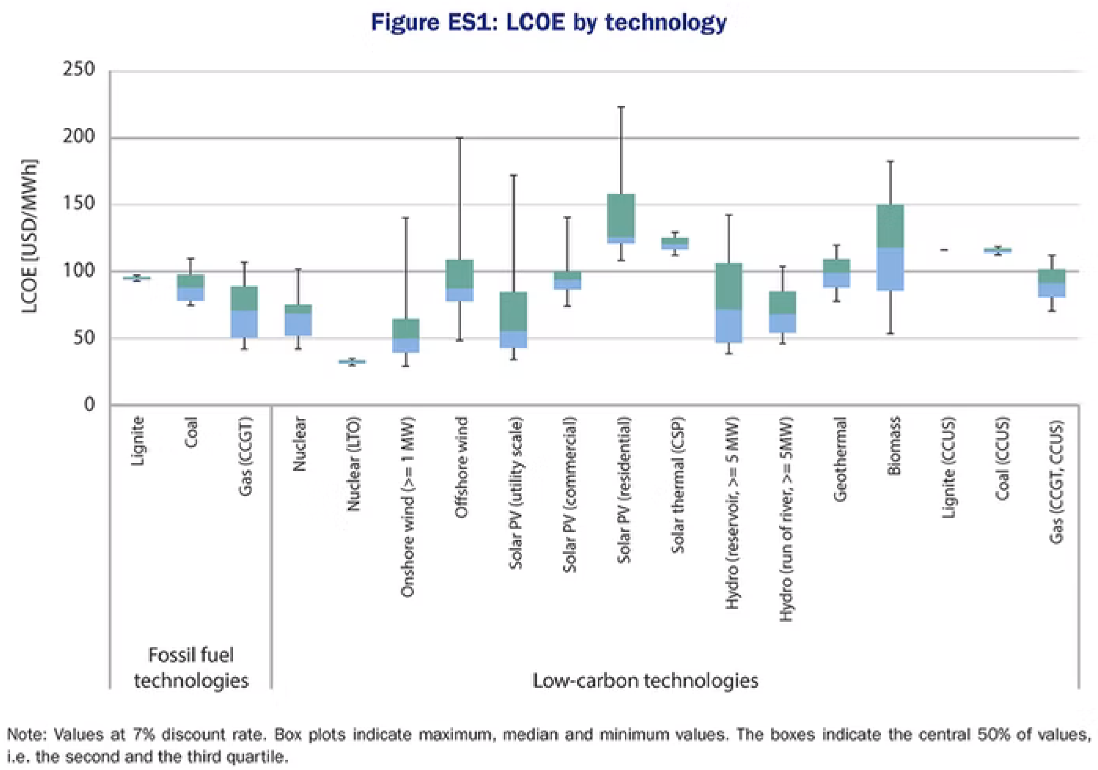


Figure ES1: LCOE by technology

Note: Values at 7% discount rate. Box plots indicate maximum, median and minimum values. The boxes indicate the central 50% of values, i.e. the second and the third quartile.

Figure 4.1: LCOE by technology [51]

First of all, being able to work as a base-load power source, as well as in load-following mode, can bring benefits to the stability of a more and more intermittent power grid; second, many nuclear plants can be operated in "co-generation" mode, so that part of their power is not directly connected to the grid, but it is used (either as thermal or electrical) for district heating or desalination (among the many options).
From the grid (and society) point of view, this can be seen as solution of low-carbon impact to problems not directly connected with the electricity generation but which certainly have an high impact on the society welfare. From the Nuclear Plant point of view, this can add a degree of elasticity and a profit opportunity which might be consistent during period of times in which their power should be decreased or totally disconnected

from the grid.

Nuclear Plants in fact, unlikely other fossil fuels plants, cannot save substantial energy from not working at full-power, because the fuel cost is usually a small part of the investment cost (as seen in the following picture, LCOE increases much faster than other energy sources when the plant doesn't work at full load factor).

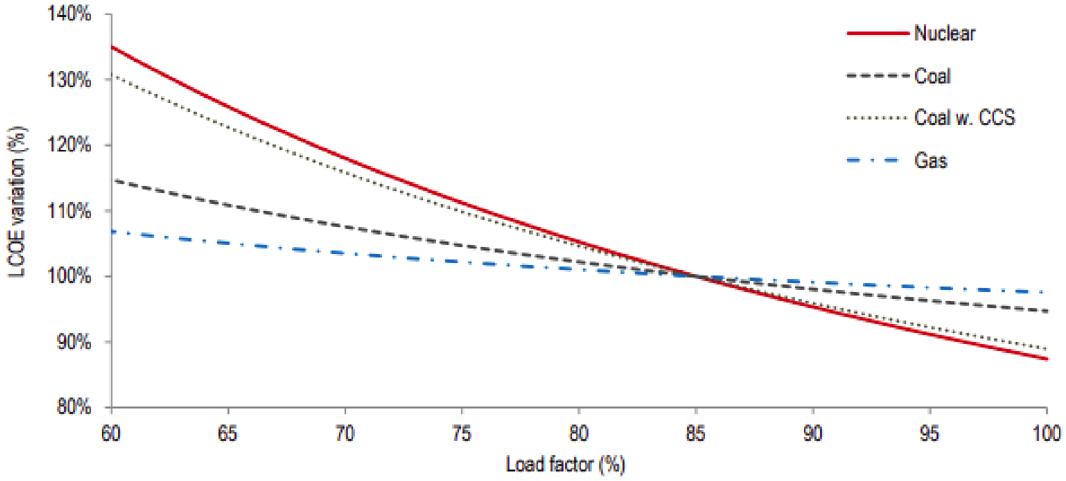


Figure 4.1: Variation of LCOE as function of the load factor for main power sources

At 5% discount rate

Figure 4.2: LCOE with load factor for different power sources

In order to account for the role of nuclear power in the grid of the future, the chapter will therefore proceed as follow: first it will be briefly described what are the main issues connected with base-load and load-following with Nuclear Plants, second it will be discussed the possibility to operate in co-generation mode, to provide the necessary (thermal) energy for a desalination plant operation. In the end, it will be provided a model of a en electric grid where nuclear power works "in cooperation" with solar and wind power to provide the energy necessary to cover the electricity demand and "in cooperation" with a desalination plant to cover the water demand.

In such a model, genetic optimization algorithms are used for sizing the grid (solar and wind capacity and number of plants working at full or cogenerating mode) and to find the everyday nuclear power profile to cover water and electricity demands.

4.2. Base-Load or Load-Following?

In a grid where electricity production comes from a complex mix, to face the problem of grid control, sources have been traditionally divided among base-load, load-following and peak-load, accounting for different change rates in the demand and with different purposes regarding the total and average electricity production.
Base-load plants are power plants that generally run at their full installed capacity and are used to meet base load demand. Except for scheduled maintenance or repairs, these facilities operate 24 hours per day, year round.
As a result, base load plants generally have a capacity factor of more than 80%: large-scale hydroelectric, coal, natural gas and nuclear power plant are preferably employed in this mode.

Load following power plants instead, have emerged to balance out the intermittent nature of renewable power sources, and their importance is forecast to grow. This will pose a big challenge for power producers, even if a new breed of "peaker" gas plants seems assured to play an important role in helping to meet this challenge.
In contrast to base-load plants, load following power plants operate at a higher load for less hours to balance out the variability of renewables. They operate with different key performance indicators (KPI) from a traditional plant: for instance, they need to have faster response times to handle transient loads or may need a zero-minute start time.
Load following plants also have to deal with more variables during power production: for example, the load may need to be changed during the ramp up, or the ramp-up speed may need to be quickened or slowed.

Peaking power plants, commonly known as "peakers", operate during times of high demand.
These plants typically run less than 1,500 hours per year, and some may operate for as few as 250 hours per year. Traditionally, peakers were ramped up to 100 percent load as quickly as possible, run during the high-demand period, and then shut down.
These peakers are typically simple-cycle gas turbines that can start up and reach full load in as little as five minutes: they generally have less efficient gas turbines than those used for base-load power, and therefore consume more fuel per unity of power produced.

In general, nuclear power plants (NPPs) have been considered as base-load sources of electricity as they rely on technology with low variable costs and high fixed costs. This is the most economical and technically simple mode of operation.
In this mode, power changes are limited to frequency regulation for grid stability purposes and shutdowns for safety purposes. Although most nuclear power plants were designed

as base-load power plants, today, the utilities have had to implement or improve the maneuverability capabilities of their NPPs to be able to adapt the electricity supply to daily, seasonal, or other variations in power demand, due to the significant increase in renewable energy sources. Nevertheless, the load following operation is economically inefficient as nuclear power generation is composed almost entirely of fixed and sunk costs. Therefore, lowering the power output doesn't significantly reduce generating costs.

To operate in load-following mode, and participating in the primary and secondary frequency control, modern nuclear plants with light water reactors are designed to have strong manoeuvring capabilities.
For example according to the current version of the European Utilities Requirements (EUR) the NPP must at least be capable of daily load cycling operation between 50% and 100% of its rated power with a rate of change of electric output of 3-5% of power per minute.
In the case of pressurised water reactors (PWRs), the change of the reactors' power level is performed by control rods movements and by changing the concentration of the boric acid in the primary coolant.
In the case of the boiling water reactors (BWRs), the power regulation is performed by changing the coolant flow rate (using the recirculation pumps) and the control rods [4].
In the primary control, in order to adjust the frequency the grid operator sends a digital signal to the NPP to modify their power level by in the interval of ±5% of power. In E.U. NPPs are also demanded to take part in secondary frequency control.

Even if load-following is not related with new design challenges for NPPs, however, leading to a decrease of the average load factor in the range of up to 10%, this operation mode is not optimal, but it is just suited to the necessity of the power grid. Even if load following has a very small impact on the acceleration of ageing of large equipment components, it has some on the ageing of some operational components, with a slight increase of the maintenance costs. Moreover, load cycling leads to variation in the coolant temperature, and thus in the temperatures of different components of the plants causing cyclic changes in the mechanical load in some parts of the equipment, which could induce localised structural damage for fatigue.

An alternative to operate in load following mode which partly avoids the downsides, is the co-generation operation, as aforementioned. This is a much more efficient solution, because allows to maintain the primary circuit at full power and to use the excess power for cogeneration.
In the next section therefore this operation mode will be deeper investigated, in relation to the possibility of NPPs connection with a desalination unit.

4.3. Nuclear Desalination

Rapidly increasing populations together with higher standards of living and expansion of irrigation in agriculture have already led to acute water shortages and stresses in many regions of the world [3].

A non-conventional alternative to cover the increasing water demand is seawater desalination.

This is because:

- a large fraction of the populations of water stressed countries resides near the sea coasts;
- seawater reserves are practically unlimited;
- desalination technology is now available at affordable costs [3].

Nuclear desalination is defined to be the production of potable water from seawater in a facility in which a nuclear reactor is used as the source of energy for the desalination process. Electrical and/or thermal energy may be used in the desalination process [3]. The facility may be dedicated solely to the production of potable water, or may be used for the generation of electricity and production of water, in which case only a portion of the total energy output of the reactor is used for water production.

In this context, nuclear desalination now appears to be the only technically feasible, economically viable and sustainable solution to meet the future water demands, requiring large scale seawater desalination for the following reasons:

- it is economically competitive, as compared to desalination by the fossil energy sources;
- it can use waste heat at an ideal temperature;
- it can improve a sustainable development model due to the high energetic resources required by the desalination process, which would be otherwise covered by fossil fuel plants.

Regarding the last motivation, if nuclear instead of fossil fuels would be used for the production of 10 million m^3/day (actual daily water production in the world is of about 23 million m^3/day), this could avoid the production of:

- 200 million $t/year$ of CO_2,;
- 200000 $t/year$ of SO_2;

- 60000 $t/year$ of NO_x;
- 16000 $t/year$ of other hydrocarbons [3].

The commercial seawater desalination processes that are proven and reliable for large scale freshwater production can be divided in two categories: those which employ evaporative desalination (multi-stage flash (MSF) and multi-effect distillation (MED)) and those which use membranes (reverse osmosis (RO)).
For desalination plants rated at more than 4000 m^3/day per unit, MSF is still more prevalent than any other process; however, the RO and MED process are increasing their market share every year. Electrical and/or thermal energy may be used in the desalination process: for RO electrical energy is preferred, while MED uses mainly thermal power.

The selection of the desalination technology depends both on the reactor type considered and the required product water quality, e.g. drinking, industrial or commercial use. Thermal desalination plants (MSF, MED) provide very pure water that is directly usable for industrial process applications, RO plants instead provide drinking quality water as per WHO standards.

Nuclear plants which provide energy for desalination can be dedicated solely to the production of potable water, or may be used for the generation of electricity and the production of potable water, in which case only a portion of the total energy output of the reactor is used for water production. In either case, the notion of nuclear desalination is taken to mean an integrated facility in which both the reactor and the desalination system are located on a common site and energy is produced on-site for use in the desalination system. It also involves at least some degree of common or shared facilities, services, staff, operating strategies and outage planning [3].

It is evident that when a desalination plant is connected to a nuclear plant, it must be decided if such a reactor will operate as co-generating or as single-purpose heating. Such a decision must incorporate first of all the amount of power and water needed in the region where a nuclear desalination plant is to be built and the economic feasibility of both option, with largely depend on public sector financing.
Co-generating plants, producing both water and power have limited operating flexibility and quite long lead times; single-purpose heating reactors instead are best suited to optimizing coupling, have a shorter lead time and a simpler design. Moreover, if co-generating nuclear reactors are chosen, careful consideration should be given to the power-to-water ratio, which is defined as power required per m^3/day of fresh water produced.

Nevertheless, a co-generation plant has several economic advantages over single purpose plants. The specific financial investment is lower, owing to the sharing of facilities. Also, specific fuel and manpower costs are lower because the total costs are distributed to both products.
At the same time, to efficiently run the desalination plant, a constant power must be withdrawn from the power plant and is dedicated to the desalination installation.

Finally, as a side note, efforts are under way to create integrated solutions and systems to use multiple energy sources, including nuclear and renewable energies for water desalination. This may allow for resource optimization while minimizing the overall environmental impact of the proposed integrated solution.

Among the many design possibilities for coupling a nuclear and a desalination plant, in the literature [65] [46] [50] an interesting choice is to operate one (or more) small modular reactor(s) for co-generation.
Small modular reactors (SMRs) are advanced nuclear reactors that have a limited power capacity (in the range of $300MWe$) per unit. In contrast with the economy of scale which in the past has lead to the design of large nuclear reactors, they have a capacity of about one third compared to traditional PWRs, but have some advantages inherently related to the nature of their design – small and modular.
Prefabricated units of SMRs can be manufactured and then shipped and installed on site, making them more affordable to build than large power reactors, which are often custom designed for a particular location. SMRs offer therefore savings in cost and construction time, and they can be deployed incrementally to match increasing or intermittent energy demand.
This is one of the reason why they are well suited for developing countries, where electricity demand is expected to grow rapidly and capital funds are often low.
Moreover,in areas lacking sufficient lines of transmission and grid capacity, SMRs can be installed into an existing grid or remotely off-grid, as a function of its smaller electrical output, providing low-carbon power for both industry and the population [7].

In comparison to existing reactors, proposed SMR designs are generally simpler, and the safety concept for SMRs often relies more on passive systems and inherent safety characteristics of the reactor, such as low power and operating pressure. This means that in such cases no human intervention or external power or force is required to shut down systems, because passive systems rely on physical phenomena, such as natural circulation, convection, gravity and self-pressurization.
On the fuel consumption side, SMRs may require less frequent refuelling, every 3 to 7

years, in comparison to between 1 and 2 years for conventional plants and some SMRs are designed to operate for up to 30 years without refuelling. Being modular, it is reported [7] to offer savings even in terms of O&M or spare parts management.

These characteristics position SMRs to play a key role in the clean energy transition, while also helping countries address the Sustainable Development Goals. As global efforts seek to implement clean and innovative solutions, the increased use of renewable energy coupled with the introduction of SMRs has the potential to fill such gaps.

For all these reasons, SMR could offer a very interesting solution if coupled with a desalination plant, because the power output connected to the desalination plant can be chosen at will and even more, it is possible to design some reactors which are always connected to it, while others operate at full power (to provide electricity).
The simulation model developed, described in the following section, taking inspiration from [50] aims therefore at developing a grid where the power and water demand can be matched at any time: to do so, some design parameters such as solar, wind and battery capacities, number of nuclear plants (SMRs) and dimensions of the water reservoir are supposed to be optimized.

Important to notice, the carbon emission cost of such a model is virtually zero.

4.4. Smart Grid Simulation Model

As anticipated, we hereby present a simulation model obtained with *Python* and the Genetic Algorithm package *DEAP* [31].
The purpose was to find an optimization model to efficiently size the power sources in a grid in order to always match power and water demands.
For simplicity, water and electricity demands have been taken as constant throughout the year. This is quite a strong assumption and doesn't suit well the real case: hence a first suggestion for a future development of the model is to take into account the variability in power demand (water demand, within certain limits can be accurately considered constant).
Water demand has been set at a value of 15000 $m^3/hour$ and power demand at 800 $MWh/hour$. Water price has been set at $7/m^3$, but the electricity (residential) prices have been taken as varying throughout the year (in the range of 0.05-0.75 €).
Solar and wind power profiles have been considered as inputs of the model, so that renewable power could only vary in magnitude selecting different solar and wind capacities (corresponding to the amount of necessary investment in solar panels and wind turbines).
Even if this might seem a quite strong assumption, because solar and wind profile are nei-

ther similar year after year nor predictable from one year to another, however their total sum along a year is value close to a constant: hence such an assumption is appropriate.
Furthermore, the investment in nuclear power has also been taken as a decision variable: the model including the possibility to add to the grid a maximum of 4 SMR working either at full-power or in co-generation mode.
The model accounts also for the possibility to connect a battery storage power station (modeling residential battery storage as a whole), which charges whenever the load exceeds the demand and discharges otherwise. The efficiency for such a battery storage has been taken as 90%.
Lastly, for the desalination plant it has been considered a unit with maximum water output of around 19000 m^3/h and an energy need of about 49 kWh/m^3 of drinkable water produced: 90% of energy has been considered to be provided as thermal power from the cogenerating plant, while the other 10% represents a more general electric consumption. Such data are in accordance with the model found in [50].
In addition to that, a water reservoir whose dimensions need to be optimized for a suitable allocation of the drinkable water has been connected to the desalination plant, together with pipes and pumps, in order to account for hydraulic losses and pumps power consumption. However, in the absence of real data, it is assumed that in the calculations of the model, such pipes and pumps account for greater losses and consumption than in the real case. This should also be revised in a deeper analysis.

To summarize, the grid model contains the following variables to be optimized:

- a wind farm of varying total capacity (from 100 to 1 million kWh);
- a solar farm of varying total capacity (from 100 to 1 million kWh);
- a battery storage power station (representing both a power station and the singular residential batteries) of varying total capacity (from 100 to 1 million kWh) ;
- a varying number of small modular reactors for energy production (from 0 to 4);
- a varying number of small modular reactors for water production (from 0 to 4);
- a water reservoir (to be sized) to store the water produced from a desalination plant.

The optimization was then divided in two steps:

- find the optimal dimensions of the grid variables, considering SMRs working either at full electricity or full "water" production;
- provided day-by-day data on the power and water consumption, as well as electricity

and water prices, find the optimal power profile of the nuclear plant(s) which gives the maximum daily income.

In addition, production and load have been considered at hourly timesteps, differently from the model described in the next chapter, where the time resolution applied is of one minute, so that the total numbers of steps in the simulation is 8760.
Before moving to the simulation results, it should be given a short consideration about the price of water: even if 7 $€/m^3$ might seem quite a high value if compared to the market value in Italy, in the results it will be discussed how the cogeneration mode in the simulation is profitable even for values below 1 $€/m^3$.
In addition, as said above, power pumps consumption and water losses miscalculations contribute in lowering the real output of the plant and the power-to-water ratio is also quite high, if compared with other studies on the same subject.
Furthermore, considering that desalination plants connected to the SMR might solve problem of scarcity of water where this water need might make a difference between life and death, that should stimulate a reflection about what might be the "right" price of water.

In the next section the results of the simulations will be discussed, considering also future possible developments.

	Full El. SMR	**Cogen SMR**
El. power per unit	335 MWe	335 MWe
Th power per unit	1000 MWt	1000 MWt
Min Th. power Desal.	-	231 MWt
Max Th. power Desal.	-	922 MWt
Min Th. power Turb.	1000 MWt	78 MWt
Max Th. power Turb.	1000 MWt	770 MWt
Min El Power	335 MWe	0 MWe
Max El Power	335 MWe	258 MWe
Min El Power Desal.	-	10 MWe
Max El Power Desal.	-	41 MWe
Different Power Levels	-	5
Maximum daily changes	-	5

Table 4.1: SMR specifics ([50])

	Inv. Cost	**Maint. cost (%/y)**	**Exp. Life**	**Afterlife Inv. Cost (%)**
Solar Farm	500 [€/kW]	20%	10	80%
Wind Farm	850 [€/kW]	30%	25	80%
SMR	1500 [€/kW]	20%/n_{plants}	60	20%
Battery Storage	400 [€/kW]	20%	7	100%
Water Reservoir	40 [€/m^3]	2%	100	20%
Pumps	-	5%	25	100%
Pipes	-	5%	25	100%
Desal Units	-	18%	25	100%

Table 4.2: Data for Cost Calculation

4.5. Simulation Results

4.5.1. First Step Simulation Results

In the first step of the model, the purpose was to find the optimal values to match water and electrical load in the cheapest way with a mixture of renewable sources, battery storage, nuclear power and a desalination plant. For this reason, different approaches have been used: a simple genetic algorithm, a NSGA-II and a NSGA-III. In the first case the basis of the optimization has been taken as the net income from the water and electricity sale subtracting the investment and maintenance costs, as well as the necessary costs to cover the demands when those could not be satisfied by the model itself.

In the second and third cases, the solution wanted to minimize at the same time: the overall LCOE (interest rate at 5%), the water mismatch and the electricity mismatch. Moreover, such mismatches have been considered both in absolute value (to avoid an oversize of the model) or just when negative (the real situation in which they represent a cost for the grid). The best solution (genome) was then chosen as a reference point to proceed with the second part of the simulation: moreover for the cases where a multi-objective GA was used, preference was given to those solutions with the lowest LCOE. All the solutions in this step have been obtained with the *Python* package *DEAP* [31].

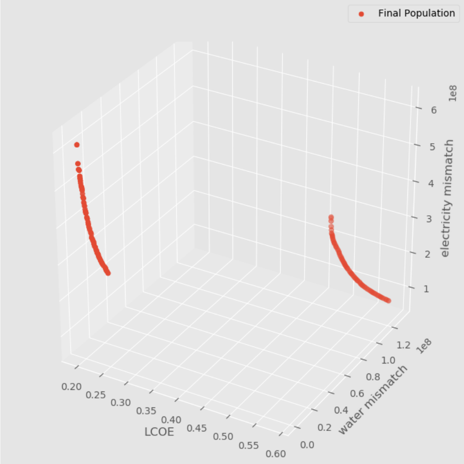


Figure 4.3: NSGA-II solutions (H_2O and el. missing if < 0)

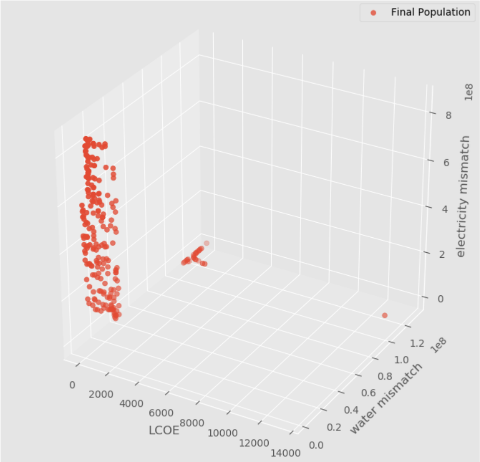


Figure 4.4: NSGA-II solutions (H_2O and el. missing in abs. value)

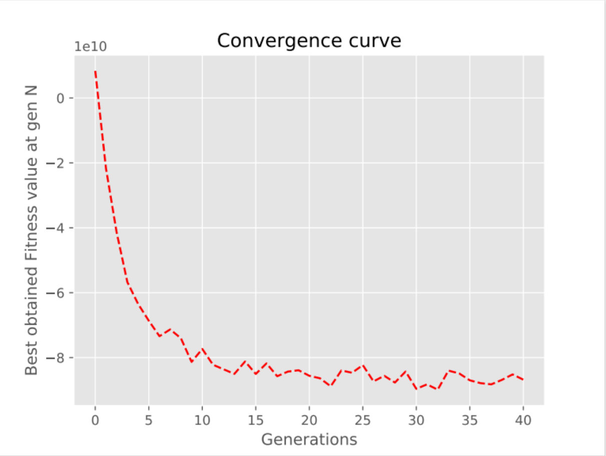


Figure 4.5: GA solution convergence

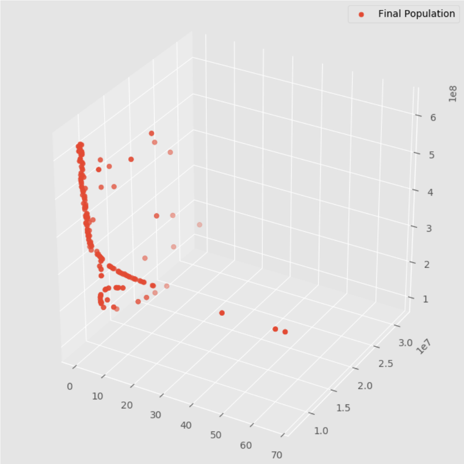


Figure 4.6: NSGA-III solutions chromosome

	solar	**wind**	**reservoir**	**battery**	**SMR f.**	**SMR cog.**
GA	975678[kWh]	988881[kWh]	210669[m^3]	3402180[kWh]	2[units]	1[units]
NSGA-II (1)	655672[kWh]	474198[kWh]	210669[m^3]	177068[kWh]	2[units]	1[units]
NSGA-II (2)	643026[kWh]	421111[kWh]	210669[m^3]	139266[kWh]	2[units]	1[units]
NSGA-III	551268[kWh]	411075[kWh]	44216[m^3]	76258[kWh]	2[units]	1[units]

Table 4.3: First step GA results

As previously discussed, the lowest LCOE reached is in the range of 0.17-0.19 €/kWh: a value quite high, but still influenced by the large electricity consumption as well as the inclusion of the water reservoir and its connected appliances in the computation of the total cost.
When for the water mismatch was considered only the negative part of the difference between water production and demand, this could reach a value of 0.
The previous solutions underline certain similarities among one another, however, considering the cogeneration plant always at full water production have a scarce influence on the reservoir size, because the maximum water production (around 19000 m^3) is always capable of covering the daily consumption (15000 m^3).

Taking as solution the one provided by the NSGA-II (2nd case), we added the value of the genome with the lowest LCOE in the day-by-day simulation whose results are discussed in the following section.

4.5.2. Second Step Simulation Results

Once the grid has been sized, we considered that for every day, a prediction on the future consumption was available, so that the co-generation plant could plan its power profile and coordinate it with the desalination unit to match also the demand of drinkable water. In such a way the communication between the plant (or TSO) and the consumers is one-directional: no certainty is given about whether the profile will be the predicted one and it is just the power plant which needs to shape its load on the forecasted demand.
In the next section a reversed model for optimization in the grid will be described, where through pricing signals a central authority can convince the consumers to shift their demand according to the central authority needs.
In an hypothetical model, it might even be possible to send messages from the TSO to the consumers back and forth, until a "compromise" solution on a proper load/consumption profile is found.

To simplify the algorithm research, the profile was supposed to change at maximum 5 times per day and 5 is also the number of power levels between the lowest and the highest the cogeneration plant can operate at (as in the table of the previous section); this is to keep the simulation in accordance with the regulations and to prevent high "charge-discharge" rates in the power production, which may endanger the structure of the plant due to fatigue, as well as to simplify the calculation for the genetic optimization.
Such a constraint was obtained applying a "penalty" (-10^3) whenever the profile was changing power level more than 5 times a day.

For the optimization of the profile, it was decided to use a single-objective (income minus costs) GA.

The simulation has been calculated for every day during a year and it was performed with or without the presence of the batteries, to understand their contribution to the total income.

	total income	**total cost**
1 year sim.	$3.58e9$€	$9.15e7$€
10 days sim	$6.96e7$€	$6.09e6$€
10 days sim. (w/o batt. storage))	$6.90e7$€	$6.36e6$€

Table 4.4: Second step GA results

The results clearly shows that the battery storage increases the income of about a 10%, while reducing the costs of about 5%. Considering that this solution has been obtained after a sizing of the grid based on the LCOE, we can deduce that investing in a battery storage power station may be beneficial.

Naturally, a better optimization model should take into account all the power variations in the grid, which were not present in the simulation. A different approach might be for instance to do a MC simulation with different (real) data of electricity loads and consumptions and check the differences in the results.
Considered the small computational power available, the simulation results are, therefore, quite satisfactory
Moreover, if we calculate the income for the grid without the desalination plant, considering that all the thermal power reserved to cogeneration can be transformed in electricity (this would be the case of a load-following plant), we obtain an income of $2.79e9$€, to be compared with the much higher value obtainable with the sale of water: $3.58e9$€. To have the equivalence between the two results, we should provide a constant water price of $0.95€/m^3$.

Last but not least, it must be mentioned again that the power of the model lies also in the fact that mixing renewable power together with nuclear power can deliver a solution to both electricity and water demand at a virtual cost of almost null carbon emissions. Again, we see that even in this case, thanks to the mutual cooperation of nuclear power and renewable energies we can reach a higher level of grid stability at a very low environmental impact.

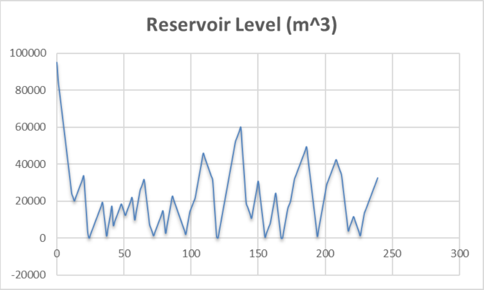


Figure 4.7: Water reservoir level (10days)

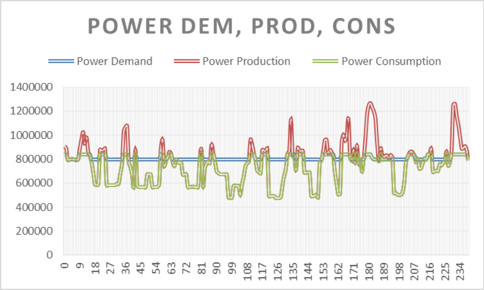


Figure 4.8: Electricity Production, Consumption and Demand (10 days)

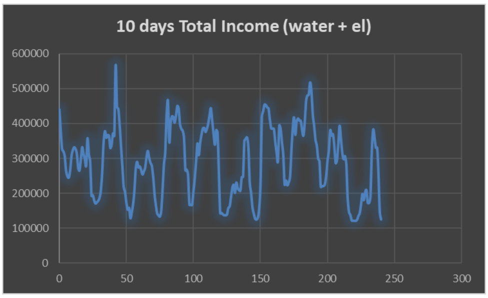


Figure 4.9: Total Income (water + el, 10 days)

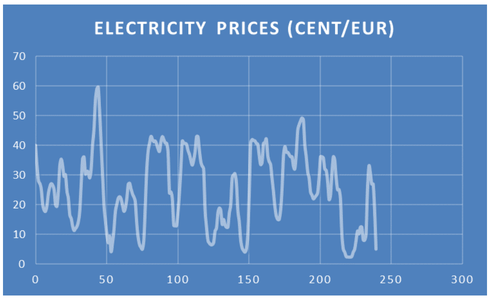
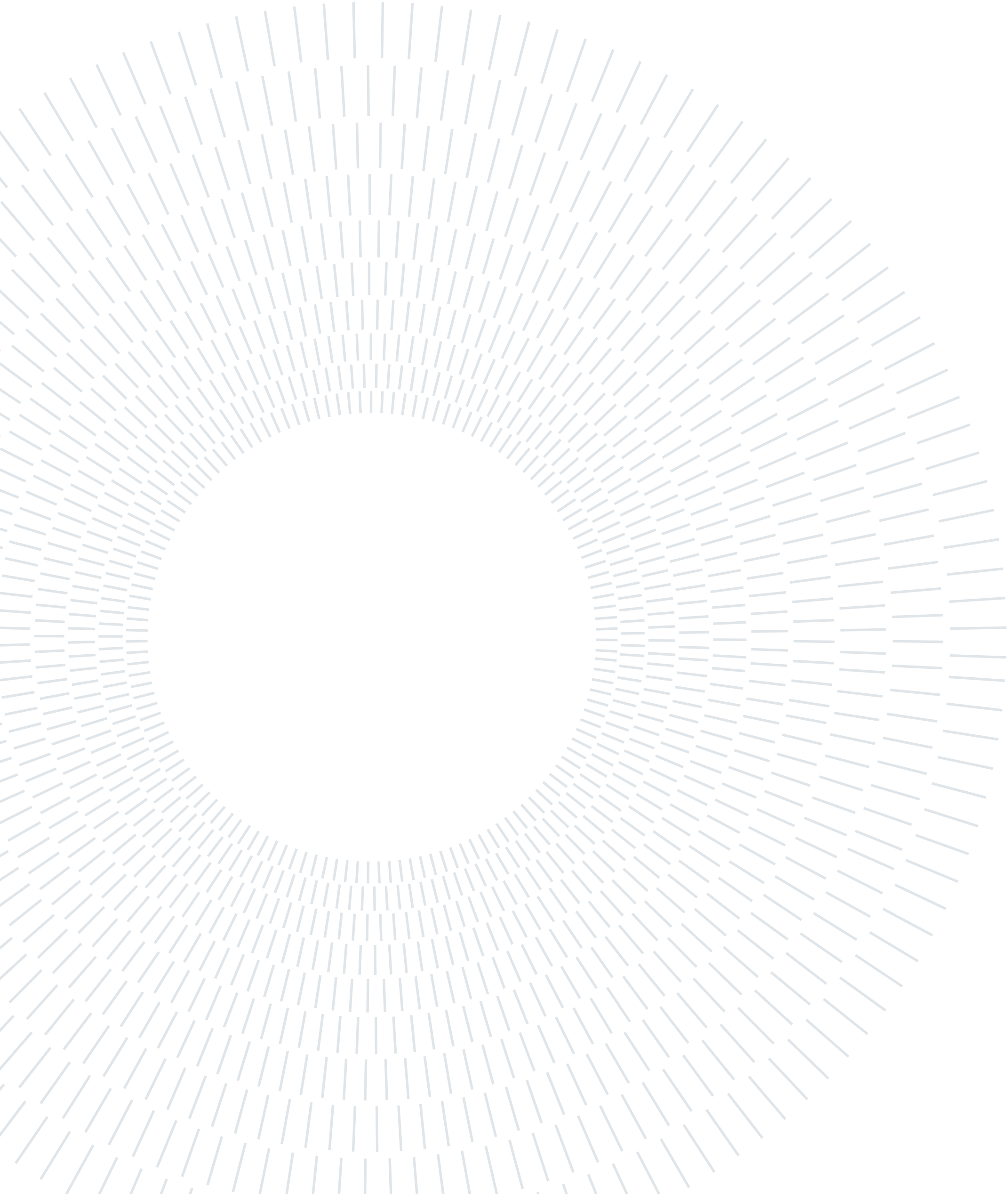


Figure 4.10: simulated electricity prices (10 days)

From the last plots, which cover a period of ten days taken from the simulation, we see how the optimization model doesn't cover the demands at all times.
Of course, this represents an issue, but it was not the purpose of the analysis: be it so, we would have used a different parameter from LCOE to be minimized.
Moreover, during the high production peaks battery storage can partially recover the energy overproduction and if we think that renewable investments are growing all over the world, we see that the situation should probably be tackled from another point.
Eventually, there is still plenty of investigation space for a better optimization of the smart grid.

To push the investigations further, first of all we will consider demand-side management as a true viable option to smooth energy peaks; going ahead, in chapter 7, it will be considered a case where it is the consumer who takes the responsibility of (its own) battery storage: being driven from an egoistic behaviour, it will be again the (micro)grid task to steer its own consumption in a "smarter" (for the grid) way.



5 | A Pricing Policy for Electricity Demand Management

"As scarce as truth is, the supply has always been in excess of the demand"

Josh Billings

"Supply always comes on the heels of demand"

Robert Collier

An Agent-Based Model incorporating residential demand-side management for the Smart Grid.

5.1. Introduction to the model

With the previous model we tried to analyze the situation of an electric grid where a mixture of source at low-carbon impact was optimized in order to match electricity (and water) demand every day.
However, such a model didn't take into account the variability of energy and water demand, which are inherently intermittent and can be precisely forecasted only some minutes before the actual consumption and still, without certainty.
In addition, solar and wind profiles were provided as inputs of the model, but even they, although contributing in lowering the LCOE of the market, suffer of a low predictability and cannot be planned in advance at will.

Considered that, the second part of the previous simulation still offers a good way of tackling the dispatch problem, given that forecasting models (machine learning models, among the other) are becoming more and more precise, so that it is not unlikely to have very precise 24 hours-ahead forecasts.

If water and energy demand management can be helped with the use of reservoirs and

storage, in the case of electricity it might be not an optimal option, because of the inefficiencies connected to electrochemical (the most diffused) charge and discharge.
Moreover, in the residential sector, demand unpredictability might even get worse in the future, with the widespread adoption of electric vehicles: most trips by household-owned vehicles are daily trips to workplaces and back and most people charge their cars at about the same time of the day, causing peaks in electricity consumption in the late afternoon hours. As mentioned previously,therefore, the use of smart-appliances (which can autonomously "decide" to postpone energy consumption) and real-time pricing in the residential sector, might offer another way to efficiently tackle the dispatch problem.

Demand response is an alternative approach to matching electricity supply and demand and involves reducing electricity demand in times of scarcity or whenever the Grid (or a central authority, like the TSO) needs.
This is dependent on electricity markets or a central authority that incentivizes flexible demand by time-variant pricing and on infrastructure, such as smart grids and smart-meters in order to make cooperation with the utility distributor beneficial to the subscribers.

In the following, it is described how a simplified pricing model for residential demand management can be developed with *Python*.

5.2. Computational Agent-Based Model

In recognition of the issues described in the previous chapter and in view of a stronger influence of the demand-side-management in an energy market market more and more influenced by the presence of renewables, the agent-based model proposed tries to represent a demand control system which, without compromising the privacy of the subscribers, allows the (smart) control of multiple smart-appliances, in cooperation with the utility distributor.
The demand control algorithm, on which the model is built, motivates the users to use energy at specific times by means of time-of-use electricity price tariffs, with different timing of low and high prices for each connected household.
In order to reach our goal and verify the validity of the model real-time publicly available data have been used, from which have been extracted probability distributions for each appliance.

The investigated situation is a static one where the electricity distributor provides a pricing policy specific to each consumer 24 hours before, based on statistical data of the consumption.

For simplicity, such a pricing policy is represented by two different tariffs which can be set for a minimum time span during the day up to a limit of hours. In addition, differently from the previous model, such tariffs and the consumption have been calculated minute by minute.
In order to prevent strategic behaviours, which can cause the same spikes in the consumption of electricity the model is willing to avoid, the pricing policy is not a deterministic one, but grants the same prices and the same interval lengths of low prices to all the users.

The policy is expected to influence just the subscribers who belong to the residential sector, who account for just a part of the energy consumption; hence the distributor must separate the total target demand profile into the base demand and the household demand. The electricity prices for each household are then assigned so that more households get a high price when their demand should be low, and a low price when their demand should be high. The electricity prices are later distributed to the domestic agents, and the decision on when to turn their appliances on is left to them, expecting a rational behaviour as a response.
In this way the privacy of the subscribers is protected, since they do not need to divulge the information about the usage of their appliance and the subscribers are incentivized to use energy in coordination with the needs of the distributor.
Even in this model, predictions are excluded, to keep the calculations as simple as possible. Furthermore, it is assumed to have access to statistics of subscriber behaviour, appliance usages and appliance properties.
The data for appliances, in the same way as have been included in other similar studies [57], have been taken from the Pecan Datastreet database [6] and the U.S. National Household Travel Survey [8]. For the base-load total electricity demand, a general profile has been adapted to the model, instead.

5.2.1. Algorithms

The basic pricing algorithm works as follow: after identifying the target demand per minute of the following day, the ratio of the target demand divided by the largest value of target demand in the time window works as a probability distribution, from which the pricing values are assigned randomly to every user, proportionally to the calculated distribution. In this way electricity prices for each user are assigned so that more households get a high price when their demand should be low, and a low price when their demand should be high, in such a way that is not totally predictable and not the same for all users.

Algorithm 5.1 Basic Pricing Policy Algorithm

```
given a daily time window $T$ divided in intervals $t$
given $N$ agents with the same target consumption $tgtCons_t \ \forall \ t \in T$
given the low and high prices signals values: $lowPrice$ and $highPrice$
for $agent \in N$ do
    for $t \in T$ do
        $lowPriceProb_t \leftarrow \frac{tgtCons_t}{\max tgtCons_t}$
        if $rand[0,1] \leq lowPriceProb_t$ then
            $price_t \leftarrow lowPrice$
        else
            $price_t \leftarrow highPrice$
        end if
    end for
end for
```

The target demand might be calculated based on different purposes: in the previous model for example, the nuclear cogeneration plant could try to keep an electricity production profile as uniform as possible, while providing for the water needs, for example.
However, in the simulation, it has been considered to be just the profile which smooths out the peaks in the electricity load while at the same time being high enough to cover the demand of the simulated households: a situation which might be more suited to a TSO which would like to avoid the risks of overloads in the grid.
Moreover, it is assumed that such a demand control policy has no impact on the electricity loads not connected with the residential sector, so that the total load profile would still have some peaks.

Since the previous algorithm might be prone to many "jumps" among the minutes with low and high prices, while most house appliances are used for a longer times, a second and more accurate algorithm to send the pricing signals to the users includes the feature that such prices signals are kept for a minimum period of time adding up to a predetermined numbers of hours along the day.

Algorithm 5.2 Second Pricing Policy Algorithm

```
given a daily time window $T$ divided in intervals $t$
given $N$ agents with the same target consumption $tgtCons_t \; \forall \; t \in T$
given the calculated $lowPriceProb_t$ and the values of $lowPrice$ and $highPrice$
given the minimum minutes per day each agent gets a low price $minCheapMins$
given the minimum minutes length of the low price interval $minCheapInterval$
for $t \in T$ do
    $pricProb_t \leftarrow \frac{lowPriceProb_t}{\sum_{t' \in T} lowPriceProb'_t}$
end for
for $agent \in N$ do
    for $t \in T$ do
        $cheapMins_t \leftarrow 0$
    end for
    while $\sum_{t' \in T} cheapMins'_t \leq minCheapMins$ do
        $startInterval \leftarrow$ random choice minute with $priceProb$ distribution
        $startMin \leftarrow \max(0, startInterval - minCheapInterval/2)$
        $endMin \leftarrow \min(T, startInterval + minCheapInterval/2)$
        $cheapMins_t \leftarrow 1 \forall t \in [startMin, endMin]$
    end while
    for $t \in T$ do
        if $cheapMins_t == 0$ then
            $price_t \leftarrow highPrice$
        else
            $price_t \leftarrow lowPrice$
        end if
    end for
end for
```

Multiple appliances consumption data are taken after analyzing the Pecan database [6], in order to provide profile consumptions and dimensions of appliances as close to reality as possible.

Such appliances, among which have been included cars as electric in order to investigate a model which includes *Vehicle-to-grid* storage capacities, have been divided based on then different consumption profiles. For every kind of appliances, some proper algorithms have been used to take advantage of the price signals in different ways. Appliances have therefore been split between those that are continuously connected to the grid (i.e. fridges, heaters, etc.) and those that can be used intermittently during the day (dishwashers,

electric cars, ovens, etc.): for the first ones, the consumption strategies focus on finding a continuous charging strategy along the day, while for the second ones, the strategy is prevalently related to a shift of the consumption in a cheaper time window.
Electric cars have been considered as chargeable only during periods when they are parked at home, which is why it has been made use of statistical data on car travels in the U.S. [8].

Appliances have been divided among accumulators, batteries and delayable devices.

Accumulators represent appliances that work as capacitors, accumulating energy that they discharge later uniformly (for instance, as heat dissipation in the case of fridges and heaters). For this appliances, the energy stored is kept within their capacity limits and the discharge profile is simulated randomly from the data, extracting the data according to the date where calculations are made (in order to prevent, for instance, high air conditioning consumption during winter).
The amount of energy stored is kept as close as possible to a constant value and losses through dissipation are considered of little importance.
Based on four different algorithms, we simulated its consumption in the following ways:

- choosing the cheapest minutes to keep the stored energy at a constant value. The minutes do not need to be consequent (Cheapest Strategy);
- Similarly to the previous strategy, but choosing to charge starting from the longest time interval with low prices, accordingly to the needs (Cheap Interval Strategy);
- charging the appliance every time it is used (if possible), or whenever it is fully discharged (Uncontrolled Strategy);
- charging the appliance up to the capacity limit, and again, when the energy stored is below the minimum level (Uniform Interval Strategy).

Batteries represent appliances that need to be recharged after every use, at their maximum charging power (assumption). Therefore for each simulated day a connection and disconnection time is randomly generated, along with the amount of energy needed to recharge the battery (from public data).
With different strategies algorithm, it is possible to select when it is more appropriate to charge the battery, based on statistical data and price signals. The battery is considered available for charge at the end of its use interval. Based on four different algorithms, we simulated its consumption in the following ways:

- choosing the cheapest interval of times to charge completely (or up to availability), once given the price signals. Those intervals do not need to be consequent (Cheapest Strategy);

- choosing the cheap intervals in the day and trying to charge the battery uniformly just in those intervals (Cheap Interval Strategy);
- choosing the first available interval, not considering price signals (Uncontrolled Strategy);
- choosing a constant amount of charge per minute, in order to charge the battery uniformly during the availability time (Uniform Interval Strategy).

Delayable devices represent appliances which can function at will and therefore their use can be postponed to the best interval. However, once they start functioning, they need to finish their program (i.e. washing machines, ovens, etc.). In this case, appliances statistics can give information on the "willingness" of the residential owner to postpone their use. Therefore, for each day, at time t is selected a (random) working program, based on usage statistics of that same day (the appliance in principle may or may not be used).
Based on four different algorithms, we simulated its consumption in the following ways:

- choosing the cheapest interval to run the program, calculating the cost of every possible interval (Cheapest Strategy);
- in view of a possible delay of the working time, choosing the longest interval that might grant the cheapest costs of consumption (Cheap Interval Strategy);
- choosing to run as early as possible (Uncontrolled Strategy);
- choosing to start at the middle of the availability interval (Uniform Interval Strategy).

After calculating the different consumption strategies for each appliance, the data of every user have been normalized to the average user consumption [6], in order to give a more appropriate basis for the comparison of the results.

5.2.2. Simulation Results

We performed some simulations of the model of 100 residential agents (due to computational effort) at different time intervals of the year.
To each residential agent, a range of appliances has been connected based on the Pecan [6]

Dataset ownership ratios. For each day, a power profile, or a charge state, or a charging power capability has therefore been associated with each appliance owned.

To see if the demand management pricing policy could motivate subscribers to cooperate with the needs of the utility distributor, it has been in the end calculated the net saving of money for every consumption profile. However, such prices have been taken just as the average of the total prices sent to each users, so the final result is an underestimate of the possible savings.
Nevertheless, it can be showed how a well designed demand management might offer the possibilities: to the agents to spend less money with the same advantages and to the central authority (or TSO) to meet the requests for a better grid management.
Notably, the results might improve with a better suited pricing policy, changing the values of low and high prices as well as the length of the intervals such prices can stay at a low level.
For the purpose of the model, this has not been further investigated and the first issue to face, as shown in the results, is to prevent spikes at the end of each day, which are present in the *Cheapest Strategy* model, because of the preferential night charging of the cars.
The situation gets a bit better when we set larger values for the capacities of the appliances, as it is shown in the next plots for a summer period.
Apart from the spikes, the model perform quite good in diminishing the load when it is demanded to.
In the following plots are presented the simulation results for a low price time window of minimum 60 minutes, up to 360 minutes every day, with a high price value of 0.25€and a low price value of 0.05€.

One issue in the model might be the higher and spiked night consumption of some strategies (*Cheapest Interval Strategy*) because the electric charge of vehicles has only been considered to happen at night in the residential properties. However, in reality it is possible to charge them even at workplace or other locations, offering further options for load-balancing.

The different consumption strategies on which the model has been evaluated are marked with:

- Strategy 1;
- Strategy 2;
- Strategy 3;
- Strategy 4.

And correspond directly to:

- Cheapest Strategy;
- Cheapest Interval Strategy;
- Uniform Interval Strategy;
- Uncontrolled Strategy.

Moreover, to check the validity of the simulation, all the strategies have been compared with the domestic average consumption profile (always, available in the Pecan Database [6]) subject to the same pricing policy as the other strategies, or to an average price for the whole time period.

It is shown that, even if the cheapest strategy may grant some savings in the daily consumption, however some demand peaks are still present: this may be due first of all because (for the model built) most appliances are asked to be switched on at night, secondly because the prices probability distribution might too often ask to some households to increase the load at the same time.
The following plot show the results for a simulation of 7 days of 100 residential agents, both with low capacities appliances and high capacities appliances.
The results obtained are quite satisfactory, providing savings of the order of 10-15%. However it is thought that the model should be improved: increasing the statistical data, increasing the number of agents, adopting different pricing policies. Again, it is important to notice that the results obtained would have been different (increasing the savings) if real expenses had been calculated for every household, based on their own local price signals.

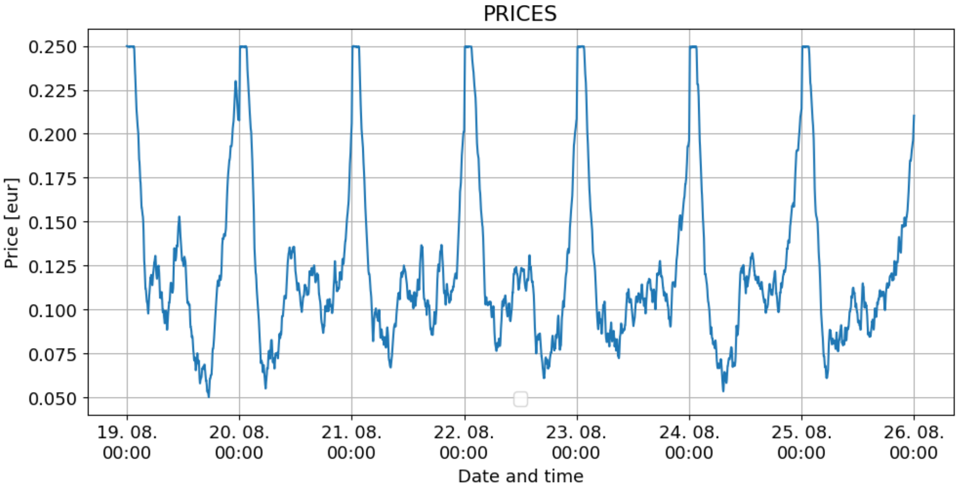


Figure 5.1: Average Prices Signals

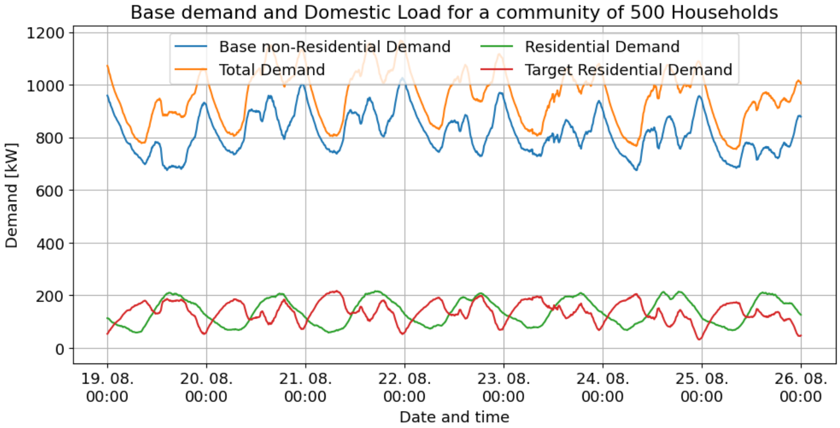


Figure 5.2: Base Demand, Residential Demand and Target Residential Demand

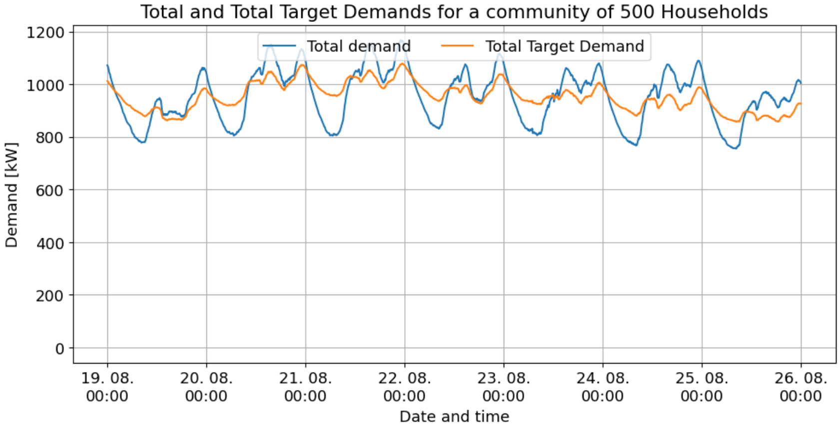


Figure 5.3: Total Target Demand

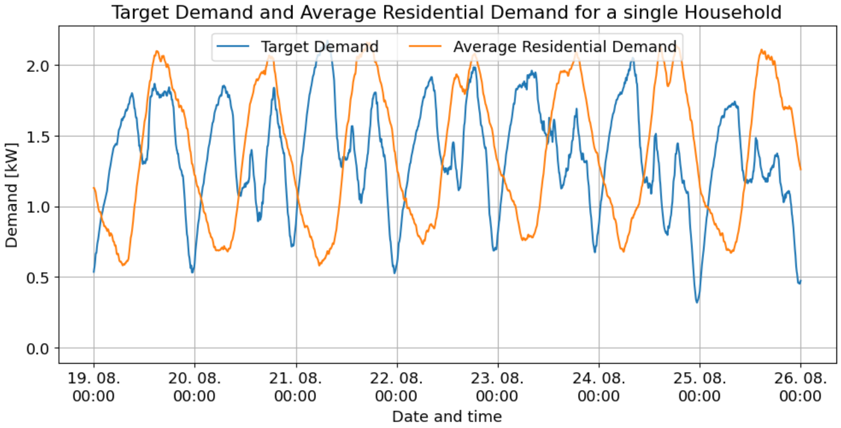


Figure 5.4: Target demand for Single Agent

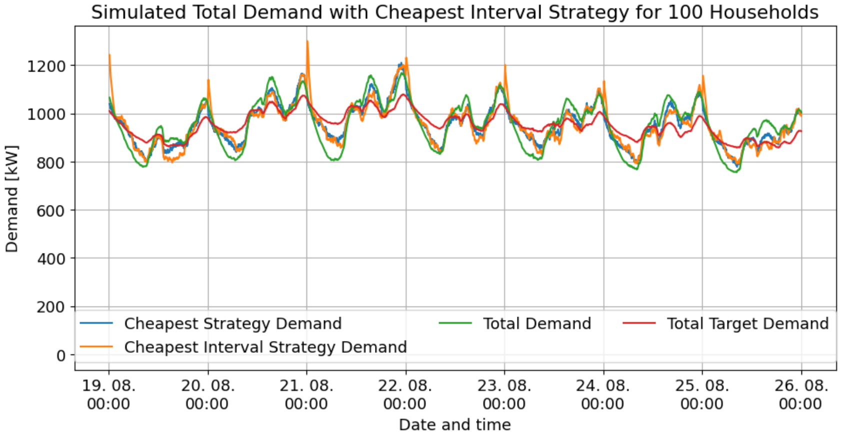


Figure 5.5: Total and Simulated Demands

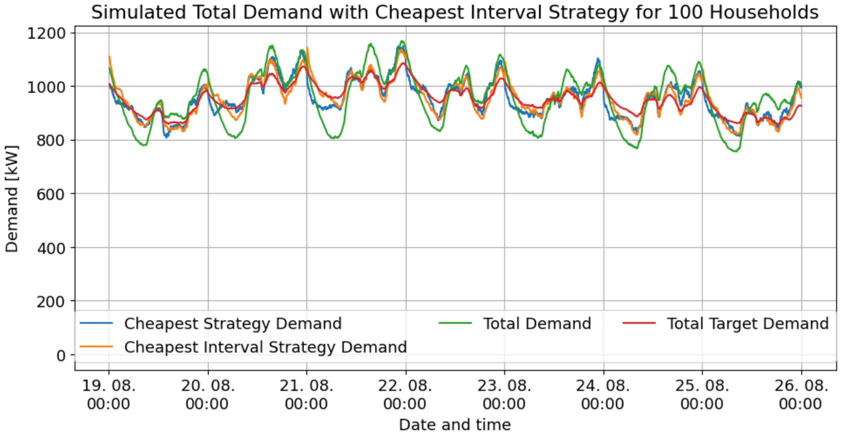


Figure 5.6: Total and Simulated Demands (increased capacity)

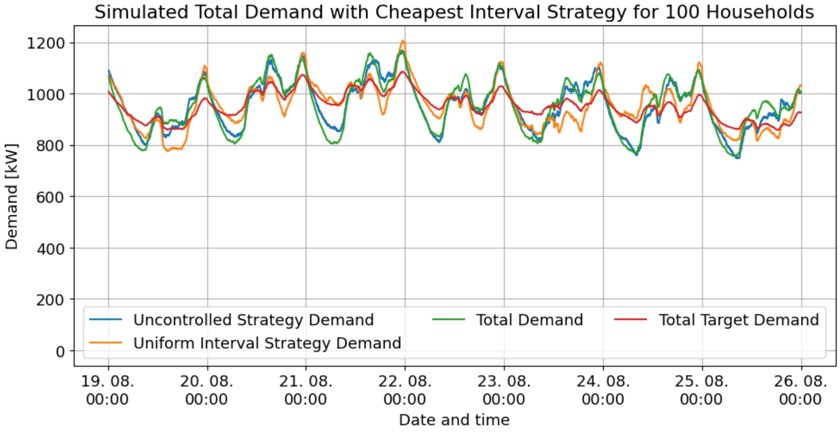


Figure 5.7: Total and Simulated Demands (increased capacity)

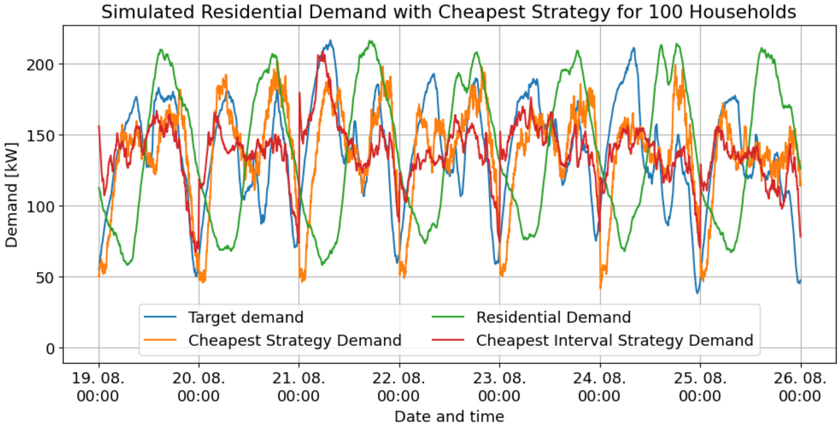


Figure 5.8: Comparing Different Strategies with Target Demand

	Strat. 1	**Strat. 2**	**Strat. 3**	**Strat. 4**	**AvDem**	**AvDem2**
daily exp. [€]	3.35	3.47	3.72	3.71	3.69	3.71
daily exp. (> capac.) [€]	3.15	3.37	3.52	3.70	3.68	3.71

Table 5.1: Daily Expenditure per Household (av. price: 0.15 €, av. cons. : 28.2 kWh)

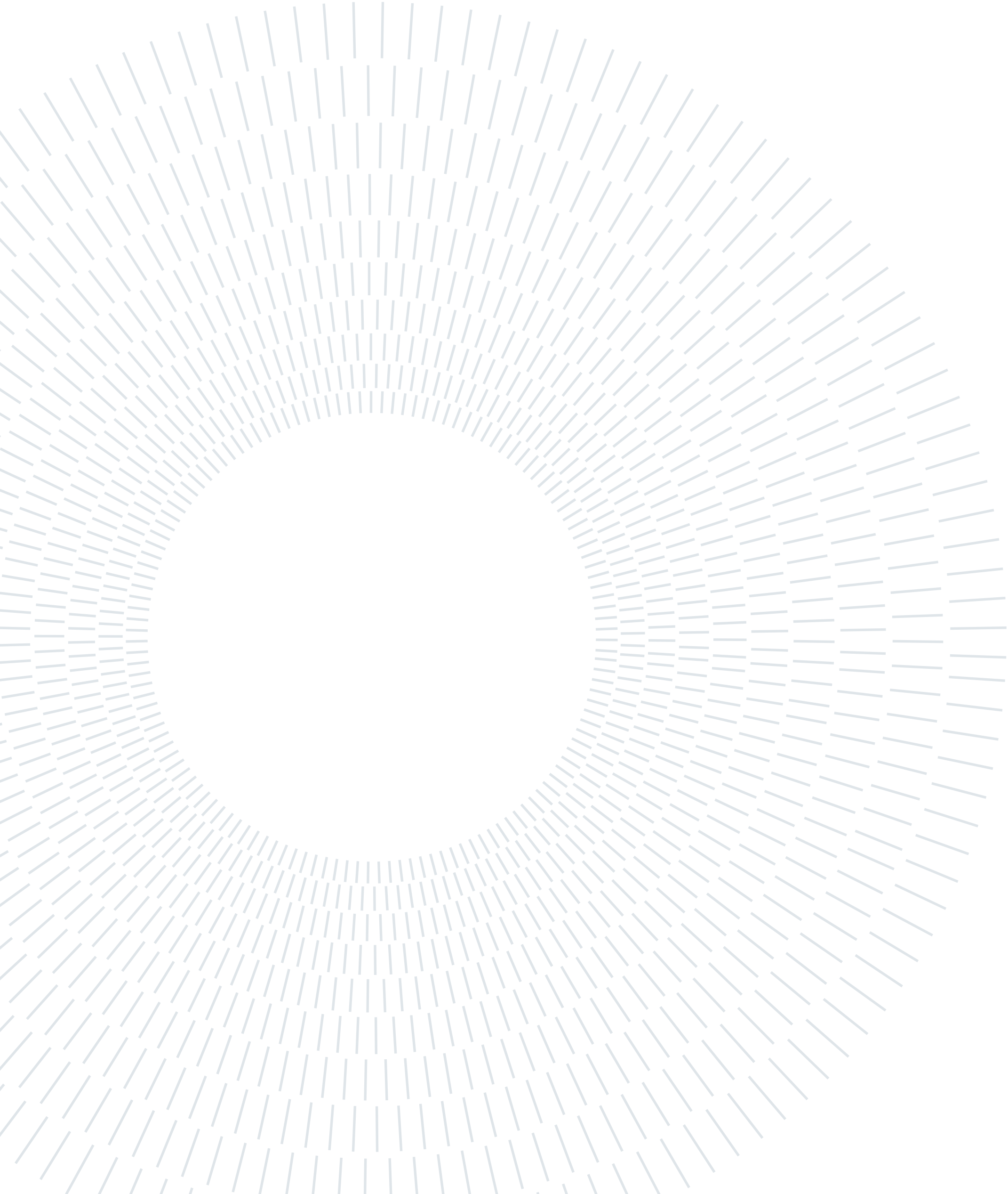
Both the present Agent-Based Model and the Optimization Model of the previous chapter are based on a central authority, identifiable with the subject responsible for the management of the grid (TSO, DSO, Energy Generator, to give some examples).
More recently however, an ever larger part of the grid users is trying to "break free" from the centralized authority and the grid is rapidly evolving into self-autonomous units which go under the name of "microgrids", where the simultaneous use of battery storage and

residential photovoltaic panels is significantly diminishing the residential demand to the (general) electric grid.
This (r)evolution has been driven by economical incentives, but a large contribute derives from the attitude of the society which is increasingly shifting its behaviour toward an environmental awareness in every aspect of daily lives.

However, as of today, most carbon emission reduction policies do not influence directly the lives of people, but are regulated on a higher level, often obtaining contradicting results.

Moving the electric-grid in the direction of micro-grids, it is possible to exploit this diffuse environmental awareness so that every user could become directly responsible of its own electricity and GHG consumption. Even more, if it were possible to monetize such an environmental friendly behaviour, than the shift to less polluting grid could happen sooner than expected.

To motivate such a research, it is necessary to learn from the errors of the past, so the next chapter is entirely devoted to a discussion about the successes and failures of the policies to fight the climate change.



6 | Carbon Emission Reduction Policies

> *"Try again. Fail again. Fail better"*
>
> S. Beckett

A chapter to discuss about the effectiveness of carbon-reduction policies, with a focus on EU-ETS.

Electricity, as a commodity, has the peculiarity of being particularly difficult to store and being subjected to exchange "as-soon-as possible". Unfortunately it is also subjected to high inefficiencies which overall determine a waste of resources: the difficulty (sometimes impossibility) of storage accompanied with a lowering degree in quantity and quality with time (storage efficiency), the losses in the transmission lines and, not least, the overuse and intermittency on the demand side are all kinds of inefficiencies that characterize the electricity market.

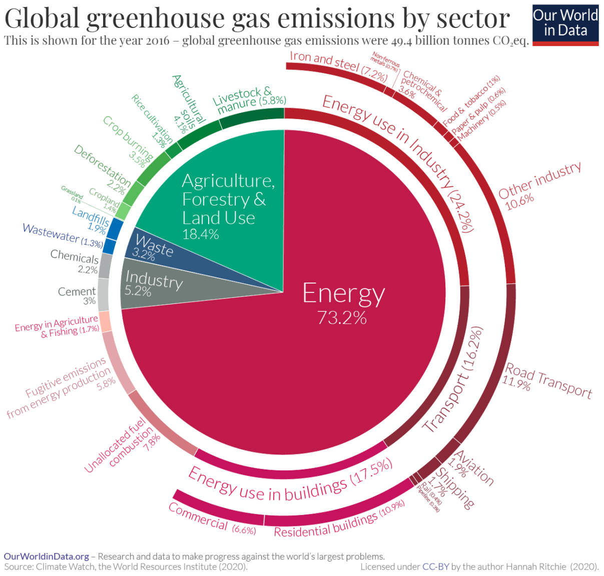


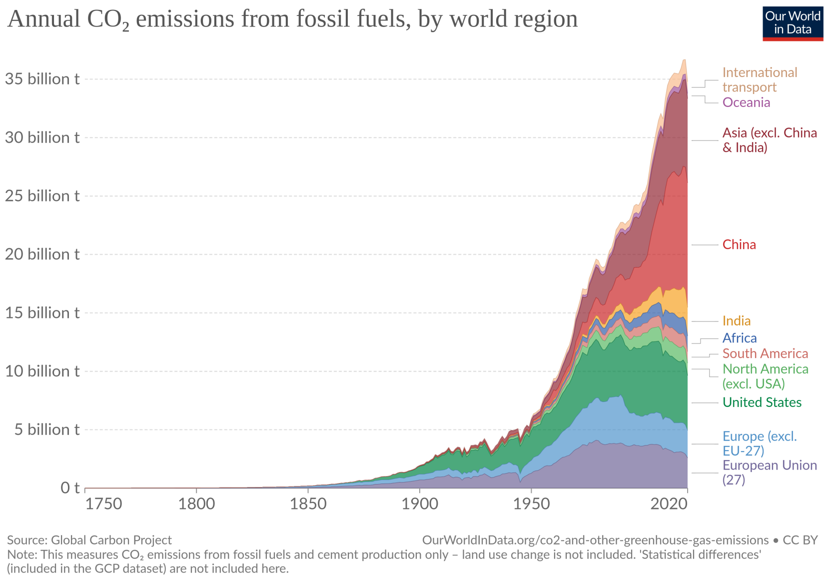
Figure 6.1: Global Greenhouse Gas Emissions by Sector [40]

If we also include the fact that in most countries the largest share of electricity is produced with fossil fuels, we can immediately understand how the energy production market (excluded the energy for transports) is accountable for more than 40% of polluting emissions around the world, with the largest shares divided between industries (24.2% of the total) and households(17.5%) [40].

GHG pollution is largely accounted as the main responsible for the climate change in the past century, whose destabilizing effects go well beyond those of the simple temperature rise and include: ocean acidification, the increase of abnormal weather patterns, arable land reduction, drinking water shortages, a drastic cut in the degree of food resources available for consumption, mass migrations, and many health concerns [16].

A first step toward the decarbonization of the energy sector, as previously described, has been introduced with a broader development of low-carbon technologies (solar, wind, nuclear, etc.), especially in the European and North-American areas.

Worldwide speaking though, we cannot state that the trend towards decarbonization is being achieved, because the only five periods, from late 1700s up to nowadays, where environmental pollution has been substantially reduced coincide with periods of global economic recessions: the Second World War (1939-1945), the 1970s energy crisis (1973 and 1979-1980), the early 1990s recession, the 2007-2008 financial crisis and the 2020-2021 Coronavirus pandemic: exceptions in a trend which see GHG emissions constantly growing.



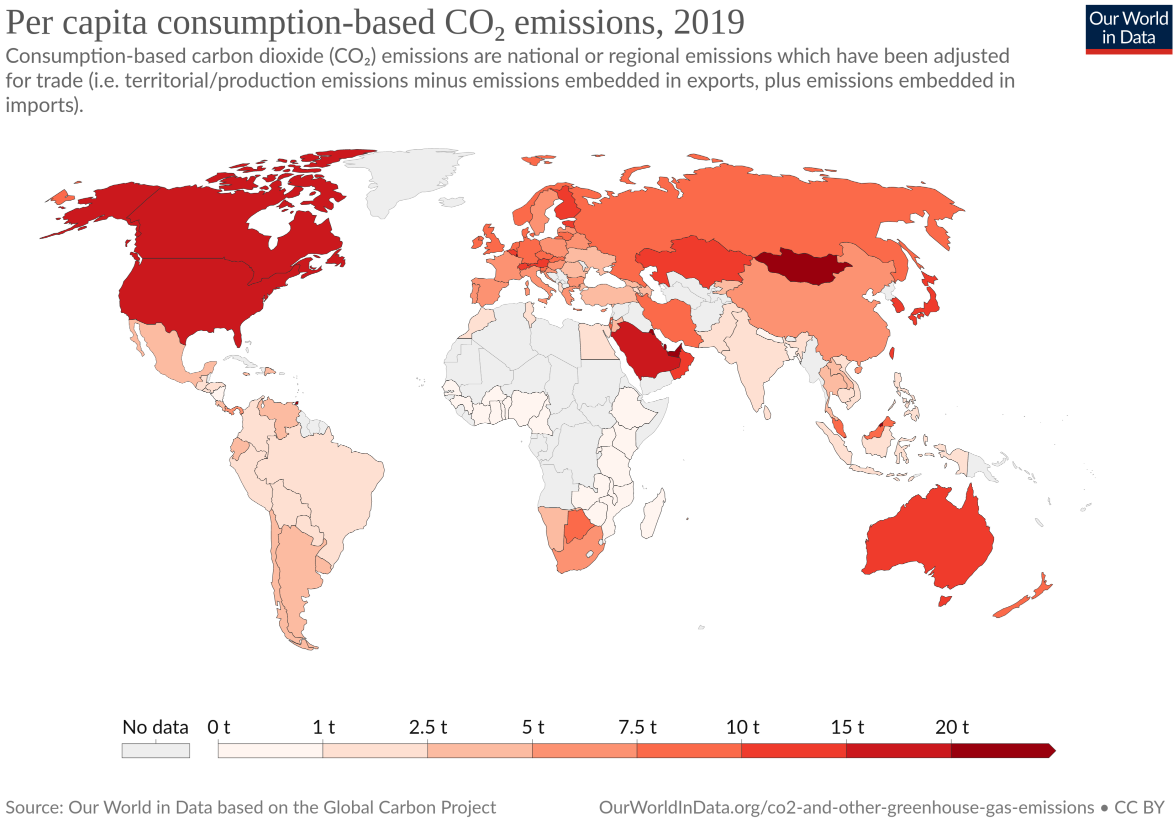
Annual CO_2 emissions from fossil fuels, by world region

Source: Global Carbon Project OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY
Note: This measures CO_2 emissions from fossil fuels and cement production only – land use change is not included. 'Statistical differences' (included in the GCP dataset) are not included here.

Figure 6.2: Global Greenhouse Gas Emissions by World Region [32]

Looking at the graph, it seems evident that there has been a substantial decrease in emis-

sions from fossil fuels both in Europe and North America in the last 30 years, which might be summarized with the statement (taken from European Commission press release): *"EU-27 greenhouse gas emissions in 2019 declined by* 24% *compared to 1990 levels"* [1].
A statement that is true concerning the emissions production.
If however the production is checked together with the consumption, comparing the level of $CO_{2_{eq}}$ per capita in the world, we immediately catch how the image depicts with a higher, almost same, level both developed and developing countries, while it reaches low levels only in countries which are still "underdeveloped".


Per capita consumption-based CO_2 emissions, 2019

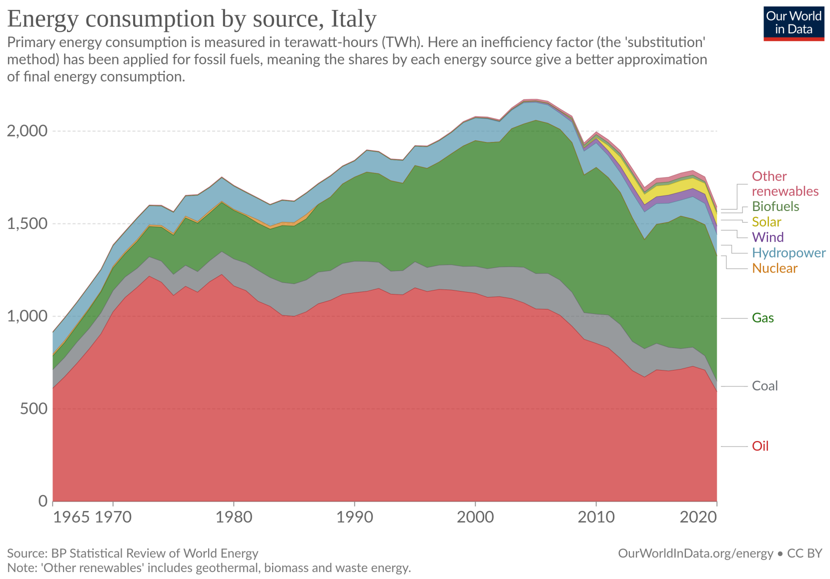
Consumption-based carbon dioxide (CO_2) emissions are national or regional emissions which have been adjusted for trade (i.e. territorial/production emissions minus emissions embedded in exports, plus emissions embedded in imports).

Source: Our World in Data based on the Global Carbon Project OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY

Figure 6.3: Global Greenhouse Gas Emissions Consumption Per Capita [14]

The reason of statements as the previous one lies in that CO_2 emissions are typically measured on the basis of production: an accounting method which is both used when countries report their emissions and set targets domestically and internationally.
However, when consumption-based emissions are taken into account, we need to track which goods are traded across the world: whenever it was imported we need to include all CO_2 emissions that were emitted in the production of that good and vice-versa need to subtract all CO_2 emissions emitted in the production of goods that were exported.
Consumption-based emissions reflect therefore the consumption and lifestyle choices of a

country's citizens and it is that one, in the opinion of the author, that should be related to climate-change politics and which, without rethorics should be publicly advertised, otherwise it won't be possible to change people's behaviour and people will still be falsely addressed, for instance, to buy electric vehicle in a country like Italy, where more than 80% of energy consumed comes from fossil fuels (including transports and agriculture).


Energy consumption by source, Italy

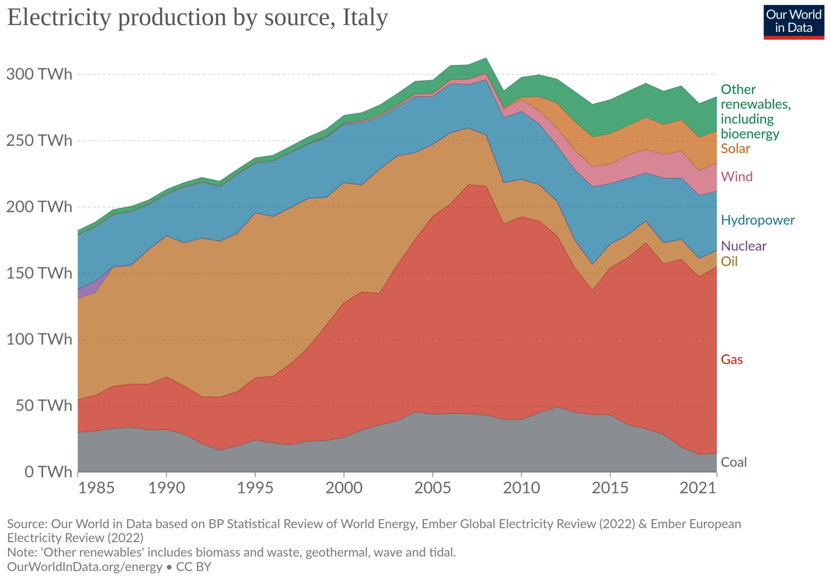
Primary energy consumption is measured in terawatt-hours (TWh). Here an inefficiency factor (the 'substitution' method) has been applied for fossil fuels, meaning the shares by each energy source give a better approximation of final energy consumption.

Source: BP Statistical Review of World Energy

OurWorldInData.org/energy • CC BY

Note: 'Other renewables' includes geothermal, biomass and waste energy.

Figure 6.4: Italian energy consumption by source [41]


Electricity production by source, Italy

Source: Our World in Data based on BP Statistical Review of World Energy, Ember Global Electricity Review (2022) & Ember European Electricity Review (2022)

Note: 'Other renewables' includes biomass and waste, geothermal, wave and tidal.

OurWorldInData.org/energy • CC BY

Figure 6.5: Italian electricity production by source [41]

To fight carbon emissions in the electric sector, many government have acted promoting and supporting the extensive use of renewable and low-carbon technologies or, by contrast, hindering the high-carbon ones.
In E.U., the most used support mechanisms for renewable electricity have been feed-in tariffs and feed-in premiums, but competitive auctions are nowadays becoming more and more common.

Nevertheless, if from one side, the higher and higher share of renewable sources in the energy market provides a way to mitigate the use of fossil sources and hence a reduction in carbon emissions, from other sides, apart from providing new and important challenges to the energy grid, their widespread use is hampered by two main factors: the still-low prices of fossil fuels and the intrinsic irregular availability of most of renewable sources.

In the European Union, to mitigate the second problem, the paradigm up to now has been the deployment of energy from wind and sun together with a substitution of old coal and oil plants towards less polluting gas energy or turbines for peak production.
The impact of such policies has not been as deep as it should: however new energy market designs, focused on the optimization of the grid and carbon consumption reduction, might curb the trend and make renewable intermission not as challenging as it is now.

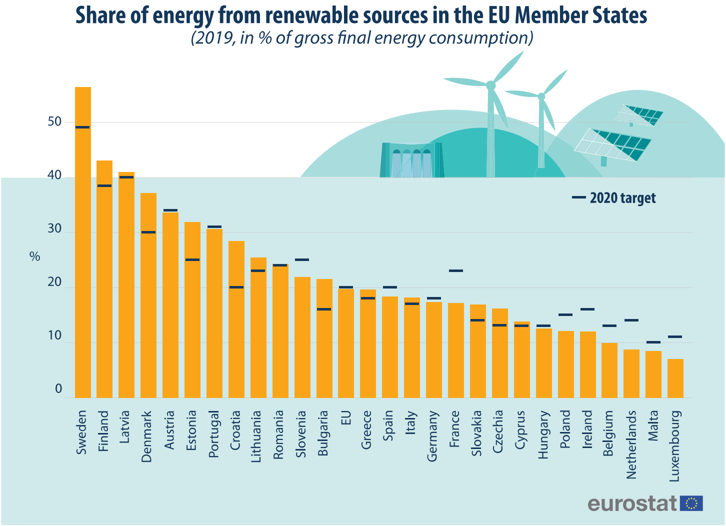


Figure 6.6: Share of Energy from renewable sources in EU [2]

To fight fossil low prices and let renewable gain competitiveness in the energy market instead, there have been a large number of proposals worldwide, ranging from subsidies, specific regulations and technology innovations to carbon taxes or the most-common approach of a cap-and-trade system, with the European Union Emission Trading System playing the role of pioneer.

To give an evaluation of some of the most important techniques and regulations applied to fight carbon emissions, the following part of the chapter will focus on each of them, trying even to give a proof of their effectiveness, both locally and worldwide.

Ultimately, the last section will be focused on the description of European Emission Trading Scheme, which represents a milestone in European Green policies, investigating the origins of its lack of success in meeting the pre-established goals.

6.1. Emission Taxes

An emissions tax, better known as carbon tax, since it is usually applied on carbon-producing fossil fuels, is probably the simplest conceptual way to internalize the cost of pollution.
The conceptual idea of such an intervention is to disincentive the use of products or energy resources associated to a high production of GHG, indirectly promoting a swift towards "greener" solutions.
Such a solution is not always easy to implement by governments, because taxes in general are not considered a positive change. However certain design elements might help in rendering such a solution more attractive.
For example, often such a tax might be used to lower social security (or other) taxes rates, or distribute the income from the tax among the actors which are most hit by its negative turn-ups.

Emission taxes are usually applied to producers (upstream tax [42]) rather than consumers, since it's producers' choice which drives the electricity (and carbon) production. Most often however producers indirectly pass the tax on consumers: a situation not completely negative because by doing so, they indirectly shift consumers' behaviour towards other energy sources.
In a market where the consumers' choice is not taken into account, such as retail electricity market, those kind of taxes can nevertheless be withheld, so that the overall effect can actually be that one of a carbon tax for consumers, without shifting its choice if not through an intermediary.

Among the positive sides in introducing a carbon tax, we can list:

- its easy and quick implementation;
- the higher intelligibility for the population;

- the direct effects on carbon economy.

Among the issues instead, the most important are the right evaluation of the tax rate, which needs to be adjusted frequently to steer the market in the desired direction and the difficulty in coordinating the emissions target with the disincentive of consumption which is, once again, strictly dependent on the tax rate.

6.2. Cap and Trade System

A cap and trade system works as a market system, creating an exchange value for emissions.
It differs from a carbon tax in that it inherently set a cap on emissions, that is the way through which it is possible to evaluate its effectiveness.
Since companies that have emissions credits can sell them for extra profit, this creates a new economic resource for industries.

A cap and trade system is usually proposed by a public entity: the government (or the regulator) sets the limit on emissions permitted across a given industry or economic sector. It issues therefore a limited number of annual allowances which grant the permission to emit a certain (prescribed for each industry) amount of carbon dioxide and related pollutants that drive global warming. In the case of EU-ETS for example, each allowance permits a company to emit one ton of emissions.
The allowances are given for free or through an auction and their number is lowered every year, thereby lowering the total emissions cap. In principle that should also make the permits more expensive, up to a point where reducing their emissions more efficiently and investing in clean technology becomes cheaper than buying permits.
Through the auction allocation method, in comparison to free allocation, additional revenue is generated for the governing body for the purpose of funding low carbon investments or other projects [42].

Companies surpassing the level of emissions in their allowances portfolio are fined a quota per each mismatched ton of GHG emitted or even penalized for a violation. On the other hand, companies reducing their emissions can trade allowances to other companies in need or save them for future use.

Once the allowances have been tallied out or auctioned off, participants who will go over their emissions cap will have to purchase allowances from under-polluting companies or face a financial penalty. The financial penalty would, of course, have to be set at an adequate level in order to encourage participation in the market rather than facing the

penalty [74].
These carbon allowances represent one ton of emissions, but they can also measure the value of emissions offset by projects commonly known as carbon offsets [25].
Carbon offset projects are an alternative available in some program designs and often are undertaken when polluters either do not have the proper number of allowances, or find it cost-efficient to pursue carbon offset projects. Some examples of carbon offset projects would be renewable energy projects, reforestation, or funding efficiency upgrades for other businesses at a lower cost.
Additionally, projects that reduce greenhouse gas emissions but are cheaper, such as the purchase of technological improvements for a different polluting sector, are generally considered a cheap way of getting out of producing real change in the sectors that need to reduce pollution.

The carbon market created with cap and trade is influenced by the forces of supply and demand, which means with fewer numbers of allowances or offsets, the price of emissions will increase with demand.
Hence, while it may be easier for companies to purchase carbon offsets initially, the idea is that as the demand for carbon offsets increases as the cap is reduced, the price will go up, eventually making it cheaper for businesses to reduce their own emissions rather than purchase offsets or buy allowances. It is because of this that the cap and trade model is generally considered a cost-effective way to reduce the emission of greenhouse gases.

Proponents of cap and trade carbon market argue that it offers an incentive for companies to invest in cleaner technologies in order to avoid buying permits, hence working both as beneficial for gaining "free" fundings in low-carbon technologies and reducing carbon emissions simultaneously.
Because the government can decide to auction emissions credits to the highest bidder, cap and trade is also a revenue source for the government, since it has the power to auction emissions credits to the highest bidder.
As a free trade system, cap and trade gives consumers more choices as well. Consumers can choose not to purchase from companies that are out of compliance, and do business with those that are trying to reduce their pollution levels.
Finally, the cap and trade system also has benefits for the taxpayers. The government sells emission credits to businesses that need them. The income generated helps to supplement the resources that taxpayers are providing the government [74].

Opponents of cap and trade instead argue that it could lead to an overproduction of pollutants up to the maximum levels set by the government each year, since allowable levels may be set too generously, actually slowing the move to cleaner energy.

Also, emissions credits (and even penalties and fines for exceeding the cap limit) are usually cheaper than converting to cleaner technologies and resources. This is the case, for example, for industries that use fossil fuels. This means that cap and trade is not a real incentive for those industries to change their practices.
It's also argued that the "trade" mechanism is not always followed. Some credits are sold at auctions to the highest bidder, or even given away, meaning that it costs a company nothing to increase its emissions.
Moreover, most industries don't have devices that help monitor and determine their amount of emissions, which makes it relatively easy for businesses to cheat on their emissions reports. For the cap trade system to be effective, monitoring systems must be implemented so that enforcement can take place.
Finally, each country has different standards and maximum caps for emissions. Some may be very lenient and permit higher levels of pollution, while others may be very strict. Unless a global cap and trade system is established, it won't be effective globally and there may be little impact on the number of emissions spilled out into the atmosphere every year.

Perhaps one of the most significant limitations within cap and trade theory is the amount of time and information that such an essential and complex program requires in order to function correctly. The benefit of a cap and trade program compared to a carbon or emissions tax is that the cap and trade program can set a definite cap on the level of emissions within the sectors covered; however, that cap requires a tremendous amount of time and information to be set correctly.

Within the neo-liberalism ideology, cap and trade constitutes the preferred option to tackle climate change and its widespread development among the occidental democracies (and not only) bears witness to this.
In contrast with a carbon tax, it has the advantage of gaining a higher consensus in public opinion (usually not confident with policies that bear "tax" in their names) and within the free-market theory is associated to an increased efficiency if compared with the "failures" of top-down state policies.
Indeed, a pure cap and trade system without price restrictions is self-balancing: with low prices prevailing in economic busts when emissions are low and high prices in booms when emissions are high.

In recent years, a specific emphasis has been posed to the European Union Emissions Trading System as a successful strategy to reduce climate change and several other ETSs have been implemented around the world to reduce greenhouse gas (GHG) emissions [24].

6.3. Other Support Policies for RES

6.3.1. Tradable Green Certificates

Tradable Green Certificates (TGC) are issued when electricity is generated using renewable energy technology.
The TGC belong to the group of flexible market instruments for environmental policy and it is also referred to as Renewable Energy Certificate (REC), Renewable Obligation Certificate (ROC) or more generally a Guarantee of Origin (GO or GoO) from a renewable energy source. They can be traded separately from the electricity produced. The generated electricity and its quality label, in the form of a certificate, are detached at the point of generation.

Green certificates, or more generally Guarantees of Origin, are purchased on a voluntary basis to get guaranteed green electricity. This allows end-users, businesses and households alike, to reduce their CO2 footprint. For corporates, this has commercial benefits, as it improves their reputation and provides a competitive edge in a society in which awareness and the importance of environmental impacts are ever increasing.
Green certificates are traded for compliance reasons or on a voluntarily basis and through them, governments can set exact targets as to the level of renewable production in a country, while the market finds the most efficient way to meet these targets. It is an alternative to other policy mechanisms, such as renewable investment subsidies, renewable production subsidies, fiscal benefits and feed-in tariffs.

A green certificate may be considered the opposite of an emission certificate. In fact, whereas emission certificates impose a cost on non-renewable production and set a maximum to the total emissions, green certificates create an extra revenue for renewable production and guarantee a minimum of renewable production.
Certificates cannot be transferred between the European markets, as opposed to emission certificates, so the total market size is often small and trading rather illiquid.

6.3.2. Feed-in Tariffs

Feed-in tariffs are a price-based policy which set the price to be paid for renewable energy per kWh generated (in the form of guaranteed premium prices). This is generally combined with a purchase obligation. Typically the costs are borne either by consumers or by the public budget. Feed-in tariffs are complemented with the obligation to purchase the renewable electricity by the grid operator.

6.4. European Union Emission Trading System

The 1990s saw the first attempt of the EU to introduce a carbon tax. However, strong industrial lobbying led to its failure. In 2005 instead, E.U. succeeded to negotiate and introduce an alternative to a carbon tax known under the European Union Emissions Trading Systems (EU-ETS).

Among the others, the Emission Trading System conceived for the first time in 2005 in the European Union has been considered as a cornerstone in the governmental policies for fighting climate change acquiring both praise and criticisms thanks to its fame.
Up to now, it has been developed in four phases (2005-2008, 2008-2012, 2013-2020 and 2021-2030) with concrete revisions at each phase in order to allow the involved businesses in the scheme time to accustom to the changes in the program and to gauge the modifications necessary at every step to reach the planned carbon emissions reduction.
As of 2021, the scheme covers around 11,500 polluters of 31 EU-EEA participant countries, covering approximately 40% of the total EU emissions and which impact can be assessed against with two primarily objectives:

1. Reduce emissions in an efficient way giving a proper price to each ton of GHG emitted

2. Promote the private investments

EU-ETS, basically, follows the "cap and trade" principle.
It sets a maximum cap on the total amount of greenhouse gases that can be emitted by all installations which are participating.
Allowances are auctioned off or allocated for free and can be traded. Each participating actor is responsible for monitoring and reporting on their emissions to their respective authority, which can be a national body or an established supranational authority. In the case of an excess to the allowed emission cap, a purchase of allowance from another actor(s) is required [74].

6.4.1. First Phase

In the first phase of the development (2005-2008), the system included both power stations and energy-intensive industries (iron, steel, cement, etc.) and the cap was set at a quota of 2096 millions of tons of CO_2, with 95% of allowances allocated for free. The penalty for non-compliance was set at 40 euros per ton of emissions.
The benchmark for free allowances was set at the "average emissions rate per unit of

output for those installations in each ETS sector constituting the 10% with the lowest CO_2 emission rate in 2005" [30] and was calculated on the basis of historical emissions reports for each participating country.

A special feature of this phase was the inclusion of Clean Development Mechanisms (CDM) and Joint Implementation (JI) credits, which facilities could substitute in place of allowances. Clean Development Mechanisms regarded the possibility of obtaining certificates that granted an involvement in projects for carbon-abatement in less industrialized countries; Joint Implementation credits instead included the evaluation of similar contributions, but restricted to industrialized countries.

Altogether, CDM and JI have represented cost-efficient solutions to use the so called "carbon offset" credits as opposed to the purchase of allowances. The first phase of EU-ETS was particularly controversial because it was a responsibility of every state to set its own cap and disbursement of allowances through the National Allocation Plans (NAP), without a proper central regulation authority. Another flaw stood in the (almost) completely free allocations of allowances and the unlimited possibility of allowances trading: more than on reducing emissions, every business was focused on gaining a profit from the sale of allowances.

Another flaw lied in setting an overgenerous cap on emissions, so that the price of allowances rapidly sank and it was more convenient for businesses to buy cheap allowances instead of promoting carbon-sustainable projects. It was admitted that such an overcalculation was caused by giving the responsibility of the cap to different National Allocation Plans, which might have created competitive distortions in the market.

This over-allocation (and free) of allowances was addressed as the first responsible of massive windfall profits for the businesses, which has been calculated in the range of 5 to 7 billions of Euros per year for the whole European market.

Moreover, empirical studies found that there is strong evidence that costs were passed onto consumers, with pass-through costs in the range of 60-100% [39].

As soon as the extreme price change after the over-allocation was evident, the market for allowances became volatile and ineffective, not only as a market for carbon emissions, but also as a framework for reducing emissions, which, being the primary goal, promoted discussions about the real effectiveness of market-based approaches for GHG reduction [39].

If the goal was to make polluting industries a significant degree of profit while producing little emissions abatement or improvement in low carbon investment, then the first phase of EU ETS program could be considered a success. Indeed, having set such a high cap for emissions, individual nations reached the expected emissions levels, hence the program was really publicly advertised as a success.

6.4.2. Second and Third Phases

With the second phase (2008-2012), the cap on emissions was reduced to 2049 millions of tons of of GHG, nitrous oxide emissions were included, free allocation was set at 90% and penalty for non-compliance was raised to 100 Euros per ton of CO_2. Businesses were still allowed to buy international offset credits and aviation sector was included [74].
The reforms of this phase were made to render the program more effective and, in principle, the direction taken was the right one.
However, in 2008 the world economy was hit by one of the biggest recessions of all times.

Figure 6.7: Time Evolution of EU-ETS prices

Because of that reason, the cap was set at a higher level if compared to real expectations and ETS prices fell again. In fact, it has been studied that the reduction in emissions throughout this phase might be attributed almost entirely to the economic recession.

Among the upsides of this phase there have been an incremented move towards auctioning, following the principle of cap and trade theory in that the polluter should pay for their emissions directly rather than being allocated a significant degree of allowances for free

[30]. Moreover, even if most allowances were allocated for free, this decision was taken to avoid carbon leakage, preserving competitiveness of those businesses more influenced by an international market.
Another big change, was the promise to abandon the NAP and agree to a program-wide cap declining at 1.74% per year starting from the third phase.

The third phase of ETS (2013-2020) saw therefore the inclusion of new chemical emissions and a newly introduced lower cap, with a linear reduction of allowances each year and with 40% of the capped allowances being auctioned in 2013. Free allocation continued in industrial sectors, but businesses who were not at risk saw their free allocation phased out from 80% of their benchmark in 2013 down to 30% in 2020 [30].
All these positive changes, were indicative of a more robust EU ETS in phase 3.
The most important innovation though was the introduction of a discretionary price management mechanism so that the cap in emissions might be modified from the central authority.

The lesson learned from the price volatility within phase 2 was in fact the need for a price stabilization mechanism executed through the management of the supply of allowances on the market. This mechanism is known as the Market Stability Reserve (MSR), and its primary function have been in the supply and withdrawal of allowances, in order to prevent the high volatile market of the previous phases.
Unfortunately, at the end of phase 3, a large number of companies reported that the EU-ETS were still elements of scarce importance compared to return on investment so the evaluation cannot be considered positive yet: the biggest drop in emissions in fact has happened between 2008-2009 (5%) showing that what inherently impacts climate change, is a change in consumer behavior, more than a complex set of market policies [39].

6.4.3. Fourth Phase

The fourth (the actual) phase of EU-ETS, after the partial failures in previous phases, has shown some improvement, making this phase a drastic departure from the previous phases.
First of all, the mechanism of Market Stability Reserve was strengthened, the price of ETS was placed in the foreground, pointing at the problems derived from a high volatility of such an instrument and viewing long-term policy stability as a way to avoid market speculation and increase trust.
Free allocation is still present for sectors at the higher risks, but for others sectors free allocation is foreseen to be phased out after 2026 from a maximum of 30% to 0 at the end

of phase 4.

Moreover, a drastic departure for the program is the interruption in the use of carbon offsets in the form of CDM and JI credits.

In previous phases these credits were used as an alternative means to fulfill businesses' emissions, abatement requirements, and while these carbon offset programs were well intended, they have often been criticized for a number of significant reasons.

In addition, several low-carbon funding mechanisms will be set up to help energy-intensive industrial sectors and the power sector meet the innovation and investment challenges of the transition to a low-carbon economy, including two new funds:

1. the Innovation Fund, to support the demonstration of innovative technologies and breakthrough innovation in industry;
2. the Modernisation Fund, to support investments in modernising the power sector and wider energy systems, boosting energy efficiency, and facilitating a just transition in lower-income Member States.

6.4.4. ETS Analysis and Alternatives

The evaluation of the effectiveness of EU-ETS as a whole must indeed take into account that the hopeful expectations which initially surrounded the program have not been met, due principally to windfall profits and a low or volatile carbon price.

These windfall profits were able to occur partly because EU-ETS did not have enough restrictions or support around the price of carbon, but other drivers were high-cost pass-through rates, the over-allocation of allowances and massive profits from the sale of over-allocated allowances.

The fact that the EU-ETS was perceived as a light-handed program with an on average low price for emissions did not send the signal that investors and businesses should look into low carbon investments in the form of efficiency upgrades or low carbon energy generation.

Furthermore, the continued free allocation of allowances to protect EU businesses from international competitiveness and prevent possible carbon leakage has illustrated that what really matters for this policy is the economy and not the environment. The EU ETS's primary goal is to reduce emissions at a balanced cost, but the issue with this is that the scale has always been more substantial on the side of economic progress.

Additionally, CDM and JI credits were overexploited, whenever possible, so that funding of innovation to reduce emissions didn't occur just because businesses were able to purchase carbon offsets in other nations and sectors.

Furthermore, it has been shown that tree plantations like the kind often funded through carbon offset projects can encourage streamflow loss, increased acidification, and increased soil salinization: hence the use of carbon offset, apart from the difficult way of assessing their real value, did not determine a carbon emissions reduction, worldwide speaking.

From another point of view, EU-ETS didn't give the expected results because of its interdependence with other climate policies in EU countries, undermining the overall effectiveness: in Germany, for instance, the generation of CO2-free electricity, which is promoted by fixed feed-in-tariffs for renewable energy sources (RES), lead to a decreased demand for emission allowances in the German power sector.
Consequently, the allowance price drop enabled market participants of other sectors and countries to purchase allowances at lower prices.
Experts say cap and trade is rarely stringent enough when used alone and that direct regulations on refineries and cars are crucial to reduce emissions; but oil representatives are engaged in a worldwide effort to make market-based solutions the primary or only way their emissions are regulated.
Even more, their influence is strong that no government in the world has been willing to place a high price on carbon up to now.

To face the intrinsic problems of EU Cap and Trade Emission Trading System, many theoretical models have been proposed. Some of the inherent issues have been addressed along its developing phases, but some others remain open and somehow leave the open question whether a different mechanism should be applied in order to get an increase in carbon emissions reduction.
Proposed alternatives within the mainstream neoclassical economic toolkit include: a pure emissions tax, a tax on varying levels, a tax with a dividend, a cap and trade model with a price floor and/or ceiling, or a mixed model which incorporates both an emissions tax and a cap and a trade program. Of those options, a mixed model that incorporates a price floor and ceiling is one of the more effective options [74].
The best elements of the hybrid cap and trade program, in the form of a price floor and/or ceiling, can be combined with an emissions tax in order to incorporate the best of both options into a mixed model. This mixed model could be similar to the emissions tax introduced in the UK in 2013 [30]. A price floor however could establish too high of a price for allowances, resulting in issues such as competitive distortions, the closure of businesses who cannot afford said allowances, or a decrease in the participation rate of the program.

The benefits of a hybrid cap and trade program are substantial, and these fixes in the mixed model could easily be applied to the EU ETS, but so could the beneficial elements of an emissions tax.

A pure emissions tax in fact, may prove more effective at reducing emissions than the cap and trade model, defining the cost of pollution at a socially acceptable rate, would not have issues such as windfall profits, and would benefit from the fact that allowances would not exist. The simple act of not distributing allowances for free would encourage the idea that all emissions should be taxed towards the source of pollution instead of the burden of those emissions being placed onto society at large. Furthermore, the many constant revisions associated with the cap and trade framework have undoubtedly incurred a degree of administrative costs where a carbon tax could provide the opportunity for a decrease in overhead [38], apart from increasing the market volatility due to a lack of stable regulation.

An intrinsic part of the EU ETS is that it establishes a market and that market is complex, open to influences beyond the governing entities control, and has the ability for participants to make a profit from said market. A problem in environmental economics is the limitless belief in market-based approaches to fight climate change, but if those who take place in the market decide that their profit imperative is stronger than the market mechanisms put in place to reduce emissions, they will find a way to ensure that they do not reduce emissions and protect their profits. If therefore one wants to really assess the problem of emission without any market influences, than it might be advisable to investigate other policies options, which decouples the profits from the environment, putting the natural world first.

One such a measure might be the imposed reduction in the use of fossil fuels.

This initiative should be pursued through policies instituted in an equitable manner, with wealthier countries supporting less wealthy countries' movement away from carbon-intensive energy sources, towards cleaner sources such as solar, wind, and hydroelectric energy. Assuming that there are remaining stocks of fossil fuels left in the ground, they might be preserved indefinitely or used in a way that supports select areas of the world where access to renewable energies is currently impossible or unfeasible.

Along with such a reduction in the use of fossil fuels, there needs to be an increase of social awareness and a paradigm shift away from sources over-consumption.

As described in the previous chapter, demand-side management through the use of smart appliances goes also in this direction and might provide good results in avoiding energy waste.

Another point which should be underlined is the power of the governments in climate stabilization policies and low carbon investments.

Governments (or the general public) in fact can simply impose reductions in emissions because of their unique position.
The general public, in the form of a government institution, has therefore the ability to fund more risky ventures in low carbon investment than other investors.
It should not be forgotten that technological breakthroughs have been historically driven by public investment and public investment in clean energy is what is needed today, because no effort to achieve deep reductions in carbon emissions, domestic or international, will succeed as long as low-carbon energy technologies cost vastly more than current fossil fuel-based energy. It is an opinion of the author that whatever effort will be put in finding the right policy to limit carbon emissions is doomed to failure and the final purpose shouldn't be to render high-carbon energy expensive, but make low-carbon energy cheap.

While it is somewhat unfair for the EU to bear the burden of the entire world's emissions, the EU also makes up the most extensive grouping of industrialized countries and is often held up as the leader of positive environmental change.
With the introduction of emission trading programs in China and South Korea, there is indeed willingness for the entire world to arrive at a mutually advantageous position; however, many industrialized nations still choose to be free-riders within this game.
Once again, a proper solution must be searched in the realm of mutual cooperation.

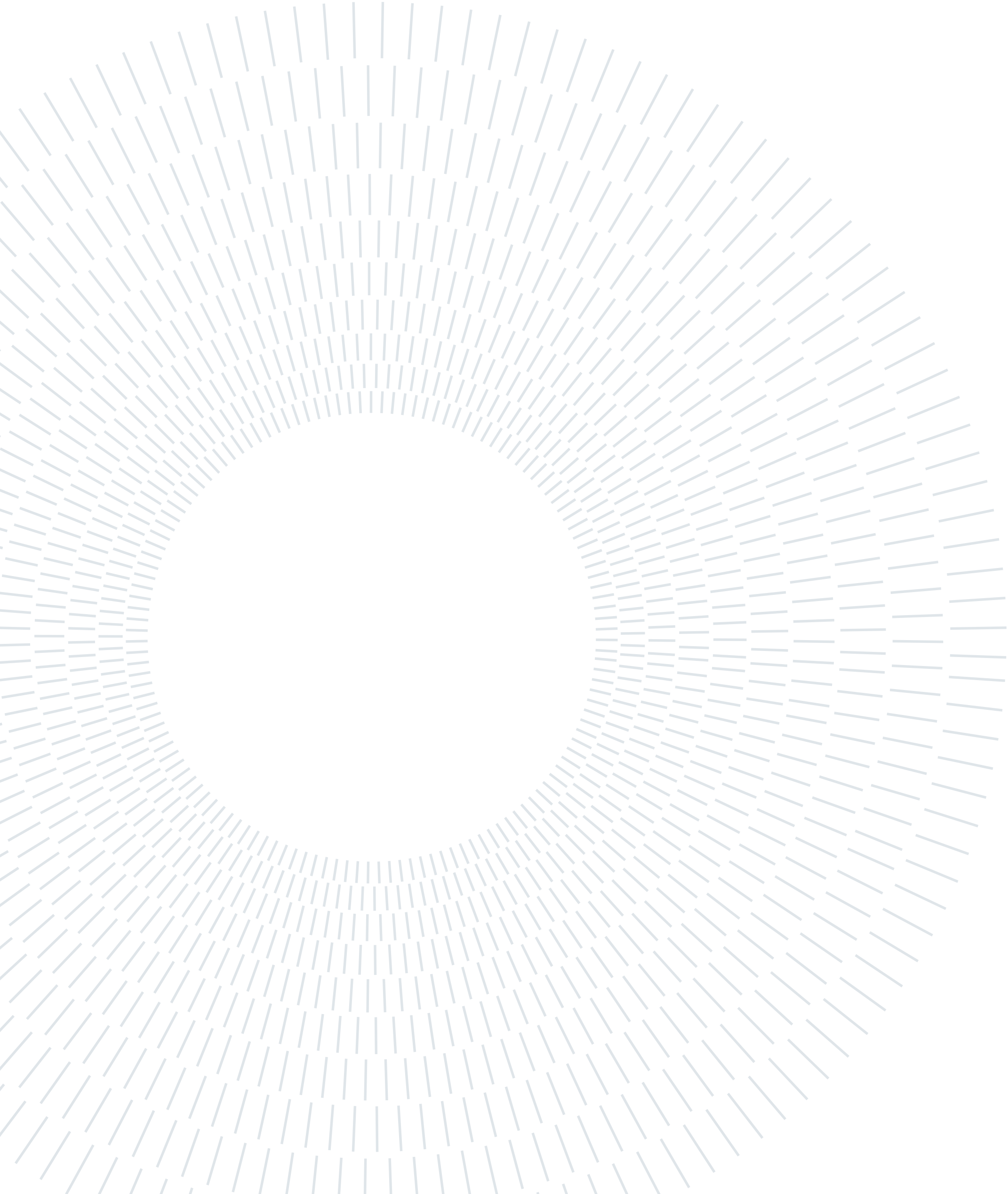
A particular defect of ETS was that through carbon offsets it was possible to "delocalize" the carbon emissions, without beneficial spillovers for the local community.
Pollution and climate change however, while being "global" problems, influence directly the community where they take place and therefore should be considered to more "local" problems.
When the local decisions match government decisions (such as happens in a cooperation environment), the aforementioned "government power" can be effectively used in order to improve policies which go in the desired direction of reducing carbon emissions, even though that implies often an assumption of responsibility of the individual in regards to the community he lives in.

In the next chapter, it will be described how some innovations in the techn(olog)ical field, namely blockchain, A.I., smart-metering and last but not least, a well-designed pricing policy, can actually enable this change of paradigm in the carbon emissions fight, putting the "prosumers" at the center of the decision process.
Such a model, which bears more similarities to a Green Certificate than to ETS, will show how, in the case where energy can be exchanged in a community (micro-grid), the direct accountability of GHG production/consumption would "burden" on prosumers' shoulders.

If such a case might resemble to a carbon tax for the participants in the grid, however, the change of paradigm is within the degree of transparency reached. It is in fact assumed that in the case where prosumers could really assess for their personal "GHG consumption", it might finally be possible for them to decide where (from which sources) and when to consume electricity in an optimal way. If given enough power, they might even steer the energetic policy of the community they live in, or at least have a direct knowledge of their impact on global (local) warming.

Moreover, if such a consumption would be associated to a "tax" or a "premium", than is possible that such a behaviour will be furtherly driven towards low-carbon policies, because they would strictly have an impact of everyone income.

On a large scale, that would impact positively the energy sector and industrial production, because it would not be possible anymore for businesses to falsely claim about their climate impact. However, to reach such a final goal a proper design of a grid (and micro-grid) must be sought.



7 | Electricity Dispatch in the Micro-Grid

> *"If you want to go fast, go alone. If you want to go far, go together."*
>
> African Proverb

A hybrid non-cooperative/cooperative game pricing mechanism to allow an optimal micro-grid electricity dispatch through the Ethereum blockchain, simulated with Python

At the present time, as it has been largely discussed previously, smart-meters and smart-appliances are making it possible to avoid a third-party mediation in the exchange of electricity between households.
The literature covering this topic is immense, especially in the last decade, so that a large number of models has been proposed to coordinate the electricity dispatch in the microgrid, involving many different aspects (frequency control, safety of the transmission line, privacy issues, economic impact, etc.) of its design.

In this chapter, the energy dispatch problem within a Microgrid will be focused on the real possibility of making safe transactions between parties, at low cost and trying to accurately consider privacy issues.
For this purpose, a simulation model of 40 connected households is described, with artificial data on energy consumption and production (taken again from the Pecan Dataset [6]) and adding the possibility for each household to own a battery storage and/or a PV installation of different sizes.
At every hour of the day (the selected time frequency for transaction, but this assumption can be modified), whenever one or more agents in the grid has energy available to exchange (either from the battery or the PV system), he can offer it to the community.
Then all the agents enter in a "tournament" where thanks to a precise pricing mechanism and selecting rules (the hybrid Stackelberg/Cooperative Game) couples or groups of agents can enter into a P2P contract without a third party.

In the end a Smart Contract on the Ropsten Ethereum Testchain is proposed, with the possibility to account both for the energy transferred and the carbon consumption directly connected with the exchanged energy.

The chapter will proceed in the following way: first a theoretical frame for the development of a hybrid non-cooperative/cooperative game is delineated; second, the role of the blockchain technology in energy trade is discussed; third, the agent-based model is put in place, together with the obtained results, the issues in the model and its future developments; in the end the Ethereum Smart Contract for the automatised control of the energy dispatch in a microgrid is represented in more detail, addressing also the issues connected to a development of such a contract in the real world.

7.1. A Hybrid Non-Cooperative/Cooperative Game for Continuous Bidding in the Microgrid

7.1.1. A Stackelberg Game Pricing Mechanism

We here illustrate the Stackelberg (Non-Cooperative, Hierarchical) Game used in the simulation to design a pricing mechanism among parties with the purpose of sharing welfare more fairly in the community.

Such a pricing mechanism, as described in [12], when applied to a Microgrid, has a unique equilibrium at which the prosumers (who offer their energy surplus) maximize their revenues while the consumers maximize their utilities subject to their local constraints. For the optimal strategies of all players, it is possible to derive closed-form expressions and based on such solutions, a power allocation game is formulated, which is shown to admit a unique pure-strategy Nash equilibrium.

Even if this equilibrium is found under the assumption that prosumers can freely allocate their power across the time horizon, it is proved that this assumption can be relaxed. In the simulation the theoretical game formulas will in fact be applied to every single time interval, even though in a future mdoel simulation it might be possible to consider a contract which extends on a longer time interval, assuming the proper hypothesis on energy consumption/production.

A Stackelberg game is a hierarchical game consisting of two kinds of players, leaders who act first (prosumers) and followers (consumers) who respond to leaders' decisions.

The leaders send price signals to the consumers, who respond optimally by choosing their demands. For the purpose of the price calculations, such demands are supposed to be directly proportional to the energy demand of every consumer.
Moreover, to capture competition among the prosumers, before sending the price signals, prosumers play a price-selection Nash game. The equilibrium point of that game is what utility companies announce later to their consumers. Consumers and prosumers enter therefore a bidding game where the latter are considered to have the privilege of "first-movers".

Defining a set of prosumers as $\mathcal{P} := \{1, ..., P\}$, the corresponding consumers with $\mathcal{C} := \{1, ..., C\}$ and the multiple-period time frame as $\mathcal{T} := \{1, ..., T\}$, a generic action of a prosumer is denoted as $\boldsymbol{a_i}$ and that of a consumer as $\boldsymbol{b_j}$. The corresponding utilities for each agent of the two groups are $\mathcal{U}_i(\boldsymbol{a_i}, \boldsymbol{a_{-i}})$ and $\mathcal{U}_j(\boldsymbol{b_j}, \boldsymbol{b_{-j}})$.

As anticipated in the chapter about Game Theory, an action vector $\boldsymbol{a}$ is a Stackelberg Nash equilibrium strategy for all the prosumers if:

$$\mathcal{U}_{Nash}(\boldsymbol{a_i}, \boldsymbol{a_{-i}}, \boldsymbol{b}(\boldsymbol{a})) \quad \geq \quad \mathcal{U}_i(\boldsymbol{a_{i'}}, \boldsymbol{a_{-i}}, \boldsymbol{b}(\boldsymbol{a_{i'}}; \boldsymbol{a_{-i}})) \quad \forall i \in \mathcal{P}$$

where $\boldsymbol{b(a)}$ is the optimal response by all consumers to prosumers decisions. For the Stackelberg Game, the pair $[\boldsymbol{a}, \boldsymbol{b}(\boldsymbol{a})]$ constitutes the global equilibrium strategy.

Each energy consumer receives all prices signals from each company at each time, aiming at maximizing its own utility along a proper defined time slot, subject to Budget and Energy constraints. In this case the variable on which the consumers can act is $d_{c,p}(t) \geq 0$. In the hybrid model however, the possibility to satisfy such a demand will also depend on the actual energy available from the prosumers side.

The utility of the consumer for the entire time horizon considered (one, in the simulation) becomes therefore:

$$\mathcal{U}_c(\boldsymbol{d}_c) = \sum_{p \in \mathcal{P}} \sum_{t \in \mathcal{T}} \ln(1 + d_{c,p}(t)) \tag{7.1}$$

The equation is known to provide proportional fairness and is widely used to model consumers' behaviour in economics [47].

Consumer c aims to achieve the highest payoff while meeting the threshold of minimum amount of energy and not exceeding a certain budget.

The consumer size optimization problem is therefore:

$$\arg\max_{d_c}(\mathcal{U}_c(\boldsymbol{d_c})); \tag{7.2}$$

subject to

$$\sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}} p_p(t)d_{c,p}(t) \leq B_c \tag{7.3}$$

$$\sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}} d_{c,p}(t) \geq E_c^{min} \tag{7.4}$$

$$d_{c,p}(t) \geq 0, \quad \forall p \in \mathcal{P}, \quad \forall t \in \mathcal{T} \tag{7.5}$$

$$\tag{7.6}$$

On the prosumer side instead, the utility is considered to be dependent on other prosumers' choices. If the prices chosen by other companies are p_{-p}, the utility for prosumer p is then:

$$\mathcal{U}_p(\boldsymbol{p}_p, \boldsymbol{p}_{-p}) := \sum_{t\in\mathcal{T}} p_p(t) \sum_{c\in\mathcal{C}} d_{c,p}(\boldsymbol{p}_p, \boldsymbol{p}_{-p}, t) \tag{7.7}$$

and, given the power availability at time t as $P_p(t)$, the prosumers' optimization problem is defined as:

$$\arg\max_{\boldsymbol{p_p}}(\mathcal{U}_p(\boldsymbol{p_p}, \boldsymbol{p_{-p}})); \tag{7.8}$$

subject to

$$\sum_{c\in\mathcal{C}} d_{c,p}(\boldsymbol{p_p}, \boldsymbol{p_{-p}}, t) \leq P_p(t), , \quad \forall t \in \mathcal{T} \tag{7.9}$$

$$p_p(t) > 0, \quad \forall t \in \mathcal{T} \tag{7.10}$$

$$\tag{7.11}$$

To solve the consumers' problem with constraints, we use an associated Lagrange function, obtaining the optimal demand:

$$d_{c,p}^{opt}(t) = \frac{B_c + \sum_{i\in\mathcal{T}}\sum_{j\in\mathcal{P}} p_j(i)}{PTp_p(t)} - 1 \quad \forall t \in \mathcal{T} \quad \forall p \in \mathcal{P} \tag{7.12}$$

From this solution it is possible to derive the necessary constraint on consumers' budgets:

$$B_c \geq \frac{E_c^{min} + PT}{\sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}} \frac{1}{PTp_p(t)}} - \sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}} p_p(t) \tag{7.13}$$

which is used in the model, after setting an adequate E_c^{min} value.
For the purpose and the limits of the model in fact, such a value should be proportional to the energy available if the total offer is below the total request, or set at the energy requested in the opposite case.
Putting optimal demands on the prosumers' optimization equation (considered at equality), we obtain the following equation:

$$\frac{\sum_{c\in\mathcal{C}} B_c + C\sum_{i\in\mathcal{T}}\sum_{j\in\mathcal{P}} p_j(i)}{PTp_p(t)} = C + P_p(t) \quad \forall t \in \mathcal{T} \tag{7.14}$$

Which with $B = \sum_{c\in\mathcal{C}} B_c$ the budget of the whole consumers, becomes:

$$B + C\sum_{i\in\mathcal{T}}\sum_{j\in\mathcal{P}} p_j(i) = PTp_p(t)(C + P_p(t)) \quad \forall t \in \mathcal{T} \tag{7.15}$$

from which it is possible to derive the optimal prices $p_p(t)$ for each time and each prosumer and its utility straightforwardly, leading to the final Stackelberg equilibrium:

$$\sum_{p\in\mathcal{P}} \mathcal{U}_p(\boldsymbol{p}_p, \boldsymbol{p}_{-p}) = \sum_{c\in\mathcal{C}} B_c \tag{7.16}$$

However, since in our model we want to preserve consumers' privacy, it will be only asked to them to provide information about the minimal budget. Then a distributed algorithm is used to calculate the optimal prices, starting from a uniform price offer from the prosumers' side corresponding to an average of the same hour price in the last 7 days.

Algorithm 7.1 Distributed Algorithm to compute prices with local information

```
choose $\delta \geq 0$ , tol=$1 \times 10^{-7}$, i=0, $p_p^{(0)}(t)$,  $\forall t \in \mathcal{T}$,  $\forall p \in \mathcal{P}$
while TRUE do
    $i + 1 \leftarrow i$
    compute $\epsilon_{p,t}^{(i)} = \frac{P_p(t)+C}{p_p^{(i)}(t)} + \delta$ , $d_{c,p}^{(i)}(t) = \frac{B_c+\sum_{i\in\mathcal{T}}\sum_{j\in\mathcal{P}} p_j(i)}{PTp_p^{(i)}(t)} - 1, \forall t \in \mathcal{T}, \forall p \in \mathcal{P}, \forall c \in \mathcal{C}$
    compute $p_p^{(i+1)}(t) = p_p^{(i)}(t) + \frac{\sum_{c\in\mathcal{C}} d_{c,p}^{(i)}(t) - P_p(t)}{\epsilon_{p,t}^{(i)}}$,  $\forall t \in \mathcal{T}$,  $\forall p \in \mathcal{P}$
    if $\|p_p^{(i+1)}(t) - p_p^{(i)}(t)\| \leq tol$  $\forall t \in \mathcal{T}$,  $\forall p \in \mathcal{P}$ then
        FALSE
    end if
end while
```

This algorithm allows a convergence of the prices towards an equilibrium value, leading to situations such as the one depicted following picture:

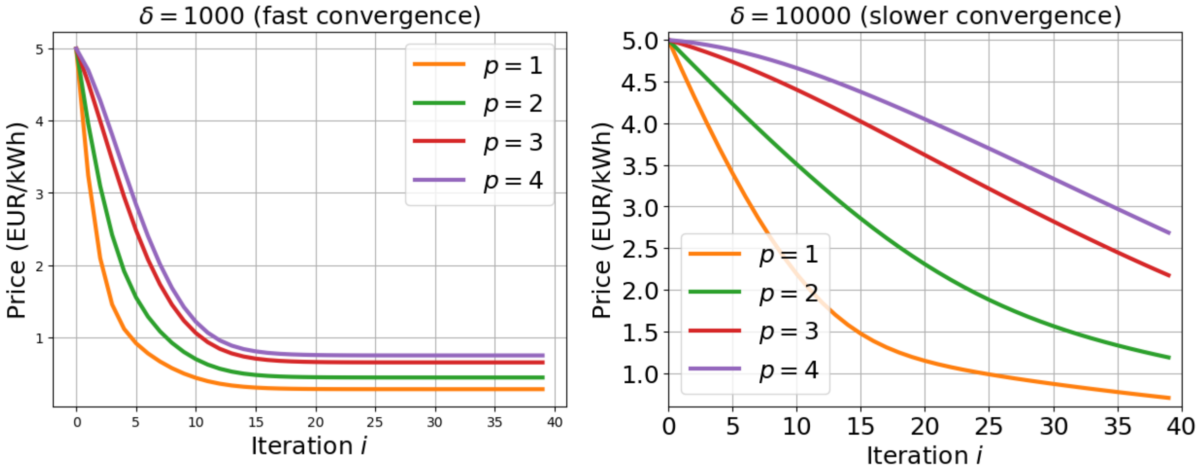


Figure 7.1: "Convergence of Pricing Distributed Algorithm"

To further avoid noncompetitive prices above the actual market price, we then set a cap at that value, whenever equilibrium prices would exceed it.
Following, a "tournament" is organized among the consumers and prosumers, in order to select couples between which allow the energy transactions.

Algorithm 7.2 Contract Formulation between consumers and prosumers

```
order $p \in \mathcal{P}$ based on their increasing price offers
order $c \in \mathcal{C}$ based on their decreasing demand offers
send ordered $p \in \mathcal{P}$ list to every $c \in \mathcal{C}$, send ordered $c \in \mathcal{C}$ list to every $p \in \mathcal{P}$
while $c_i \in \mathcal{C}$ has some $p_i \in \mathcal{P}$ to propose the contract do
    $c_j :=$ first consumer on $p_i$ list
    if $c_j$ has not been contracted yet then
        contract between $c_j, p_i$
    else if some pair $c_j, p_k$ has already contracted then
        if $c_j$ prefers $p_i$ to $p_k$ then
            $p_k$ becomes free
            contract between $c_j, p_i$
        else
            contract between $c_j, p_k$
        end if
    end if
end while
```

Transactions are therefore repeated, round after round, up to the moment when none of the prosumers is able to match any other consumer demand or when there is no more energy available to exchange (either available energy or requested energy).
In the first case, whenever possible, the community participated to a second "Cooperative Game" described in the next section.
In the second case, if there was still need of energy in the community, this was bought from the grid at the spot price, otherwise, in the case of a surplus of energy, this was used to charge every agent own battery; in case batteries were full, the energy was considered to be lost.

Actually, to really take advantage of the pricing policy that we described, a better solution would be to propose an energy profile for a longer time window than one hour. In this case in fact, it might be taken advantage of the fact that for such a policy, the optimal prosumer strategy is to to equally allocate powers across all time periods:

$$P_p^{opt} = \frac{\sum_{t \in \mathcal{T}} P_p(t)}{T} \tag{7.17}$$

This situation will be further investigated in the section devoted to the description of the model.

7.1.2. A Cooperative Game to Match Residual Demand

In the simulation, whenever none of the prosumers was able to satisfy alone any other consumers' demand, the prosumers entered into a Cooperative Coalitional game, in order to share their resources to satisfy . After forming a coalition, consumers were ordered based on their decreasing energy demands and the list was sent to the coalition.
In case the coalition was note able to satisfy totally the higher demand, it would then couple with the following consumer in the list, up to the end, when the (eventually) residual demand is sent to the consumer with the highest needs.

When the coalition is formed, the price provided to the consumer is simply an average of the prices proposed by the prosumers in the coalition. The profits however, are distributed based on the (mentioned in chapter 1) Shapley Value or better, based on the Shapley-Shubik Power Index, which can be calculated (fore every participant i in the coalition) as:

$$\sigma_i = \frac{SS_i}{N!} \tag{7.18}$$

where σi is the Shapley-Shubik power index of the prosumer i ,SS_i the number of sequence coalitions where each i is pivotal and N the number of the prosumers taking part in the coalition.

7.2. Blockchain Technology in the Smart-Grid

7.2.1. Blockchain: a Disruptive Technology

Blockchain system has been introduced in a famous 2008 whitepaper by Sathoshi Nakamoto where it was proposed as a new peer-to-peer payment system to allow online payments without going through a financial institution.
The technology behind Blockchain has been proved to be inherently secure by design, albeit lacking scalability in terms of transaction throughput and transaction costs[79].

From the design point of view, blockchain is a distributed database (distributed ledger technology - DLT) that is shared among the nodes of a computer peer-to-peer network and a distributed time-stamping server to make the system completely decentralized while relying heavily on cryptography to guarantee security.
The disruptive innovation brought about by the blockchain is that it guarantees the fidelity and security of a record of data and generates trust without the need for a trusted third party.
One of the strong positives of the blockchain that makes it so secure is that this database is not stored or centralized in one single location, but it is hosted by millions of computers on the chain so there are several copies of the ledger and consequently, it will take a tremendous amount of computing power to hack into the chain and corrupt the records.

To summarize, the main benefits that can be addressed to the blockchain technology are:

- since it is a distributed and decentralised ledger, it is truly public and can be always verified;
- it cannot be controlled by any single entity;
- it cannot be corrupted due to its distributed nature;
- the need for third party involvement in transactions can be eliminated.

One key difference between a typical database and a blockchain is how the data is structured.

A blockchain collects information together in groups, known as blocks, that hold sets of information. Blocks have certain storage capacities and, when filled, are closed and linked to the previously filled block, forming an unbreakable chain of data.
All new information that follows that freshly added block is compiled into a newly formed block that will then also be added to the chain once filled and so on. Without a link to the previous block, the new block is not deemed valid by the network, so that if one malicious attacker wanted to tamper information in an old block, than it would require to compute all the chain again; the hard problem of making such computation lengthy is what renders blockchain intrinsically secure. This data structure inherently makes an irreversible timeline of data when implemented in a decentralized nature. When a block is filled, it is set in stone and becomes a part of this timeline. Each block in the chain is finally given an exact time stamp and added to the immutable chain.

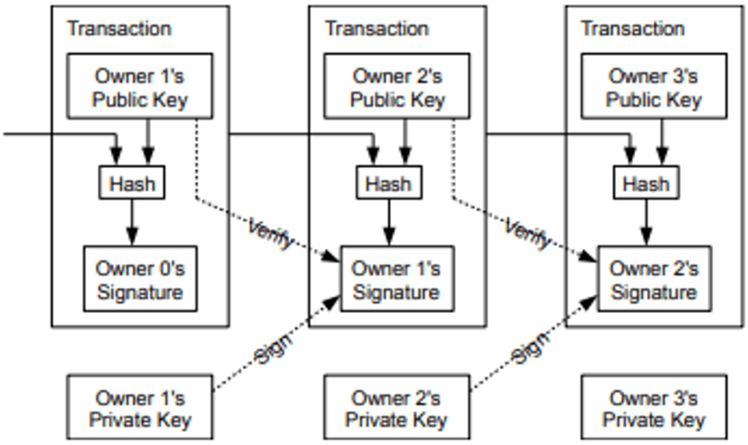


Figure 7.2: A Blockchain Transaction Structure

The blockchain, in the world-famous 2008 seminal paper, was originally proposed as a solution for the double-spending problem in digital money without any central authorization: that coincided with the birth of Bitcoin. Later on, blockchain was adapted to other contexts and applications by different platforms, one of which (Ethereum) used it for designing a new worldwide, programming environment running on the blockchain.
Programs stored and running on Ethereum take the name of "smart contracts" and run when predetermined conditions are met. They are typically used to automate the execution of an agreement so that all participants can be immediately certain of the outcome, without any intermediary's involvement or time loss; or they can also be employed to automate a workflow, triggering the next action when certain conditions are met.

In the design of blockchain, cryptography is ubiquitous: it is used to sign transaction

and keep them immutable with time, but it is also used in the consensus protocol that protects blockchain from possible attacks.
The most important features of blockchain where the influence of cryptography is determinant are: hash functions, mining and the consensus protocol.

A hash is like a digital fingerprint: it is unique for every piece of data, entity or program on the blockchain.
Transactions on the blockchain are saved thanks to a cryptographic hashing algorithm and receive a hash that is distinct to that transaction. The specific input, if unchanged, will always produce the same exact hash.
If, however, any part of the data input is changed (for example a malicious actor changes the amount transferred), the hash would change to an entirely different set of characters and make it incompatible with the rest of the chain. It is this cryptographic security that makes blockchain ledgers more trustworthy and "almost" immutable.

Mining is the most used (but not the only one) process that allows to add blocks (i.e. transaction records) to the ledger. Miners are nodes in the network that ensure the transactions in the block are valid. Specifically, they ensure that senders have not already used the funds they want to send to receivers (double-spending problem). Once miners finish the verification, they have to ask the network for consent to add the new block. In order to do so, they have to follow the consensus mechanisms chosen by the platform.

Consensus mechanisms is used instead to gather consent. Agreement among nodes regarding the "state" of the ledger is essential for the function of the blockchain ledger. The Bitcoin and Ethereum blockchains for example utilises a consensus model called Proof of Work (PoW), which requires the miner to compete against other miners to create and broadcast blocks for approval. If successful, they are rewarded in Bitcoin or Ether. There are other consensus mechanisms like Proof of Stake (PoS), Proof of Authority (PoA), Proof of Elapsed Time (PoET) and Proof of Burn (PoB): all of them are variations on the means for the network to agree on changes to the ledger.

The fact that a blockchain network doesn't need a trusted third party, it is resilient to external attacks (apart from the infamous, but highly unfeasible 51% attack) and always verifiable (because of its "immutability") makes it the perfect candidate for energy trading in a Microgrid.

7.2.2. Blockchain for Energy Trade

The decentralized structure of blockchain fits into the decentralized approach for control and energy trade in a microgrid.

However, research on blockchain applied in microgrids has only recently picked up pace, with most of projects still under development [37] [79]. Blockchain for energy trade is been thought to grow rapidly in the following years, which is the reason why it has been included in the 2050 Germany energy development program.
If the concept is interesting under many points of view, because enables a small, individual scale to generate electricity and sell it to the grid, it adds complexity to the existing system, such as how a transaction between these generators and consumers are conducted, verified and recorded; the high cost of transactions and the price of computation in the consensus mechanism (PoW).

Transactions are possibly performed with smart contracts, and the network acts as a transaction verifier. The blockchain provides immutability of the transactions, which ensure every transaction between generators and consumers will always be executed.
It also provides immutability to transaction history, which can be used for audit or solving a transaction dispute.

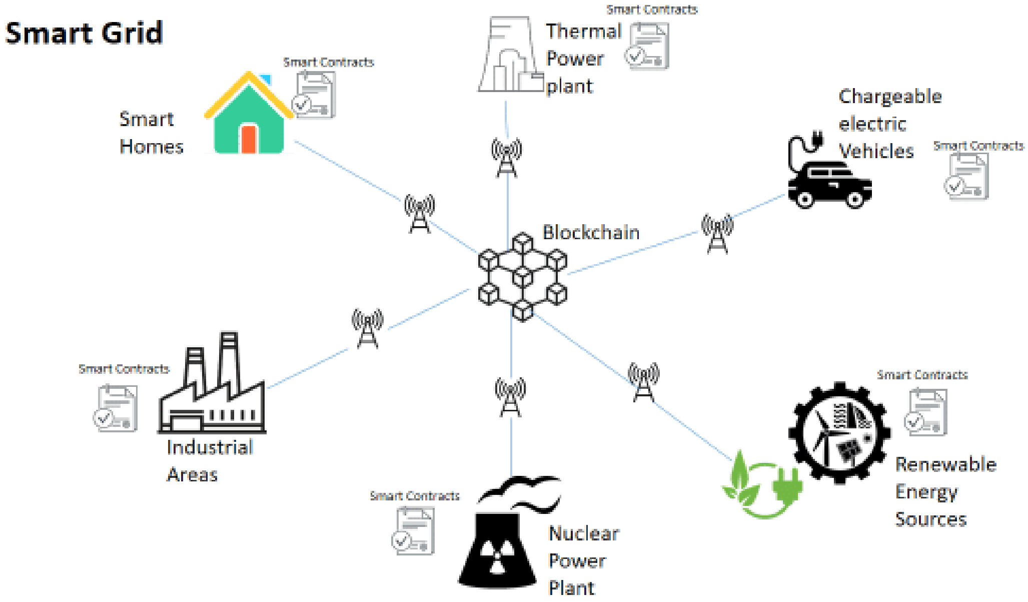


Figure 7.3: "Blockchain in the Smart Grid" [11]

Using blockchain within the micro-grid solves three distinct problems that arise when introducing decentralization.
Firstly, introducing a smart-contract as a substitute for a centralized institution governs the payments made by buyers to sellers in a decentralized fashion. In this way the microgrid becomes a transactive grid and the general transmission grid gains advantages

because it has to bear a lower load.

Secondly, a smart-contract can function as a record keeping of promises made during trading, countering fraudulence manipulation of prices.

Lastly, the communications network between agents cannot simply be assumed synchronous and the smart contract can function as a time-stamping server to create an temporal order in transactions made in the micro-grid.

Furthermore, it can contribute to:

- the elimination of distribution costs, because the current role of the electricity distributor would become redundant;
- the reduction of capacity costs, because its ability to rapidly respond to changes in supply through intensive demand response will reduce the amount and cost of back-up generation;

Not to be forgotten are the likely downsides of the stage microgrid:

- the need for the consumer to become engaged in energy pricing;
- the impact of demand response on daily life;

The combination of blockchain with smart contracts is likely to change the energy sector as we know it today – adding ways to manage and route power within the larger energy ecosystem.

Most importantly, it enables a way to open the market to new participants, thereby increasing competition and introducing peer-to-peer autonomy.

7.3. A Micro-Grid Agent-Based Model

7.3.1. Description of the Model

To verify the feasibility of blockchain energy-trade in a microgrid, we developed another Agent-Based Model with Python in order to determine the validity and the limits of the pricing mechanism above described.

The model, built with *Python* is a simulation of 40 connected households that have the possibility to enter a contract (a Smart Contract) at every hour of the day among one another to exchange electricity directly.

Moreover, the 40 household agents are assigned, with different probabilities, a PV system and/or a BESS (private battery storage), or none.

Hence, their consumption and the electricity price have been simulated, assigning 2 random value to each agent, each value representing a random set of daily data extracted

from the Pecan Database (in this case used just for solar power production and electric load).
For every agent, the first value was used to set the simulated actual data, the second one was used to set the simulated predicted data.

In the literature, there are many examples of how game theory was successfully applied to manage the microgrid dispatch problem.
in [79] for example, the community is supposed to share knowledge about their desired electricity consumptions and home battery SOCs.
Then, dividing the community between buyers and sellers according to the energy need or surplus, both groups enter into successive stackelberg games, in order to find a proper global battery management (SOCs) which can bring the max welfare to the community.

In our simulation instead, agents are supposed to be directly managing their own BESSs. This is done with a Reinforcement Learning (DQN) approach (see figure below), where giving as input the predicted electricity price, the predicted load, the predicted PV production, the actual SOC of battery (as percentage) and the average price of the last 7 days is possible to extract the next value of $SOC_{preferred}$.

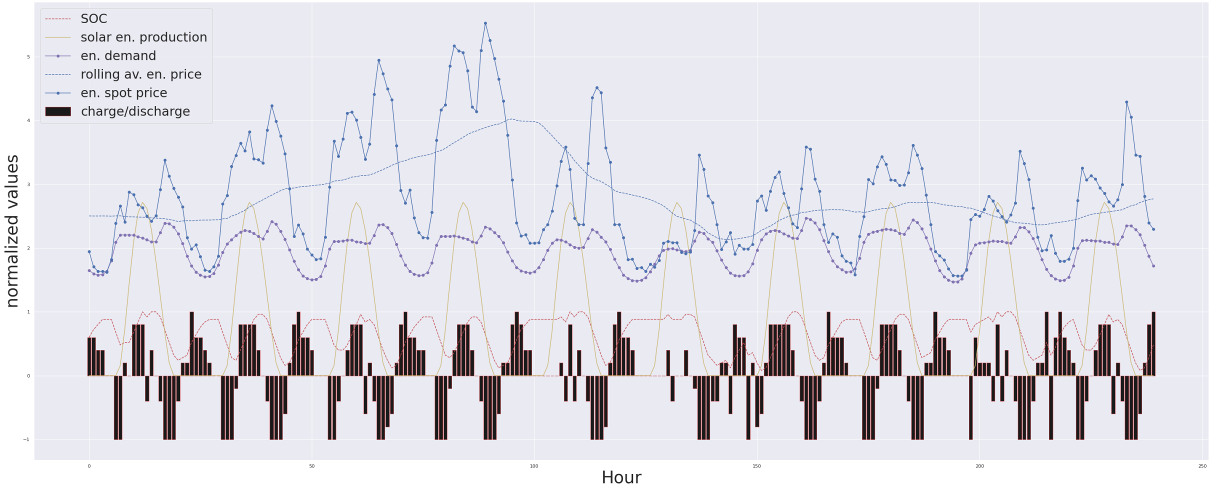


Figure 7.4: Reinforcement Learning [DQN] for battery management

To simplify the approach, the RL model have been trained on a simplified set of data, with constant solar power profiles; moreover, to avoid getting int time-consuming computations, such model has been considered the same for all the agents, while a more accurate simulation should consider a different RL model for every agent.
A different reinforcement learning model was used for those household agents who do not own a photovoltaic panel system and do not have PV production data.

After calculating the preferred SOC, predicted data is updated with the actual data and, before assigning an actual SOC value, the agents enter into the tournament defined in the previous section, determining the prices at every step through the pricing policy (Stackelberg Game Pricing Model).
Therefore, at every time step the group of agents is divided into buyers, sellers or neutral agents, based on the result of the following formula:

$$E_{surplus/gap,i}(t) = E_{prod,i}(t) - E_{cons,i}(t) - (SOC_{preferred,i} - SOC_{actual,i}) \tag{7.19}$$

If the result is positive the agent is classified as a *seller* with an $E_{surplus}$, if it is negative the agent is classified as a *buyer* with an E_{gap}. Moreover, if the agent has an E_{gap} which he can satisfy using the energy stored, the agent is re-classified as *neutral.*

After the division into groups and the price set, buyers and sellers enter the "tournament" and couples of sellers/buyers are assigned at every step in which there is energy available for trading in the microgrid. When such a situation does not exist, or when after exchanging, there is still need of energy in the grid, the demand is paired purchasing electricty directly from the grid at the spot prices. If however some energy surplus remain, those are used to recharge the (own) batteries up to the maximum, otherwise the surplus is considered as lost.

In the second part of the model, to check the feasibility of the energy dispatchment in a microgrid on the Ethereum Blockchain, a Smart Contract was developed on the Ropsten Testchain. The contract follows the guideline of an ERC20 [73] burnable and mintable token and offers the function to buy and sell the token at will. The code of the Smart Contract connection text is provided in Appendix A.
At the time of writing its feasibility has only been assessed using a simplified set of data and a simplified set of agents. A further development of the model must therefore include the Smart Contract within the "tournament" sending and receiving the transactions of the right amount.
However, the Smart Contract passed all the tests and it might be considered full-fledged valid and can be checked at the '0xc0F4E25102a668D547e36Ea2f23E5B97391c2827' address on the Ropsten Etherscan.

7.3.2. Model Results

We performed 3 simulations on a 5 day time window with hourly energy exchanges for different sets of agents (different number of BESSs, different number of PV).
At each step the profit of the community was calculated as the total amount of profit gained from the sale of energy minus the expenses from the energy purchase. The results were then compared with a situation in which the agents could only buy energy from the grid or use it for self-consumption, without the possibility of selling the surplus to the grid. The electricity spot price was at an average value of 0.05€.

	6 PV, 19 BESS	**10 PV, 22 BESS**	**16 PV, 15 BESS**
profits [€]	35.62	145.63	90.98

Table 7.1: Microgrid Community Profits for a 5 days simulation (40 agents, different sets

Such results, for a community of 40 agents, grants savings of the order of 0.18 - 0.72 per day per agent, which can therefore grant substantial benefits on the final electric bill of the month.

Among the possibilities to improve the model and get better results, first of all, it should be considered the case where the battery is no more managed on a daily basis for self profit, but on a longer time span (e.g. daily) in order to provide an energy draw as constant as possible (optimal solution of the pricing model). Such a profile can be obtained, for example, with a GA optimization on a daily basis. Such a solution is under revision at the moment of writing.

The RL model for battery management should be trained differently for every agents, because the PV and batteries have also different dimensions which can influence the model.

Moreover, to evaluate better the profits, the situation should not be compared with a situation where the agent cannot sell energy to the grid: feed-in tariffs, for example, are a common way to manage such situations in the modern grid and to have a better insight of the validity of the model, this possibility must be considered.

Furthermore, for a validity check of the smart contract, the simulation should be able to communicate directly with the Ropsten Testchain, because the Smart Contract was just used on simulated data. This can let evaluate for example, the influence of transaction prices and problems connected with transaction reversals or transaction sluggishness.

Lastly, considering the privacy problems present in using a Smart Contract on the Ethereum Blockchain, it might be advisable to try and find a solution that includes the use of zero-knowledge proofs for developing the same contract.

7.4. A Smart Contract for Energy and Carbon Trade

To enable a decentralized energy market, it was chosen to develop a smart contract on the Ethereum blockchain (tested on Ropsten network).
The choice of a permissionless blockchain instead of a private one has certainly some advantages, like the total avoidance of a central authority , but at the same time bears some disadvantages like the high transaction costs which might not render frequent trading economically profitable.

In the model proposed the choice of blockchain platform fell on Ethereum because of the possibility to program a Smart Contract in language (Solidity) largely adopted and constantly updated by many developers and for the possibility to have a rapidly available test network on which perform the trading before adapting to the real case. In particular, the Smart Contract (whose code can be found appendix B), apart from "tokenizing" the electricity transaction with an ERC20 [73] Token, requires to buy a "carbon Token" to counterbalance the carbon production linked with the electricity consumption. It is not completely unrealistic to have smart appliances interact directly on the blockchain: a real example is given by the company IOTA, an open-source distributed ledger and cryptocurrency that was explicitly designed for the Internet of things.

In this design, smart-meters must be authorized from a control authority (in order to avoid fraudes) and act autonomously (edge-computing) on the Ethereum network, being obliged to compensate directly the CO_2 consumption with "token allowances" and to automatically re-buy "token allowances" whenever their balance in the smart-meter wallet is not sufficient to compensate the actual carbon consumption.

The first issue to be recognised in such a design is of course the validity of CO_2 consumption measurements, which is not possible to evaluate completely, if the energy is exchanged between two parties that do not generate electricity but simply transfer it.
If however it were possible for this contract to be used not only by residential owner, but also by TSOs, DSOs and power plants, one could "keep track" of the carbon production along the grid (and the blockchain), in such a way that when the consumer needs to pay

for its energy (either from a Microgrid o from the general grid) he could immediately recognize the carbon impact of his consumption.
As an example, if TSO, responsible for the dispatch of the energy from the power generator to the DSO, could be able to exactly "trace" the carbon content of the energy sold, then it would be virtually possible for the DSO to directly send this measurement to the consumer.
In such a way, the carbon consumption exact calculation could be feasible and the consumer would be directly responsible for the consumption in deciding to sign a contract with a retailer.
Moreover, retailers who acquire energy at high-carbon impact would be immediately excluded from the market both because users are becoming more and more sensitive to environmental topics and because a carbon unit would actually have a real price on their electricity bills (represented by the smart contract).

The possibility to trade the "carbon token" on a public blockchain has certainly some advantages, like the possibility for such a token to have a high liquidity (in contrast for example with Green Trade Certificates, whose illiquidity was the major drawback), if adopted by many households in the world.
Such a publicly available token in fact, if internationally recognised, could make possible to trade "pollution" from a "rich" country to a "poorer" country, in a way that a m^3 of CO_2 produced in every part of the world would have the same value .

If that could be the case, it would be much easier to track the GHG emission all over the world, producing a net benefit, since it would be possible to drive low-carbon policies around the world in an efficient way, with no more excuses.

This policy is in completely contrast with the adopted carbon emission reduction policies around the world which, although claiming to avoid that GHG emissions burdens on consumers, are in fact providing large windfalls to oil an coal companies, leaving the consumers unaware. If it is considered that none of the carbon policies adopted worldwide has really provided a change in the GHG emissions growing trade, blockchain and smart contracts such as the one proposed could reverse the situation, finally making everybody aware of their carbon impact, which, at least, should make everybody more responsible about their energy (over)consumption.

They surely can serve at least as a way to helping fix a key flaw of the 2015 Paris Climate Agreement: failure to create an effective global carbon trading market, because up to now carbon markets have functioned as little more than greenwash platforms for companies to buy unreliable carbon "credits" to offset their continued high carbon polluting ways.

Moreover, among the energy sources at low-carbon impact, Nuclear Power, which is one of the energy sources with the lowest LCOE, could take advantage of such a situation, but not in a "green-washing" way.
The nuclear industry could gain in competitiveness and its big role in being able to provide large amounts of energy at low cost and low GHG emissions should be finally assessed, even by those consumers who have stron opinions against the development of new nuclear units. The idea however, it is worth mentioning, should not be seen as an a way to fiercely stand up for nuclear, but to stand up for our world.

7.4.1. Privacy Issues and Post-quantum Cryptography

Through the public ledger of a blockchain, even if identities are virtually protected by cryptography, any agents could gather gain information on load-patterns of households in the grid.
From this side therefore, Ethereum blockchain is not able to protect users data in compliance with the E.U. GDPR legislation.
To protect the privacy of the end-user, different cryptographic techniques are capable of providing solutions for privacy safe-guarding both on-chain and off-chain. Homomorphic encryption is used to obscure the information on the public ledger; ring-signatures instead are used to obscure the identity of the node in a communications network.

Applying (quasi)-homomorphic encryption on a blockchain can allow to completely hide the information within a transaction while still allowing to prove the validity of a transaction.
It is therefore applied in zero knowledge Succinct Non Interactive Arguments of Knowledge (zk-SNARKs), a proof construction where interaction between a prover and a validator is not necessary, reducing the necessary communication and saving valuable computational resources. However, ZK-SNARKs require a trusted setup which still needs some sort of "centralization" in the protocol.
At the moment of writing, they are a well developed technology (ZCash and Python package Zokrates are some real examples) and are currently applied to projects where privacy represents an issue.

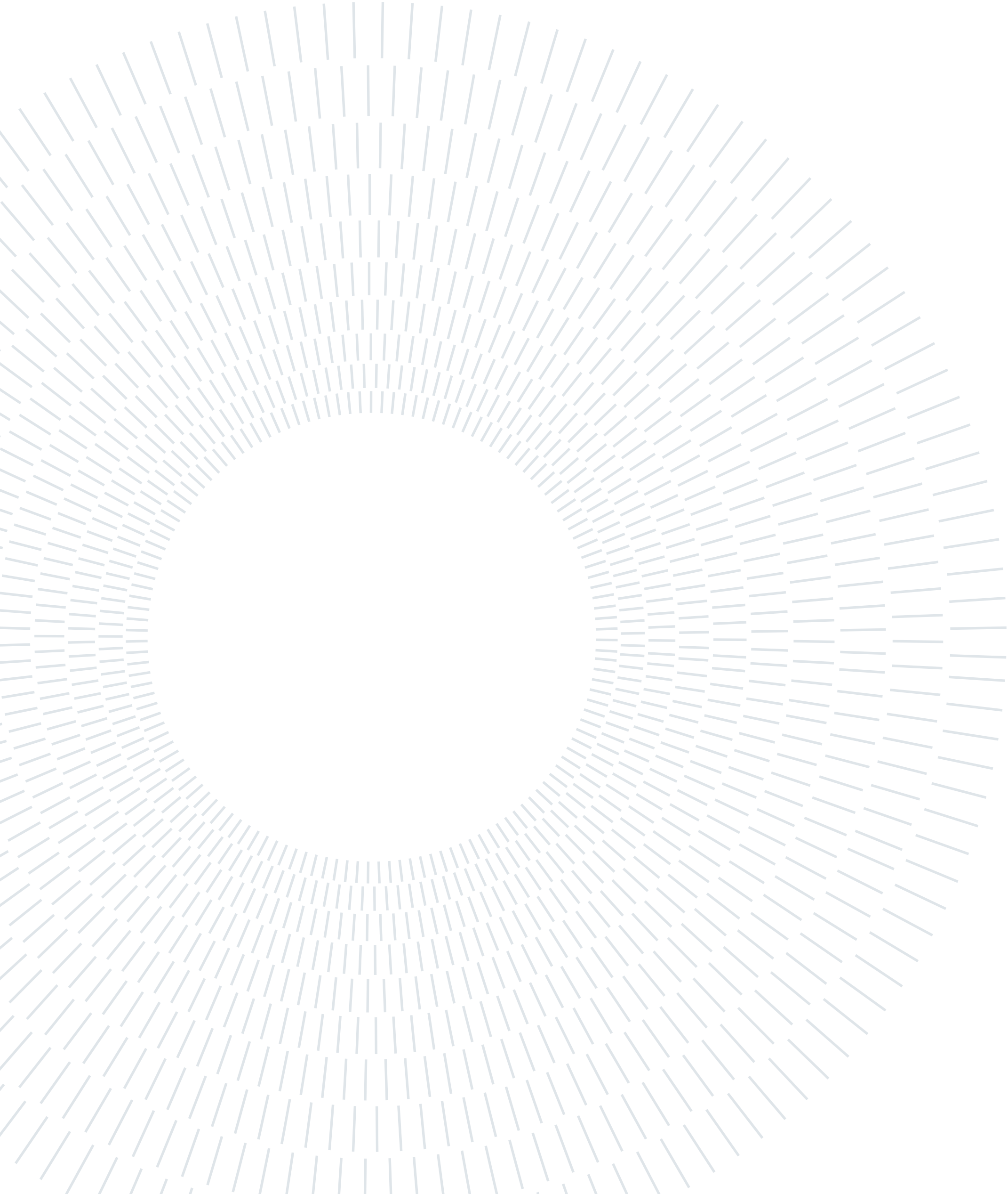
Group-signatures allow a group master to set up a pool of member that becomes authorized to produce a signature for messages on behalf of the whole group [26]. Adversaries have therefore negligible probability of specifying the original sender within the group.
The principal drawback of group-signatures is that a trusted group-master is needed to set up the group. To solve this issue, ring-signatures have been designed which, unlike

group-signatures, are completely decentralized, a key feature that makes application for privacy-preserving in decentralized systems actually possible.

Recently, with the technological advances in quantum computing, blockchains, based on "traditional" cryptography are facing an enormous issue: if quantum computers were actually able to hack the cryptography in the blockchain, all the blockchain system would be intrinsically vulnerable.

A new technological solution which could allow blockchains to survive in a post-quantum cryptography world, preserving at the same time the privacy in the chain comes from ZK-STARKs (Zero-Knowledge Scalable Transparent ARguments of Knowledge), a kind of zero-knowledge proof technology that enables users to share validated data or perform computations with a third party without the data or computation being revealed to the third-party, using publicly verifiable randomness to create trustlessly verifiable computation systems.
In addition, ZK-STARKs improve scalability by allowing developers to move computations and storage off-chain. Off-chain services will be able to generate STARK proofs that attest the integrity of off-chain computations. These proofs are then placed back on chain for any interested party to validate the computation.

All of these solutions are rapidly evolving and the possibility for a quantum-resistant privacy preserving blockchain is just a matter of time (and money).



8 | Conclusions and future developments

Electricity does not centralize, but decentralizes.

Marshall McLuhan

An overall evaluation of the obtained results, highlighting their limits and proposing future developments

8.1. Results Discussion and Further Development of the Model

To conclude the thesis work, an attempt will be made to retrace the path taken so far.

The thesis started in chapter 1 with a review of some game-theoretical tools necessary along the rest of the work: first of all game theory is needed to analyze the limits and conditions for the emergence of cooperative behaviours in individuals, but some elements of evolutionary game theory can even be used to find an optimal solution for the pricing problem in the grid.
Quite curiously game theoretical elements are present in almost every part of the thesis: there is a subtle connection between elements of evolutionary game theory and genetic algorithms, game theory has been a cornerstone for the development of blockchain technology and game theory plays a key role in the design of the correct pricing policy to optimize energy consumption in the electrical grid.
Furthermore, even more curiously, it might be thanks to the blockchain technology (where game theoretical features are pervasive) that in the future it will be found a solution for the "Public Dilemma"game of carbon emissions reduction.

Next, we took advantage of the connections between the concept of cooperation in game theory to delineate some models in which a cooperative behaviour is necessary to obtain

the ideal result: coordination is strongly needed in the grid if we want to reach the equilibrium between profits and electricity (or water, in the case of co-generation) demand; cooperation is needed between the central entity and the household agents to have a stronger efficiency in the demand-management model; cooperation is necessary both to defend the blockhain from malicious attacks (51% attacks) and to reach an agreement between the agents in a microgrid, even considering that they are acting selfishly.
Lastly, cooperation is needed both at a local level and a global level, if we really want to tackle the climate change problem

Going further, we gave insight of the complexity of the electric grid from the technical and economical point of view: there is a reason if the electric grid has been described by the U.S. National Academy of Engineering as the greatest engineering achievement of the 20th century; however, as usually happens to great ideas or inventions, disruptive technologies are nowadays profoundly changing its shape. Hopefully for the better.
Even if those disruptive technologies certainly pose a challenge to the grid, which needs to adapt to them, they must be considered as opportunities more than challenges: with a higher penetration of smart appliances, it is possible that in the near future the need to postpone a washing machine to adapt to the grid, which represents an unthinkable effort for some people today, would become not more troublesome than to sort a plastic bottle in the right bin.

Next, we focused our attention on the connections between energy management and environmental pollution, proving that a real solution to the problem has not been provided yet, nor it is in sight if the public policies will be kept as they are.
In this sense, it was implicitly assumed that just with the right "pricing model" to account for GHG emissions together with electricity consumption, the selfish agents of the world might converge to a solution which is beneficial for everybody.
With the advent of microgids, consumers might begin to gain a central role in this sense, managing the consumption with the "climate change in mind". If this was not enough to revert the actual trend, assessing their carbon consumption directly, through the use of a smart contract like the one presented in the last chapter, might adequately motivate even those who totally underestimate the problem.
WIth the right pricing policy therefore, from one side the consumers/prosumers can be directed towards a consumption optimization, from another side, those energy sources which grant low carbon emissions with high efficiency (namely, nucleaar power) might gain the consideration they deserve.

The computational models developed and described, have plenty of chances of optimiza-

tion: in the first model we need to modify the water and electricity load profiles to check a situation more linked to reality; in the demand-side management model the pricing policy applied was surely an oversimplification of a real pricing policy and the target profile might be modified according to the real characteristics of the grid; in the microgrid model we didn't take advantage of the optimal results of the theoretical pricing model and instead of modeling a grid where agents planned to have a flatten constant demand, they have been considered just as selfish individuals trying to maximize their profits.
To say the truth, at the beginning of the thesis project, the idea was to develop the three presented model altogether. However, going deep into the realisation of the model, I could experience the difficulties in connecting the models altogether. The general idea was to find and examine the situation in order to see if it was possible to find a general model which could evidence how the introduction of disrupting technologies in the grid would natually lead to a win-win situation where it was possible to quantitatevly prove that it is possible to reach energy consumption optimization and GHG reduction at the same time

I have had to learn at my own expense however, that often to get win-win situations, one must look for a compromise.

8.2. About the development of "win-win" situations

> *"financial resources are allocated to help the world's poorest countries, but to be honest, linked with the development of that same donor countries' companies. On the other hand, developed countries simultaneously keep their agricultural subsidies and limit some countries' access to high-tech products. And let's say things as they are: one hand distributes charitable help and the other not only preserves economic backwardness but also reaps the profits thereof"*
>
> *В.В. Путин*

It might seems controversial, or provoking (and in some ways it is) to conclude my Thesis work with a citation of the President of Russian Federation. By the way, during my last years spent in Russia, I used to listen to many of his speeches, basically to improve my Russian language knowledge and to get to know the thoughts of a part of population he surely represents.
Far be it from me to involve any political issue into the work or to start a debate, I personally think that one should always separate the general concepts from the person who said it, also because we can often find wisdom and space for reflection by listening with an open mind to concepts we can reinterpret in a dialectical manner.
As my father used to say to me when I was a child: *"Se te voi la verità, va dal pu piciol de la cà"* (translatable into: "if you want to reveal the truth, listen to the youngest in the house"), a popular saying which is intended to mean that often we are provided

meaningful unintentional thoughts from immature people, even insane sometimes.

The quote is a part of Russian President's intervention at 2007 Munich Security Conference, a conference that I have personally always thought to be pivotal in determining today's world international affairs and to which, unfortunately, it was probably not payed the necessary attention; after all, less than one year later, the world was facing the most dangerous financial crisis of the century and all other questions took a second place.

At the time, these words publicly let the genie out of the bottle, because the situation was clear to most of the participants, even if nobody was addressing it explicitly and it was, so to speak, not too much advertised.
It was not surprising the message itself , but it was unexpected that such words could come out of the mouth of the leader of one of the biggest economies in the world, publicly addressing other leaders' to their responsibilities.
In view of the previous analysis about European Emission Trading System, and especially in regards of the role played by Joint Implementation and Clean Development Mechanism, those words should let the reader reflect about the not-always-driven-by-ethical-principles behaviour of developed countries towards developing ones: a behaviour that certainly prevents all-round cooperation and which certainly is the source of a rising sentiment of suspect among developing and underdeveloped countries' populations.
After the recent occurrences in south-western Ukraine, with the outbreak of a war[1], we have to recognize that for cooperation to prevail over hostility, it is important to listen to every country's (and everybody's) needs, even when they seem in contrast with our common sense or with our interests, because the hope is that within the sphere of dialectics a compromise can be (almost) always found.

I personally decided to cite this quote from the (in)famous speech held in Munich in year 2007 because from it we can extract a part of today's truth which I would paraphrase as: there cannot be a concept of cooperation among people (and peoples) if we don't think about the worldwide application of the concept itself.
Peoples are different for whats concerns traditions, costumes, attitudes, but one unifying factor is the struggle for a better life, better conditions and a positive view of the future. As we have seen cooperation emerges in clusters because if groups' interests are often in conflict among one another, it is easier to fight for them joining a team that will pursue them. Nevertheless, a short-time self-interest vision of resources exploitation can often

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[1] Special Operation[2]

[2] War

lead to the so-called "tragedy of the commons": a lose-lose situation with no progress for anybody.
Extrapolating these words in the context of International Cooperation, albeit the will is not to start a thorough discussion in this sense, they certainly reveal somehow the inherent incoherence of today's world: a world designed by neoliberalism policies where competitiveness should be regarded as a mantra and therefore promoted in a wide sense, which is in total opposition with the monopolistic politics of some countries, whose race towards financial and economical resources is certainly the main responsible of most of wars and devastation.

With the introductory short historical overview about the growth of a cooperation economy in Trentino, the purpose was not only to give a practical example of the birth of the concept of cooperation into a society, but also to give evidence of its achievements thanks to a choice of political autonomy in regards to many sectors, last but not least, the energy market. Obviously, the story of this success should include also territory resources' availability, the almost 100 years-long period of peace in Europe, as well as a reflection about whether the "values" of cooperation have not been betrayed along with its development, but this is not the place to discuss about that. Certainly, the creation of small cooperatives has largely contributed to the economic development of the region in the last decades and the Federation of Cooperatives is now a cornerstone of its economy. The fact that this cooperative movement was born in a period of crisis and lack of resources and not driven by any political beliefs should be the source of a deeper thinking.

In an ultra-connected world, the "tragedy of the commons" is certainly an option not viable and even if year after year COP26 Climate Change Conference warn about the urge of immediate actions against the growing global warming, still what drives people and nations is the more immediate self-interest and from one side we understand why many developing countries don't want to compromise their economical growth to implement more and more sustainable technologies while developed countries are reluctant to spend their own resources to promote those same technologies in the poorer countries, if not granted benefits.

At the same time, especially in Europe, it's indubitable the growth of a common sensitiveness about such topics as ecology and sustainability with the continuous birth of movements that claim for better climate policies to be applied. But if from one side people put a lot of efforts into finding viable solutions to reduce GHG emissions locally (and many EU-actions go into this direction) for a "greener" future, they often take ad-

vantage of incentive policies which can "drug" the energy market and therefore prevent the development of the same sustainable technologies in nearby countries. Even more, in EU-EEA we attend the growth of movements with a tendency to criticize those same developing countries that decided to recuse oneself from the climate plans while at the same time gaining profits from maintaining the situation as it is. Emblematic in regards to that, is the case of Norway, [55] a country internationally acclaimed as one of the "most sustainable" in the world, whose economy is still largely relying on the revenues of oil exportation.
Unsurprisingly, in the so-called developed countries consumers are also often mislead by aggressive "Green-washing" market strategies and the impossibility of verification often leaves the consumers either in a state of unconsciousness, or profound distrust in regards with the possibility of a more sustainable energy market.

Even more, as it was seen before, local incentives not always pursue the expected purposes: as explained in a chapter before, European ETS Market has lead to massive windfall profits for energy generator companies, price volatility, and in general for has failed to meet its goals.

Nowadays, on the edge of a new political era of distrust and global insecurity, energetic independence has recently become a popular topic of debate in daily TV talks or on the newspapers. This is quite understandable since dependency on energy in modern day society has become a capability for social welfare and economic growth[15] and not unexpectedly, energy resources still play a giant role in international relationships. Based on that, nuclear option has become a hot topic on the table, but rather from entering into a real discussion with professionals who devoted their lives on the topic, we see how this option is growing as a response to an external attack, as to manifest its own independence against the enemy, repeating the *"Metus Hostilis"* scheme which had been known thousand of years ago in the Roman Empire. Once again, the debate in Italy has flattened between those who advocate a fast "recovery of the lost time" in the nuclear development against those who are strict fierce opponents, maybe without a real knowledge of the impossibility of the existence of an energy market based solely everywhere on renewable technologies. At the same time, this situation of instability has had as a drawback the immediate return to the use of dismantled carbon plants, with a perspective of substituting natural gas with billions of tons LNG shipped from the other side of Atlantic ocean. Large debates are currently opening about the future strategic plan of European Union and hopefully it will be found a good balance between the need of a strategic independence of the energy sector and the limitation of GHG emission which will prevent us from putting our goals of air pollution reduction more far away in the future. The personal hope is to avoid that, once again, with one hand European Union will try to apply subsidies that can convince the population of the application of serious measures in contrast with the exploitation of non-renewable sources, while with the other end these same subsidies will contribute in lining the pockets of those same companies that prevent the development of renewable technologies in developing countries.

The thesis work, in his small contribution, has tried to concentrate on the development of a Smart-Grid with the purpose of resources allocation optimization and cost reduction. It is that sense that the coordination between a nuclear plant and many household properties can afford the goal of reducing GHG emission and at the same time, for instance, contribute in the solution of a problem like water availability which is going to be a big deal in the next years [62]. We therefore started from the consideration that in a Smart-Grid all actors are governed by self-interested to obtain a common goal, such as an Energy Market Leader would pursue in an evolutionary game.
If it could be possible to evaluate an energy system through its intrinsic efficiency and whole GHG emissions, it would be certainly more feasible, even for a normal citizen of the world, to have a clear benchmark to verify if a solution is moving towards the climate goals or not. In this case, the use of a Smart-Contract on the blockchain for energy training would allow to the consumer to verify the actual consumption of the smart-grid. In a certain sense, a public blockchain could possibly be the means through which we will pass from a society which gives value to trust from one where verification is the paradigma. Of course the road is not easy and many complications are present, such as transaction costs on the Ethereum blockchain and privacy dangers.

But somehow the hope of this thesis work is still that with a trustable verification process among peers, small communities will somehow find that possibility to cooperate among each other that would render affordable any goal, even the most difficult ones.

8.3. The End: a Christmas Truce

The work on cooperation in the Smart-Grid is a simple model supported by Game Theory which helped me in providing a real feasible solution to the economic dispatch problem. What is fascinating about Game-Theory is that in a certain way it tells more about us then we are supposed to know, in the same way as sometimes a physical model, grown from mathematics, can tell more about the reality than we could catch at a glimpse. The fact that through the application of the Metropolis algorithm we can build a physical model which resembles the evolution of clusters in an evolutionary game is probably the more curious result that pushed through including this theoretical model in the Thesis. It is not always easy to give a direct meaning to the temperature variable in game theory as is the Ising model. Nevertheless it is shown that the lower the temperature, the easier is for clusters to aggregate, "cooperate" to merge into a single one.

It was certainly cold on Christmas 1914 on the Western Front. Despite strict orders not to fraternize with the enemy, British and German soldiers left their trenches, crossed No Man's Land, and gathered to bury their dead, exchange gifts, and play games. It is not known exactly of how many soldiers were composed both armies , nor how cold it had to be for that to happen.

Hopefully however, the Temperature in Ukraine would reach the same order of magnitude, in order for what seems to be a "tragedy of the commons" to shift towards a $WIN \times n$ situation with $n = 43280258$[3]

Figure 8.1: "A Christmas Truce between Opposing Trenches"

A Christmas Truce between Opposing Trenches" Illustrated by AC Michael. Published in The Illustrated London News, January 9, 1915.

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[3] the population of Ukraine on 26th March, 2022

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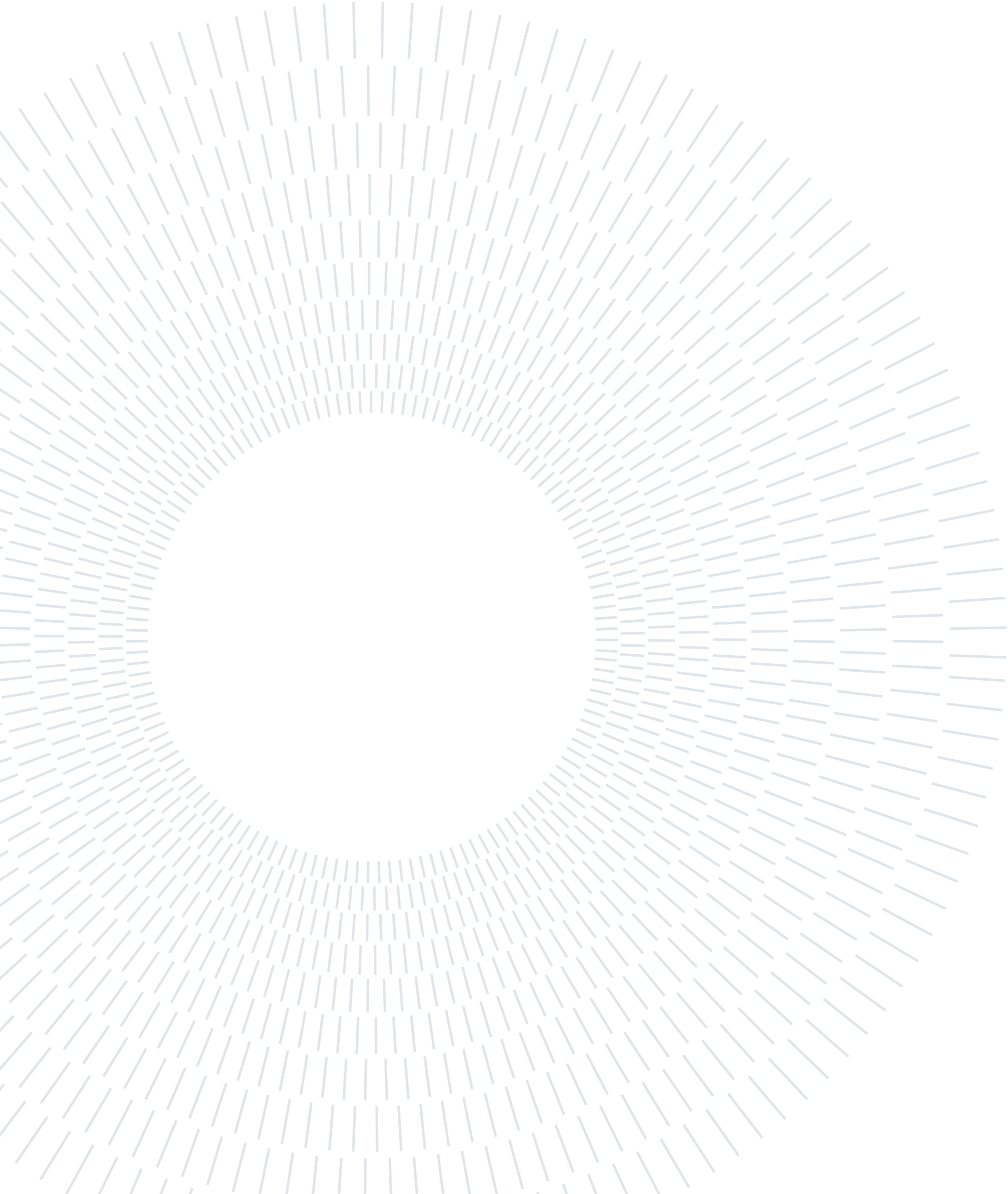
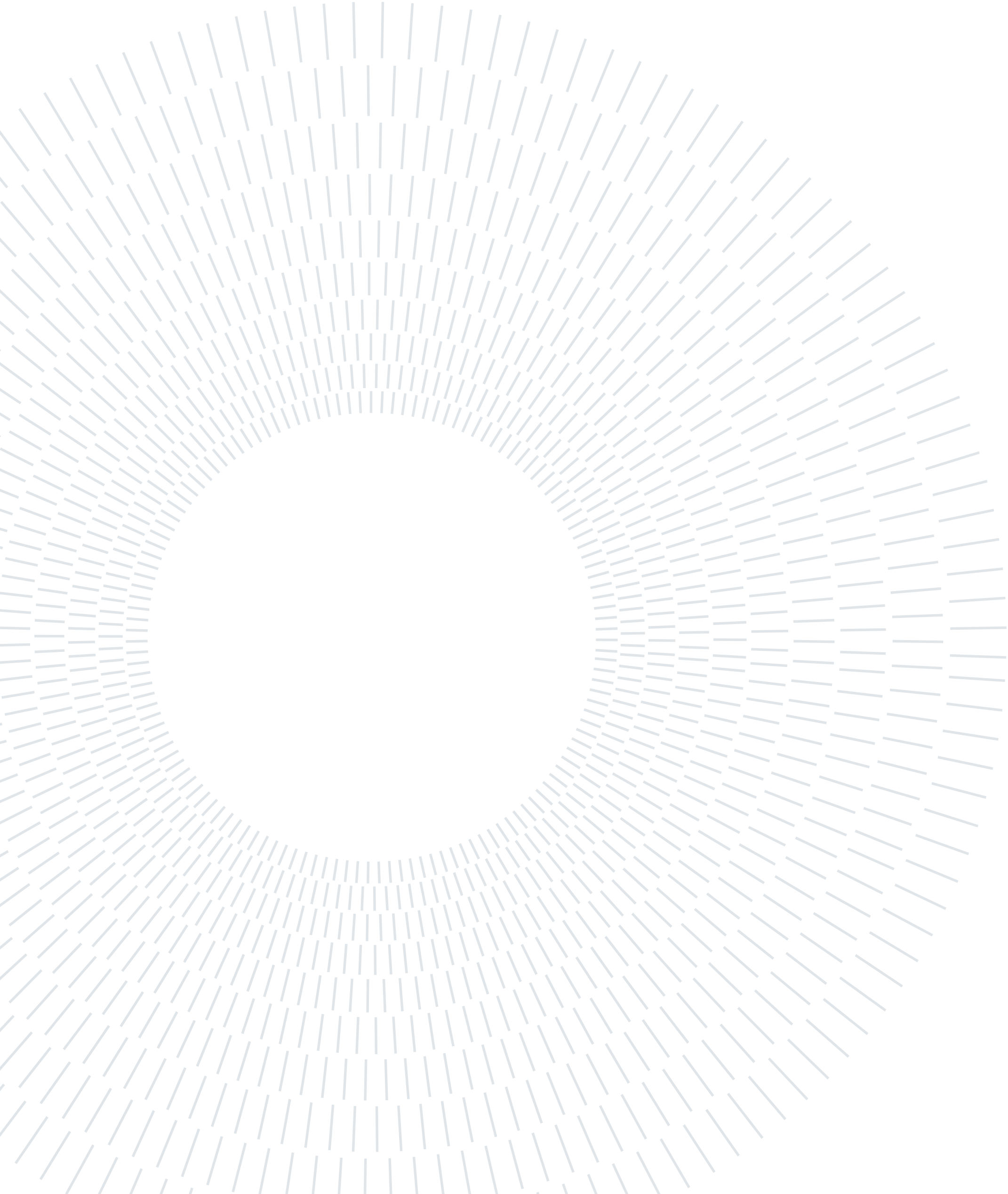


A | Code for S.C. Deployment on Ropsten Testchain in Python

```
import os
import pprint
import random
from solcx import compile_source, get_solc_version
print(’solidity version is: ’ + str(get_solc_version()))
from web3.middleware import construct_sign_and_send_raw_middleware
from web3.auto.infura.ropsten import w3
from web3.gas_strategies.time_based import medium_gas_price_strategy #,fast_gas_price_strategy

print(’is ETHEREUM connected? -- ’ + str(w3.isConnected()))
accts=[]
N_accounts=20
print(’LIST OF ETH ADDRESSES IS : ’)
print(’ ’)
print(’------------------------------------------’)
for i in range(N_accounts):
    privateKey = ’PRIVATE_KEY’ + str(i+1)
    acct=w3.eth.account.from_key(os.environ.get(privateKey))
    print(acct.address)
    accts.append(acct )
print(’------------------------------------------’)

trans = random.sample(range(1, 100), N_accounts)
trans1 = int(100*random.random())

def compile_source_file(file_path):
   with open(file_path, ’r’) as f:
      source = f.read()
   return compile_source(source,allow_paths=’.’)

compiled_sol = compile_source_file(’emissionToken.sol’)

contract_id = list(compiled_sol.keys())[3]
contract_interface = compiled_sol[contract_id]
token_id = list(compiled_sol.keys())[1]
token_interface = compiled_sol[token_id]

contractAddress = ’0xc0F4E25102a668D547e36Ea2f23E5B97391c2827’

contractInstance = w3.eth.contract(address=contractAddress, abi=contract_interface["abi"])
tokenAddress = contractInstance.functions.token().call()
tokenInstance = w3.eth.contract(address=tokenAddress, abi=token_interface["abi"])

def buy(w3, contract_instance, token_instance, userAddr, value):
    value_int = int(value)
    transaction = contract_instance.functions.buy().buildTransaction({’value’ : value_int,’maxFeePerGas’: 20000000000, ’maxPriorityFeePerGas’: 1000000000})
    gas_estimate= contract_instance.functions.buy().estimateGas({’value’ : value_int,’maxFeePerGas’: 20000000000, ’maxPriorityFeePerGas’: 1000000000})
    #transaction.update({’maxFeePerGas’: w3.toWei(’2’, ’gwei’),})
    transaction.update({ ’gas’ : gas_estimate })
    transaction.update({ ’nonce’ : w3.eth.get_transaction_count(userAddr) })
    tx_hash = contract_instance.functions.buy().transact({’from’ : userAddr,’value’ : value_int})
    consumer_receipt = w3.eth.wait_for_transaction_receipt(tx_hash, timeout = 240)
    #print(consumer_receipt)
    bal = token_instance.functions.balanceOf(userAddr).call()
    return bal

def approveSell(w3, contract_instance, delegate, userAddr, value):
```

```
    value_int = int(value)
    transaction = contract_instance.functions.approve(delegate, value_int).buildTransaction({'maxFeePerGas': 20000000000, 'maxPriorityFeePerGas': 1000000000})
    gas_estimate= contract_instance.functions.approve(delegate, value_int).estimateGas({'maxFeePerGas': 20000000000, 'maxPriorityFeePerGas': 1000000000})
    transaction.update({ 'gas' : gas_estimate })
    transaction.update({ 'nonce' : w3.eth.get_transaction_count(userAddr) })
    tx_hash = contract_instance.functions.approve(delegate, value_int).transact()
    consumer_receipt = w3.eth.wait_for_transaction_receipt(tx_hash, timeout = 240)
    #print(consumer_receipt)
    allowance = contract_instance.functions.allowance(userAddr, delegate).call()
    return allowance

def sell(w3, contract_instance, token_instance, userAddr, value):
    value_int = int(value)
    transaction = contract_instance.functions.sell(value_int).buildTransaction({'maxFeePerGas': 20000000000, 'maxPriorityFeePerGas': 1000000000})
    gas_estimate= contract_instance.functions.sell(value_int).estimateGas({'maxFeePerGas': 20000000000, 'maxPriorityFeePerGas': 1000000000})
    transaction.update({ 'gas' : gas_estimate })
    transaction.update({ 'nonce' : w3.eth.get_transaction_count(userAddr) })
    # transaction.update({ 'from' : userAddr})
    tx_hash = contract_instance.functions.sell(value_int).transact()
    consumer_receipt = w3.eth.wait_for_transaction_receipt(tx_hash, timeout = 240)
    #print(consumer_receipt)
    sold = token_instance.functions.balanceOf(userAddr).call()
    return sold


print('---------------------------STOP FIRST PART -------------------------')

def sendToken(w3, contract_instance, userAddr, value):
    value_int = int(value)
    transaction = contract_instance.functions.transfer(userAddr,value_int).buildTransaction({'maxFeePerGas': 20000000000, 'maxPriorityFeePerGas': 1000000000})
    gas_estimate= contract_instance.functions.transfer(userAddr,value_int).estimateGas({'maxFeePerGas': 20000000000, 'maxPriorityFeePerGas': 1000000000})
    transaction.update({ 'gas' : gas_estimate })
    transaction.update({ 'nonce' : w3.eth.get_transaction_count(w3.eth.default_account) })
    # transaction.update({ 'from' : userAddr})
    tx_hash = contract_instance.functions.transfer(userAddr,value_int).transact()
    consumer_receipt = w3.eth.wait_for_transaction_receipt(tx_hash,timeout = 240)
    #print(consumer_receipt)
    bal1 = contract_instance.functions.balanceOf(w3.eth.default_account).call()
    bal2 = contract_instance.functions.balanceOf(userAddr).call()
    return bal1,bal2

i=0
fund = int(max(trans)*1.5)
n = [x for x in range(20)]
random.shuffle(accts)
for agent in accts:
    w3.middleware_onion.add(construct_sign_and_send_raw_middleware(agent))
    w3.eth.default_account = agent.address

    transaction = contractInstance.functions.buy().buildTransaction({'value' : fund,'maxFeePerGas': 20000000000, 'maxPriorityFeePerGas': 1000000000})
    gas_estimate= contractInstance.functions.buy().estimateGas({'value' : fund,'maxFeePerGas': 20000000000, 'maxPriorityFeePerGas': 1000000000})
    transaction.update({ 'gas' : gas_estimate })
    transaction.update({ 'nonce' : w3.eth.get_transaction_count( agent.address) })
    tx_hash = contractInstance.functions.buy().transact({'value' : fund})
    consumer_receipt = w3.eth.wait_for_transaction_receipt(tx_hash,timeout = 240)
    #print(consumer_receipt)

    userAddr = accts[int(random.random()*N_accounts)]
    while agent.address == userAddr.address:
        userAddr = accts[int(random.random()*N_accounts)]
    bal1,bal2 = sendToken(w3,tokenInstance,userAddr.address,trans[i])
    print('after transaction balances: ' + str(bal1) +' , ' +str(bal2))
    i+=1

print('---------- BEGINNING CO2 TRADING ---------')

emissions = random.sample(range(1, 30), N_accounts)
limitEm = 25
i=0
for agent in accts:

    communityLeader = accts[3]
    w3.middleware_onion.add(construct_sign_and_send_raw_middleware(communityLeader))
    w3.eth.default_account = communityLeader.address

    transaction = tokenInstance.functions.approveAgent(agent.address).buildTransaction({'maxFeePerGas': 20000000000, 'maxPriorityFeePerGas': 1000000000})
```

```
    gas_estimate= tokenInstance.functions.approveAgent(agent.address).estimateGas({'maxFeePerGas': 20000000000, 'maxPriorityFeePerGas': 1000000000})
    transaction.update({ 'gas' : gas_estimate })
    transaction.update({ 'nonce' : w3.eth.get_transaction_count(communityLeader.address) })
    tx_hash = tokenInstance.functions.approveAgent(agent.address).transact()
    consumer_receipt = w3.eth.wait_for_transaction_receipt(tx_hash,timeout = 240)
    #print(consumer_receipt)
    w3.middleware_onion.add(construct_sign_and_send_raw_middleware(agent))
    w3.eth.default_account = agent.address
    transaction = tokenInstance.functions.approveIOTCounter(agent.address).buildTransaction({'maxFeePerGas': 20000000000, 'maxPriorityFeePerGas': 1000000000})
    gas_estimate= tokenInstance.functions.approveIOTCounter(agent.address).estimateGas({'maxFeePerGas': 20000000000, 'maxPriorityFeePerGas': 1000000000})
    transaction.update({ 'gas' : gas_estimate })
    transaction.update({ 'nonce' : w3.eth.get_transaction_count(agent.address) })
    tx_hash = tokenInstance.functions.approveIOTCounter(agent.address).transact()
    consumer_receipt = w3.eth.wait_for_transaction_receipt(tx_hash,timeout = 300)

    IOTAddress = tokenInstance.functions.getIOTCounter(agent.address).call()
    if IOTAddress == agent.address:
        print('check for correct IOT device passed')
    else:
        print('problem with IOT recognizing')
    transaction = tokenInstance.functions.addEmissions(agent.address, emissions[i]).buildTransaction({'maxFeePerGas': 20000000000, 'maxPriorityFeePerGas': 100000
    gas_estimate = tokenInstance.functions.addEmissions(agent.address, emissions[i]).estimateGas({'maxFeePerGas': 20000000000, 'maxPriorityFeePerGas': 1000000000
    transaction.update({ 'gas' : gas_estimate })
    transaction.update({ 'nonce' : w3.eth.get_transaction_count(communityLeader.address) })
    tx_hash = tokenInstance.functions.addEmissions(agent.address,emissions[i]).transact()
    consumer_receipt = w3.eth.wait_for_transaction_receipt(tx_hash,timeout = 300)

    emissionsCertified = tokenInstance.functions.getEmissions(agent.address).call()
    if emissionsCertified > limitEm:
        #check for token balance:
        bal = tokenInstance.functions.balanceOf(agent.address).call()
        if bal < (emissionsCertified - limitEm):
            val = emissionsCertified - bal
            bought = buy(w3, contractInstance, tokenInstance, IOTAddress,val)
        transaction = tokenInstance.functions.compensate(emissionsCertified).buildTransaction({'maxFeePerGas': 20000000000, 'maxPriorityFeePerGas': 1000000000})
        gas_estimate = tokenInstance.functions.compensate(emissionsCertified).estimateGas({'maxFeePerGas': 20000000000, 'maxPriorityFeePerGas': 1000000000})
        transaction.update({ 'gas' : gas_estimate })
        transaction.update({ 'nonce' : w3.eth.get_transaction_count(communityLeader.address) })
        tx_hash = tokenInstance.functions.compensate(emissionsCertified).transact()
        consumer_receipt = w3.eth.wait_for_transaction_receipt(tx_hash,timeout = 240)

    emissionReceipt = tokenInstance.functions.getEmissions(agent.address).call()
    print('agent ' + str(i+1) +' emissions: ' + str(emissionReceipt))
    i+=1
print('------------------------- END ------------------------')
```

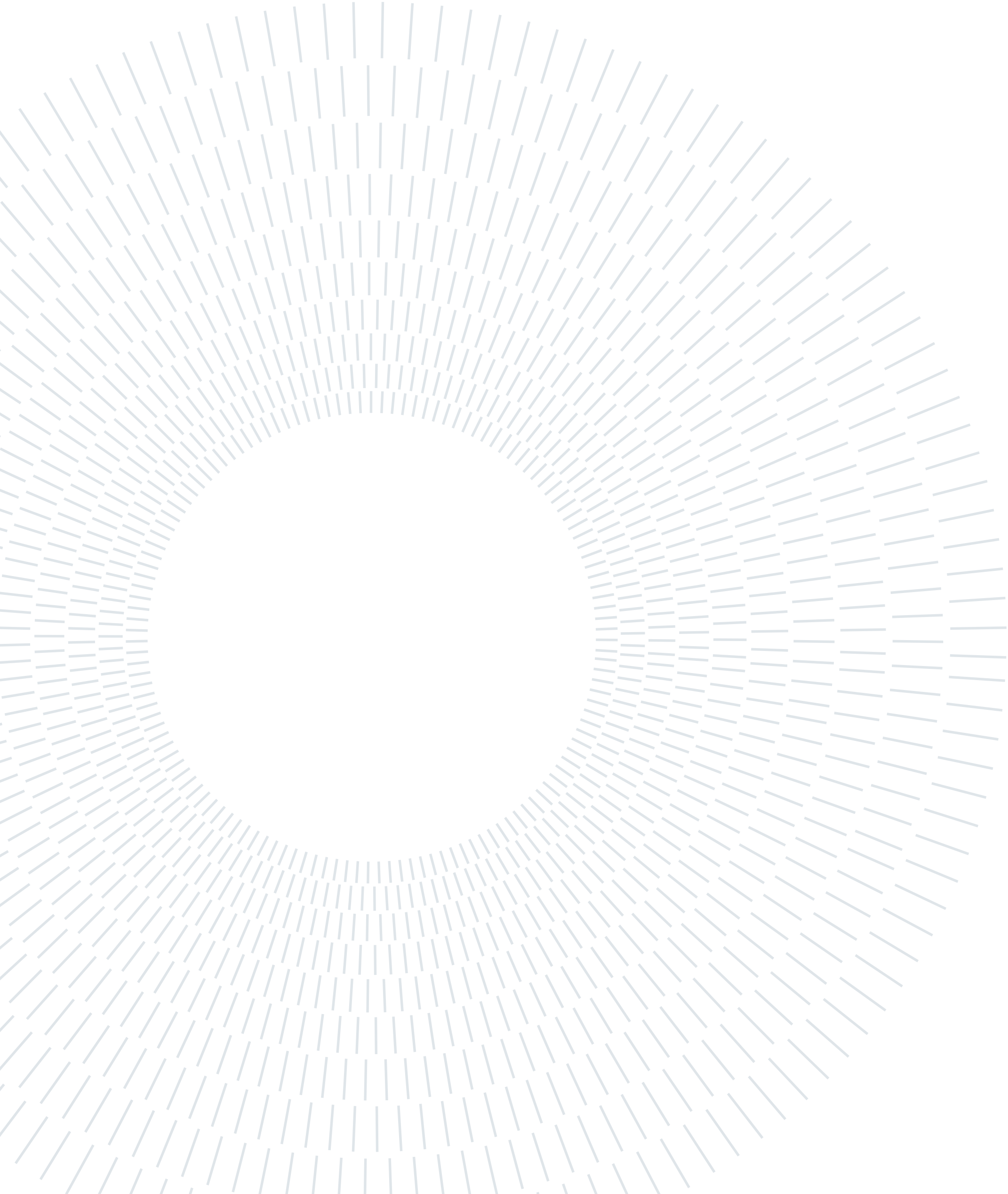


B | Smart Contract Code for Energy and CO2 consumption trading

```
// SPDX-License-Identifier: MIT

pragma solidity \^0.8.4;
interface IERC20 {
    function totalSupply() external view returns (uint256);
    function balanceOf(address account) external view returns (uint256);
    function allowance(address owner, address spender) external view returns (uint256);
    function transfer(address receiver, uint256 numTokens) external returns (bool);
    function approve(address spender, uint256 numTokens) external returns (bool);
    function transferFrom(address sender, address receiver, uint256 numTokens) external returns (bool);
    // function decimals() external returns (uint8);
    event Transfer(address indexed from, address indexed to, uint256 value);
    event Approval(address indexed owner, address indexed spender, uint256 value);
}

contract ERC20Basic is IERC20 {
    string private _name;
    string private _symbol;
    uint8 private _decimals;
    mapping(address => uint256) _balances;
    mapping(address => mapping (address => uint256)) _allowances;
    uint256  private _totalSupply;

   constructor(string memory name_, string memory symbol_,uint256 totalSupply_) {
       _name = name_;
       _symbol = symbol_;
       _totalSupply = totalSupply_;
       _balances[address(this)] = _balances[address(this)] + totalSupply_;
       emit Transfer(address(0),msg.sender,_totalSupply);
    }
    function _transfer(address sender, address receiver, uint256 numTokens) internal {
        require(receiver != address(0),"ERC20: transfer from zero transfer");
        require(sender != address(0),"ERC20: transfer from zero transfer");
        require(numTokens <= _balances[sender]);
        _balances[sender] = _balances[sender]-numTokens;
        _balances[receiver] = _balances[receiver]+numTokens;
        emit Transfer(sender, receiver, numTokens);
    }
    function _approve(address owner, address spender, uint256 numTokens) internal {
        require(spender != address(0),"ERC20: transfer from zero transfer");
        require(owner != address(0),"ERC20: transfer from zero transfer");
        _allowances[owner][spender] = numTokens;
        emit Approval(owner, spender, numTokens);
    }
    function _mint(address account, uint256 numTokens) internal virtual {
        require(account != address(0), "ERC20: mint to the zero address");
        _beforeTokenTransfer(address(0), account, numTokens);
        _totalSupply += numTokens;
        _balances[account] += numTokens;
        emit Transfer(address(0), account, numTokens);
    }
    function _burn(address account, uint256 numTokens) internal virtual {
        require(account != address(0), "ERC20: burn from the zero address");
        _beforeTokenTransfer(account, address(0), numTokens);
        uint256 accountBalance = _balances[account];
        require(accountBalance >= numTokens, "ERC20: burn numTokens exceeds balance");
        _balances[account] = accountBalance - numTokens;
```

```
        _totalSupply -= numTokens;
        emit Transfer(account, address(0), numTokens);
    }
    function _beforeTokenTransfer(address from, address to, uint256 numTokens) internal virtual { }
    function name() public view returns (string memory) {
        return _name;
    }
    function symbol() public view  returns (string memory){
        return _symbol;
    }
    function decimals() public view returns(uint8) {
        return _decimals;
    }
    function totalSupply() public override view returns (uint256) {
return _totalSupply;
    }
    function balanceOf(address tokenOwner) public override view returns (uint256) {
        return _balances[tokenOwner];
    }
    function transfer(address receiver, uint256 numTokens) public override returns (bool) {
        _transfer(msg.sender,receiver,numTokens);
        return true;
    }
    function approve(address spender, uint256 numTokens) public override returns (bool) {
        _approve(msg.sender, spender, numTokens);
        return true;
    }
    function allowance(address owner, address spender) public override view returns(uint256) {
        return _allowances[owner][spender];
    }
    function transferFrom(address sender, address receiver, uint256 numTokens) public override returns(bool) {
        _transfer(sender, receiver, numTokens);
        _approve(sender, msg.sender, _allowances[sender][msg.sender] - numTokens);
        return true;
    }
}

contract buySellToken {
    event Bought(uint256 numTokens);
    event Sold(uint256 numTokens);
    IERC20 public token;
    constructor() {
        token = new ERC20Basic("energyToken", "ET", 100000000000000000000);
    }
    function buy() payable public {
        uint256 amountTobuy = msg.value;
        uint256 dexBalance = token.balanceOf(address(this));
        require(amountTobuy > 0, "You need to send some ether");
        require(amountTobuy <= dexBalance, "Not enough tokens in the reserve");
        token.transfer(msg.sender, amountTobuy);
        emit Bought(amountTobuy);
    }
    function getbal(address wallet) public view returns (uint){return token.balanceOf(wallet);}
    function sell(uint256 numTokens) public {
        require(numTokens > 0, "You need to sell at least some tokens");
        uint256 allow = token.allowance(msg.sender, address(this));
        require(allow >= numTokens, "Check the token allowance");
        token.transferFrom(msg.sender, address(this), numTokens);
        payable(msg.sender).transfer(numTokens);
        emit Sold(numTokens);
    }
}

contract EmissionsTradeToken is ERC20Basic{
    mapping(address => uint256) EnergyTraded;
    mapping(address => uint256) GHGEmitted;
    mapping(address=>address) approvedIot;
    address public owner;
    constructor() ERC20Basic('EmissionsTradeToken', 'ETT', 100000000000000000000){
    owner = msg.sender;
    }
    modifier onlyOwner(){
        require(msg.sender == owner);
        _;
    }
    modifier onlyIOT(address company){
```

```
        require(msg.sender == approvedIot[company]);
        _;
    }
    event Buy(address indexed to, uint indexed EnergyTraded, uint indexed amount);
    event Emission(address indexed to, uint indexed GHGEmitted, uint indexed amount);
    event Compensate(address indexed to, uint indexed GHGEmitted, uint indexed amount);
    function mint(uint amount) public onlyOwner{
        _mint(address(this), amount);
    }
    function addEmissions(address company,uint emission) public onlyIOT(company){
        GHGEmitted[company] += emission;
        emit Emission(company,emission,emission);
    }
    function getEmissions(address company) public view returns(uint){
        return GHGEmitted[company];
    }
    function getIOT(address company) public view returns(address){
        return approvedIot[company];
    }
    function compensate(uint amount) public{
        require(balanceOf(msg.sender)>= amount, "buy ETT to compensate for GHG emissions!");
        _burn(msg.sender,amount);
        GHGEmitted[msg.sender] -=amount;
        emit Compensate(msg.sender,amount, amount);
    }
    function approveIot(address spender) public{
        bool isApproved = approve(spender,getEmissions(msg.sender));
        if(isApproved)
            approvedIot[msg.sender]=spender;
    }
    function changeOwner(address newOwner) public returns(bool){
        require(owner == msg.sender);
        owner = newOwner;
        return true;
    }
}
```



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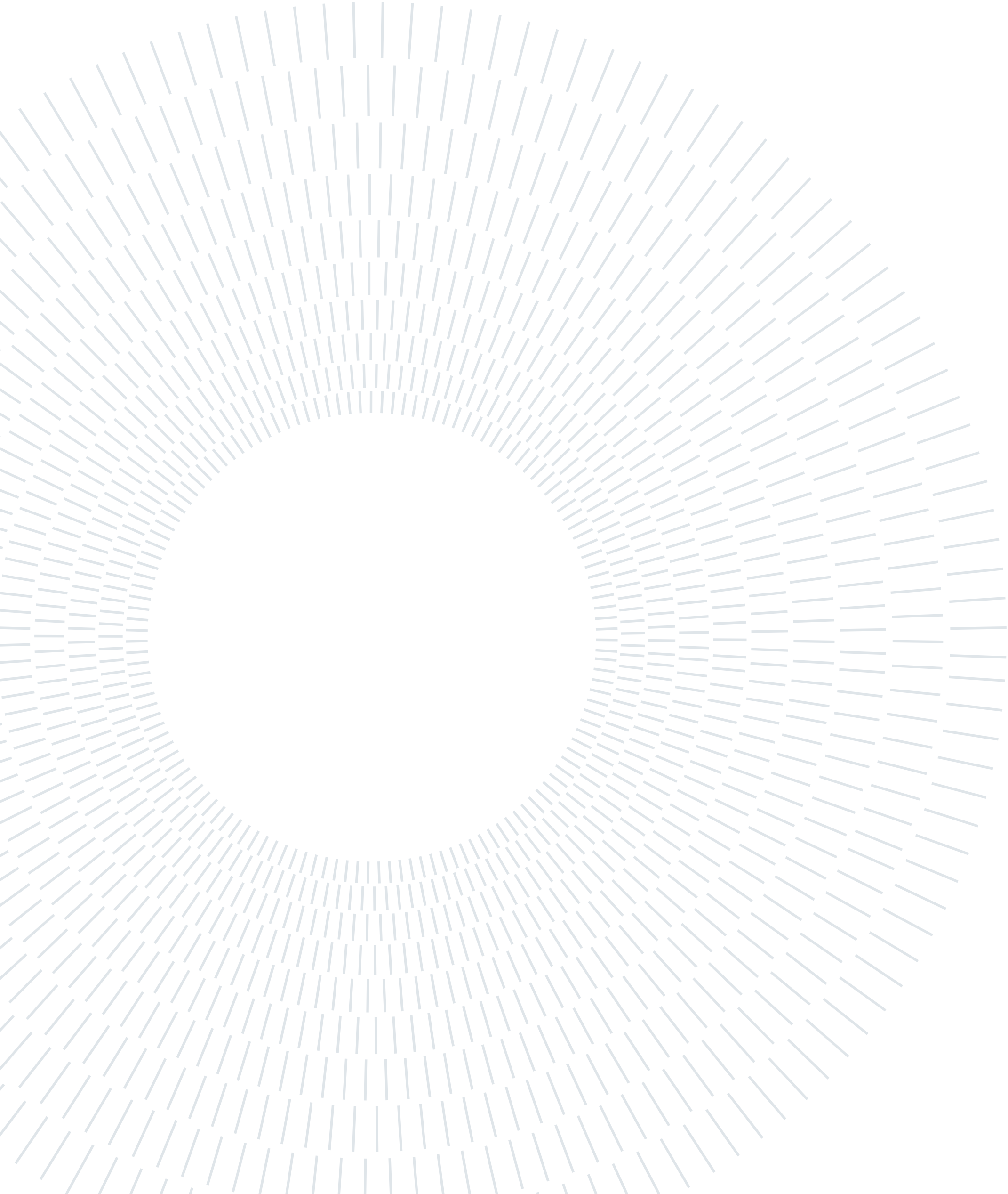

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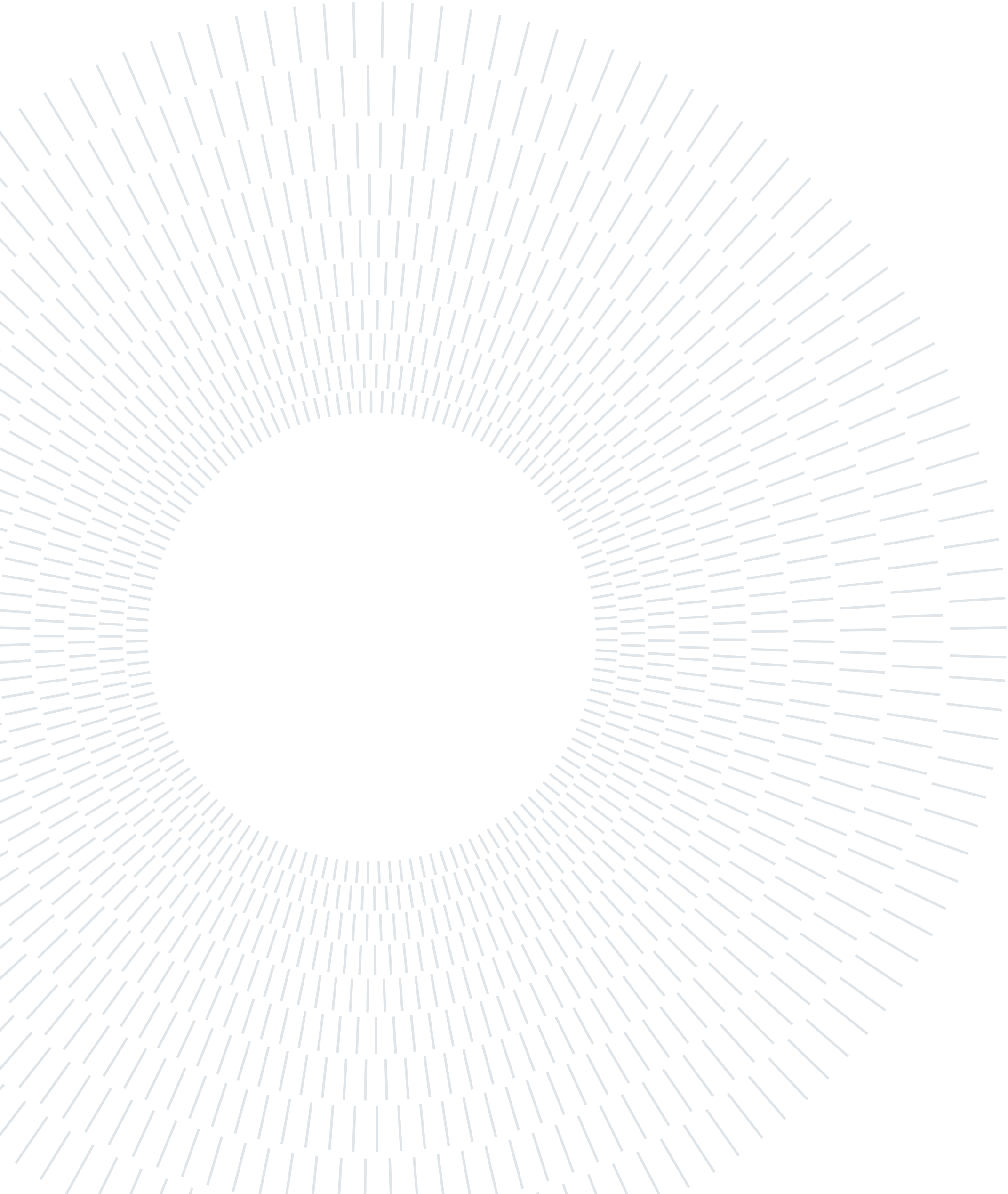

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