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# Investigating the regional contributions to the Italian decarbonization: an Energy Modelling multi-regional approach.

TESI DI LAUREA MAGISTRALE IN  
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# Abstract

With the growing concern for climate change, the call to address a gradual decarbonization of the energy system, must be at the forefront of any development plan. Energy System Optimization Models (ESOMs) are one of the most effective tool for assisting policy-makers, however, an optimization based only on the minimization of the costs (least-cost solution), proved that it might suffer of an uneven distribution of the resources, low capacity factors, high land usage and low social acceptance. In order to make the model more flexible, this study explores a wide range of alternative solutions, in order to understand which are the technologies that are necessary to be included in the development plan. Starting from a multi-objective optimization, which leads in finding a set of optimal solutions that constitute the so called Pareto frontier, is then proposed a novel methodology, aiming at finding near to optimal solutions based on a cost increase of 5%, 10% and 20%. The results reveal that, for the case study of Italy, photovoltaic (PV) technologies coupled with batteries, together with on and off shore wind, biofuels and waste, pumped hydro storage and hydro power plants, are *must have* technologies, meaning that they cannot be substituted and are essential for the future energy mix by 2050. Additionally, also the cutting-edge carbon capture and storage (CCS) technologies, could be considered a possible future must-have, being present in all the alternative options but the least-cost. Additionally, all the scenarios are compared through two key indicators: the system's load factor and the carbon cost (defined as the ratio between the cost increase and the emission decrease). Although all the near to optimal solutions present a decrease in the emissions and land usage, coupled with higher load factors, a 5% cost increase is already enough for gaining significative environmental benefits (31% of emission decrease) with reasonable carbon costs. Higher cost relaxations are thus feasible and attractive, but they are characterized by higher carbon costs due to the deployment of larger and more expensive technologies which have low specific emissions but are costly to implement.

**Keywords:** Energy systems; multi-objective optimization; Pareto frontier; MGA; near to optimal; system scales



## Abstract in lingua italiana

Con la crescente preoccupazione per il cambiamento climatico, l'obiettivo di attuare una graduale decarbonizzazione del sistema energetico sta alla base di ogni piano di sviluppo. Gli attuali modelli energetici, sono uno degli strumenti più efficaci per assistere politici e stakeholder, anche se un'ottimizzazione basata solo sui costi (soluzione least-cost), ha dimostrato di poter presentare diverse problematiche quali una distribuzione disomogenea delle risorse, bassi fattori di carico ed un elevato utilizzo del suolo. Al fine di rendere il modello più flessibile, questo studio è volto a generare una vasta gamma di soluzioni alternative, con lo scopo di individuare quali sono le tecnologie essenziali alla transizione energetica. A partire da un'ottimizzazione multi-obiettivo, che porta ad individuare un insieme di soluzioni ottimali che costituiscono la cosiddetta frontiera di Pareto, sono state successivamente trovate delle soluzioni di semi ottimo, caratterizzate da un aumento dei costi del 5%, 10% e 20% rispetto alla soluzione least-cost. I risultati rivelano che, per il caso studio dell'Italia, il fotovoltaico (FV) abbinato alle batterie, insieme alle centrali eoliche onshore e offshore, impianti a biomassa e idroelettrici, e accumulo idroelettrico, sono tecnologie indispensabili, ovvero che non possono essere sostituite e sono essenziali per il futuro mix energetico al 2050. Inoltre, anche i nuovi sistemi all'avanguardia di cattura e stoccaggio del carbonio (CCS) possono essere considerati possibili impianti necessari per il futuro, essendo presenti in tutte le alternative tranne che nella soluzione least-cost. Gli scenari sviluppati sono stati successivamente analizzati attraverso due indicatori chiave: il fattore di carico del sistema e il carbon cost (stimato come il rapporto tra l'incremento dei costi e la diminuzione delle emissioni). Il confronto dimostra che, sebbene tutte le soluzioni vicine all'ottimo presentino una diminuzione delle emissioni e dell'uso del suolo, insieme a fattori di carico più elevati, un aumento del costo del 5% è già sufficiente per ottenere significativi benefici ambientali (diminuzione delle emissioni del 31%) con carbon cost ragionevoli. Un incremento dei costi più elevato, invece, porta a soluzioni fattibili e allettanti, ma con un aumento del carbon cost a causa dell'impiego di tecnologie caratterizzate da basse emissioni specifiche, ma onerose da implementare.

**Parole chiave:** Sistemi energetici; ottimizzazione multi obiettivo; frontiera di Pareto; MGA; soluzioni di semi ottimo; scala del sistema



# Extended abstract

## 0.1. Introduction

In recent years, human activity's impact on the planet has become significant, leading to climate change and posing risks to health. The Paris Agreement, ratified by 194 countries since 2015, aims to limit global warming to prevent further environmental damages and preserve ecological systems [66]. Europe's ambitious *European Green Deal* targets a 55% reduction in emissions by 2050, emphasizing renewable energy, efficiency, storage and carbon capture systems [8]. Additionally, due to the war in Ukraine, Europe is willing to become independent from Russian fossil fuels by reducing natural gas imports through the ambitious *REPowerEU* plan [34]. The plan has hence the dual objective of intensifying the energy security, diversifying the resources, saving energy and tackling the climate change.

Focusing on Italy, its total energy supply, in 2020, consisted of approximately 40% renewable resources, 50% natural gas and the remaining 10% of coal and oil [41]. For this reason, in the Italian Integrated National Energy and Climate Plan (INECP) [27], long term strategy [10], and the most recent National Recovery and Resilience Plan (NRRP) [11], Italy is willing to allocate around 10 billion€ for the green transition, which includes a great roll out of the renewables and boost in the transmission and storage system. The goal is to reach by 2030 a share of renewables for the electric generation of 55% [27] in order to reach the most ambitious target, stated in the Long-term strategy, of 95% by 2050 [10].

Finally, also hydrogen is gaining rapid momentum, serving as an energy carrier and storage for multiple sectors and being its development and consumption an additional key factor for achieving the decarbonization. The Italian hydrogen National strategy, has estimated an hydrogen penetration of 2% in the final energy consumption by 2030 (corresponding to approximately 0.7 Mton/year), and of 20% by 2050[37]. Moreover, in order to tackle such ambitious goal, the government foresees the installation of approximately 5 GW of electrolyzers by 2050 [37].

This study aims at implementing a novel methodology that allows to go beyond a cost-optimal solution, being it technically feasible but often politically or socially undesirable. The objectives are hence twofold. The first one consist on carrying out a technical and economic analysis of all the possible technologies that are needed for achieving the Italian decarbonization, considering the contribution given by each region. Moreover, a special focus on different system scales is needed, in order to highlight how the scenarios might be affected by an aggregated or a disaggregated system. Finally, in order to make the model more flexible, the second objective consists on finding a new methodology, that enables to map near to optimal solutions applying a cost relaxation of 5%, 10% and 20% starting from the optimal Pareto frontier. This would allow to find a wide range of feasible alternative solutions that bring useful insights for supporting policy-makers.

## 0.2. Literature review

Energy models play a crucial role in decision-making regarding climate and energy policies. However, Pfenninger et al. [52], argue that the main challenges include: resolving time and space, balancing uncertainty and transparency, addressing the growing complexity of the energy system, and integrating the human behaviour and social risk.

When dealing with time and space, an example can be provided by simply analysing the data provided by the Italian TSO Terna [60, 61, 63, 64]. The Italian northern regions are the ones with the highest energy demand, whereas the south is more suitable for the exploitation of renewable resources, having higher capacity factors and more room for hosting these power plants. Therefore, the north is usually forced to import electricity, implying that the other regions have a production that is higher than the one needed for meeting their demand. The way in which the region of interest is modelled, has thereby an impact on the results and hence on the different scenarios and forecasts. The question then is, when defining the "scale" of the system, whether it is better to have a large-scale, that covers an entire region with a low resolution missing important aspects, or a small-scale, that covers a smaller portion of that location with a higher resolution but an increased complexity [52].

When pursuing cost-optimality, the risk is to accentuate this mismatch, as proven also by the results provided by Lombardi et al. [46]. Being costs the fundamental drivers of the energy transition, cost-optimal solutions fail to take into account social or political acceptance, which determine the final application or implementation of the forecasted policies [52]. In order to make models more flexible, new techniques have been adopted such as the modeling to generate alternatives (MGA) [36]. This method includes both a multi-

objective optimization which leads in finding a set of optimal solutions that constitute the so called Pareto front, and the possibility of analyzing also the feasible *near-optimal* area, in order to develop alternatives that consider also the previously mentioned dimensions [36].

### 0.3. Methodology

#### 0.3.1. Italy as a case study and its different scales

A Reference Energy System -res- is the framework of the energy system used in an optimization model.

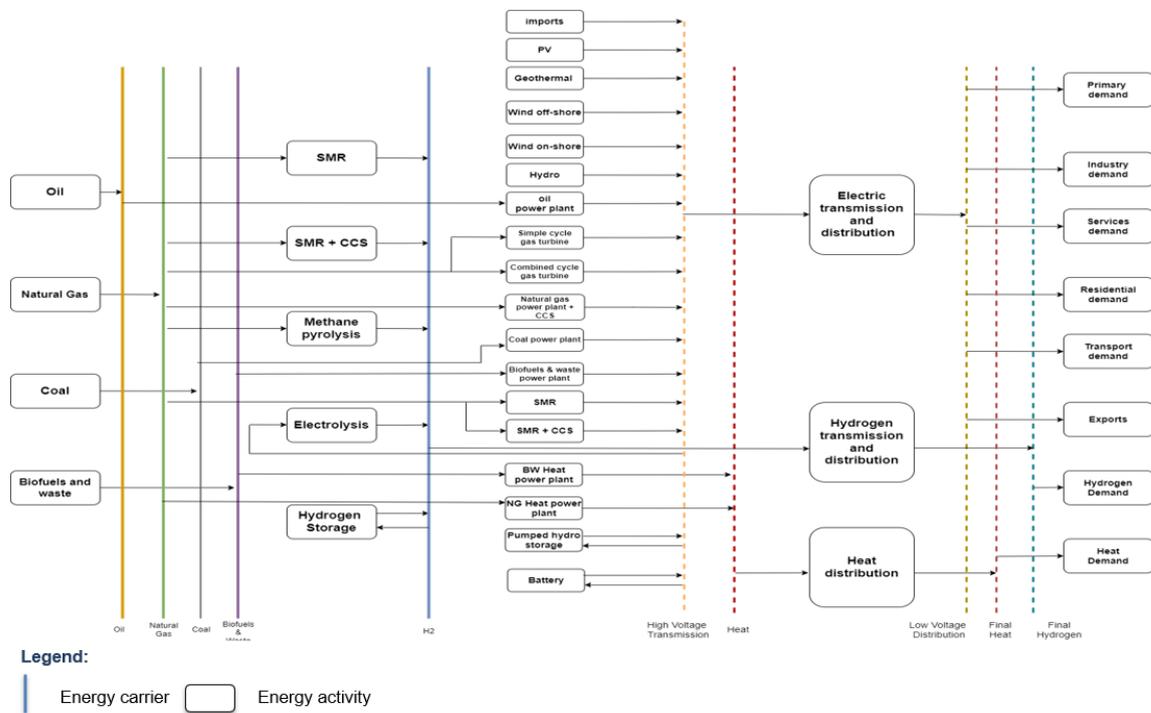


Figure 1: Italian Reference Energy System

Figure 1, is a representation of the res for the case of Italy on a global level. Being the space resolution one of the main challenges to tackle [52], the study compares two different system scales called single-region and multi-region which represent respectively Italy as a whole and the Italian six bidding zones defined by Terna [57]. Moreover, the multi-region, entails also a transmission system for electricity and hydrogen. The first one, has a fixed maximum capacity accordingly to Terna’s data for the current values and future development by 2050 [58]. On the contrary, the hydrogen transmission system has been modelled accordingly to the gas infrastructure data, due to its possible conversion

for supporting the deployment of hydrogen technologies [35].

### 0.3.2. Modelling to generate alternatives

This study explored a wide range of alternative solutions using Hypatia, an open source energy model developed by the Politecnico di Milano research group SESAM [9]. The starting point consisted in a multi-objective optimization, which combined an economic and a  $CO_2$  emission optimization function, in order to define the set of optimal solutions belonging to the so called Pareto frontier. Starting from the least-cost solution, with minimum NPC and maximum emissions, the curve extends up to the least-emission solution, with minimum emissions and maximum costs. Subsequently, the goal was to define a novel methodology for mapping the area within the optimal front and the maximum emissions of the least-cost solution.

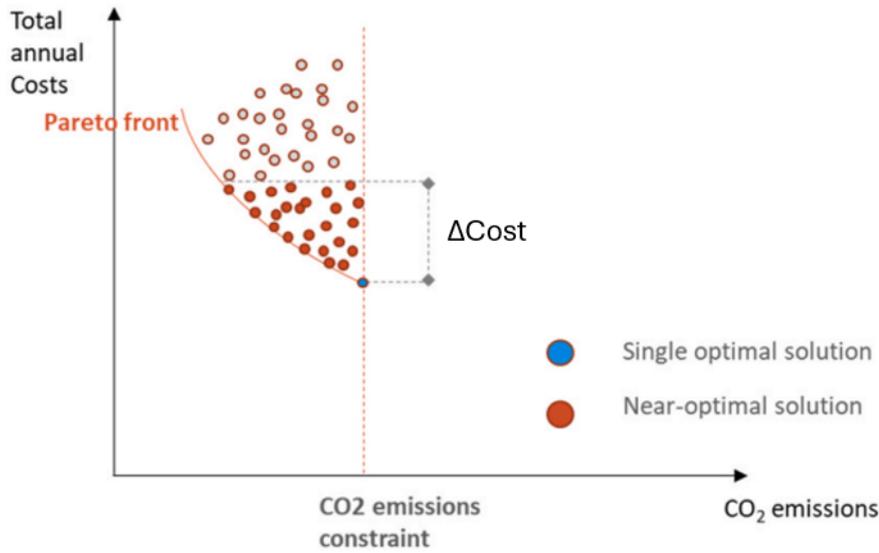


Figure 2: Near to optimal area.

*Adapted from [53]*

Figure 2, shows the area of interest for the investigation, where the maximum NPC varies accordingly to  $\Delta\text{Costs}$ , that changes based on the cost relaxation  $\epsilon$ . The latter, can indeed be considered as the increased willingness to pay with respect to the least cost solution. For this case study was considered a cost increase of 5%, 10% and 20%, constraining the cumulative costs of each solution as follows:

$$NPC_{n2o} \leq NPC_{least\_cost}(1 + \epsilon) \quad (1)$$

Then, was arbitrarily defined a new objective function that minimizes the land usage:

$$Total\_land\_usage = \sum_r^R \left( \sum_n^N P_n l u_n \right)_r \quad (2)$$

where  $P_n$  is the installed power of source  $n$  times the specific land usage  $l u_n$ , in the Italian region  $r$ . The input data adopted with the related references are reported in Appendix A.

In order to implement a new *optimization mode* into the model, was necessary to bring some changes into the main Hypatia's modules - see Appendix E for the algorithms. Calling with  $f_1(x)$  the global cost function,  $f_2(x)$  the global emission function and with  $f_3(x)$  the land usage function, the logic followed by the algorithm can be explained by Equation 3:

$$\begin{aligned} & \text{minimize} \quad \mathbf{f}_3(x) \\ & \text{subject to} \quad f_2(x) \leq F_2(t), \quad t \in 1 \dots p, \\ & \text{subject to} \quad f_1(x) \leq Max\_NPC, \\ & \mathbf{x} = [x_1, x_2, \dots, x_n]. \end{aligned} \quad (3)$$

Once the cost relaxation  $\epsilon$  and the number of solutions  $p$  are given as an input by the user, the model can run. The first solution found corresponds always to the optimal least cost, being the starting point of each optimization. Once the  $NPC_{least\_cost}$  is found, is possible to determine the maximum  $NPC_{n2o}$  allowed accordingly to Equation 1. The second step of the optimization, consists in finding the second optimal solution on the Pareto frontier, optimizing the emissions  $f_2(x)$  spending only up to the maximum  $NPC_{n2o}$ . Then the algorithm finds a list of emissions  $F_2$ , containing all the optimal emissions values that span from the maximum emissions to the minimum emission value previously found. The list contains as many values as the number of solutions  $p$ , being the distance between each emission equal to  $step = \frac{(Max\_emissions - Min\_emissions)}{(p-1)}$ .

When the list  $F_2$  is built, the model is able to find the near to optimal solutions. Finding  $F_2$  is necessary for differentiating each solution from the previous one, mapping more effectively the area of interest. Through a *for* loop, which iterates along each value in the emission list, was hence possible to embed an additional constrain on the emission, making sure to have maximally different solutions since each alternative has a higher emission cap compared to the previous one.

Finally, the comparison between the different scenarios was done based on three indicators: cumulative emissions, system's load factor for year 2050 and carbon costs defined in Equation 5.

$$\text{Load factor}_{2050} = \frac{\text{Total Energy Production}_{2050}}{\text{Total Installed Capacity}_{2050} \cdot 8760} \quad (4)$$

$$\text{Carbon cost} = \frac{\Delta \text{Costs}[\$]}{\Delta \text{emissions} [\text{tons\_of\_CO}_2]}. \quad (5)$$

## 0.4. Results and discussion

### 0.4.1. The stated policies

The first three least-cost scenarios analysed, are the ones based on the Italian intended policies: PNIEC2019 (1) [27] and PNIEC2019&longterm (2) [10, 27]. Additionally, has been studied also the *possible* future stated policy, which is the latest PNIEC2023&longterm (3) [29], since it is still under the evaluation by the European Commission (go to Appendix B for the input data).

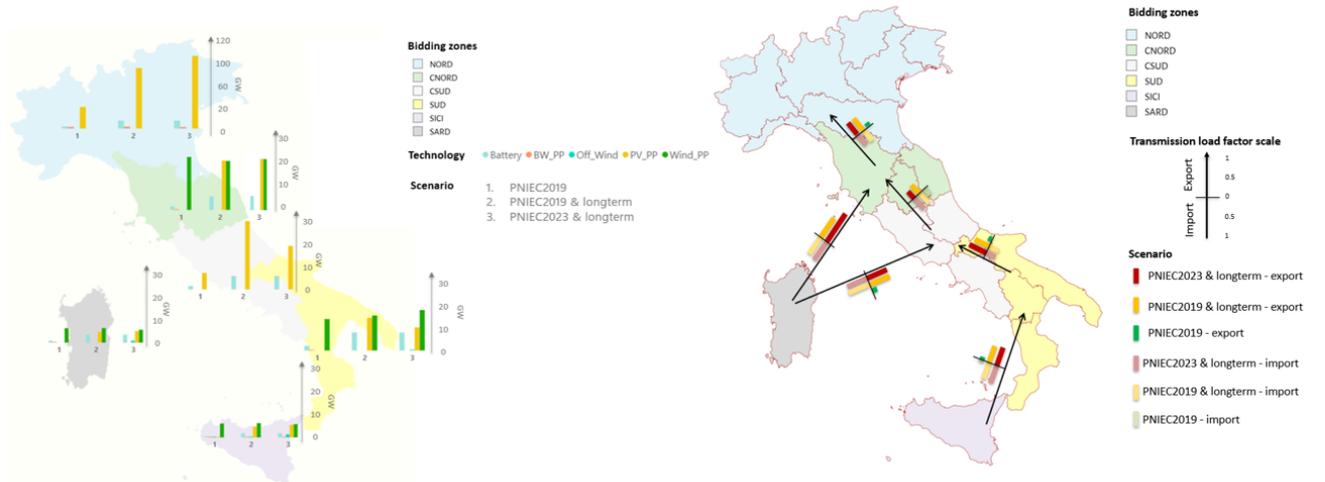


Figure 3: Installed capacity - year 2050 (left), load factor of the transmission system - year 2050 (right).

Examining the installed capacity, a significant disparity arises between scenario 1 and the other two, primarily due to the inclusion of the Long-term strategy [10] aimed at achieving

95% of electricity production from renewables and 200 GW of installed photovoltaic (PV) by 2050. Furthermore, there is an almost linear relationship between the renewables roll out and the transmission’s load factor, with the most ambitious PNIEC2023 achieving the highest values.

However, it is possible to note also an uneven distribution of the RES, particularly for PV and wind power plants, with an over-concentration in NORD and CSUD for the former and in CNORD, SARD, SUD and SICI for the latter. Additionally, this imbalance, extends also to the utilization of the transmission system, accentuating the mismatch between regions aforementioned in Section 0.2.

### 0.4.2. Different system scales

The comparison between two different system scales, was carried out based on the scenario PNIEC2019&longterm , for both a least-cost and a least-emission solution (which minimizes only the  $CO_2$  emissions).

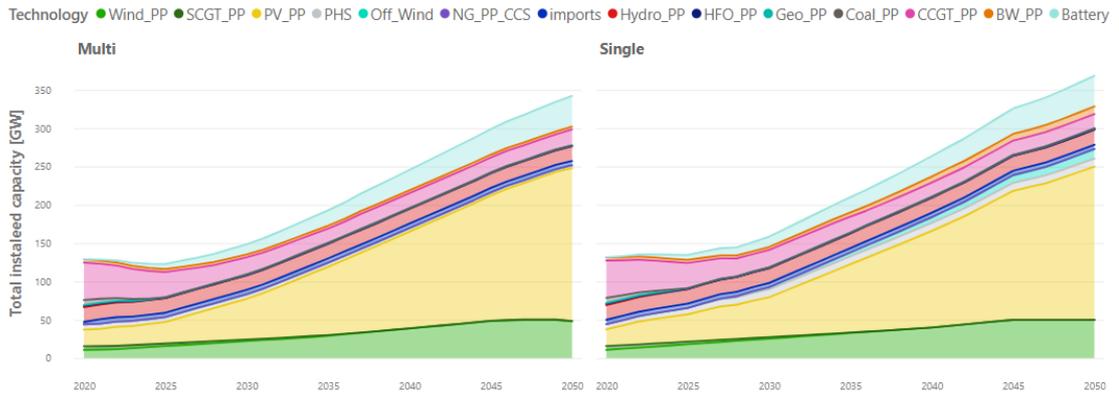


Figure 4: Total installed capacity for electricity - least cost solution.

Starting from the least-cost, being the minimum PV installed capacity quite constrained due to the Long-term strategy, the main differences between the two scenarios are related to on shore and off shore wind power plants. Although the constraints and the minimum stated capacities are the same on a global level for both scenarios, when considering a single region there is a higher installed capacity for both technologies. This is mostly related to the different capacity factor considered: for a Multi scenario, each zone has indeed its own capacity factor, allowing to have a more detailed and precise estimation with respect to the Single where there is only one global average value. Moreover, the whole system in Single, misses the potential benefit provided by the transmission system,

which enables to reduce the local installed capacity if the electricity can be imported from the neighbouring region.

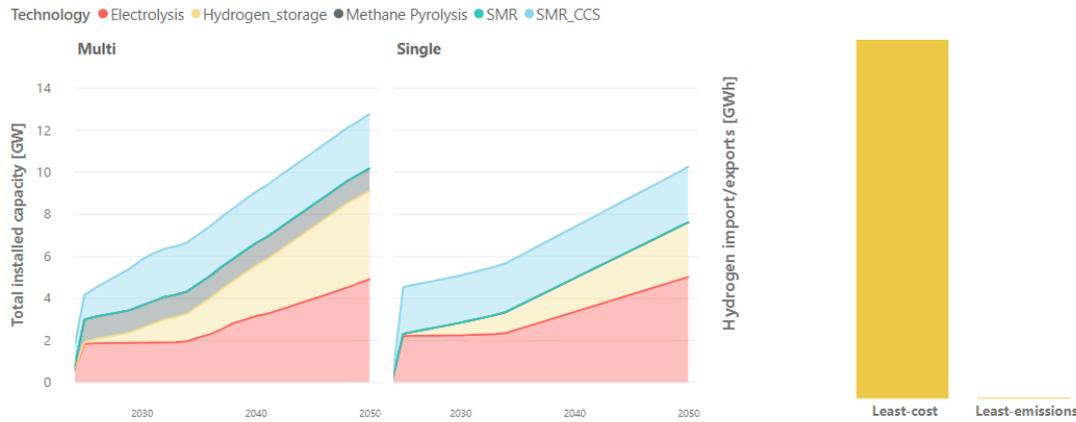


Figure 5: Total installed capacity for hydrogen (left) ; hydrogen import/exports (right) - least emission solution.

For the least-emission solution, the differences are almost irrelevant for electricity, while a great change can be seen in the installed hydrogen technologies that have the highest contribution in the emissions reduction. In Multi, there is indeed the deployment of an additional technology: methane pyrolysis. Moreover, the disaggregated scenario, allowed to focus also on the transmission system. Since Italy is still debating on which strategy is better to follow in order to tackle the great forecasted hydrogen penetration [37] (entirely on-site production, on-site production coupled with energy distribution), the comparison between the least-cost and the least-emissions scenarios, shows how the methodology adopted and, in this case, different objective functions, influence a possible answer to this question: for minimizing the costs, it is preferable to have an on-site production coupled with energy distribution, while entirely on site is privileged if the goal consists of minimizing the emissions.

Finally, when limiting the study on a single cost-optimal scenario, it is feasible and also more interesting to consider larger system boundaries, in order to better represent possible demand fluctuations, different capacity factors, potential of the renewables and the benefits of the transmission lines of such a complex system. However, when the aim is to entail also more complex analysis such as multi-objective optimization or near to optimal solutions which need multiple runs, it is crucial to take into account also the computational power required and the related problems that it might bring when it is underestimated. For this reason, the study will explore the modelling to generate alternatives considering only the first stated policy scenario PNIEC2019, modelled as a single node.

### 0.4.3. Modelling to generate alternatives

Figure 6, shows the Pareto Frontier (with no maximum NPC, least emission solution 10) and the near to optimal solutions found for each cost relaxation (5%, 10% and 20%)

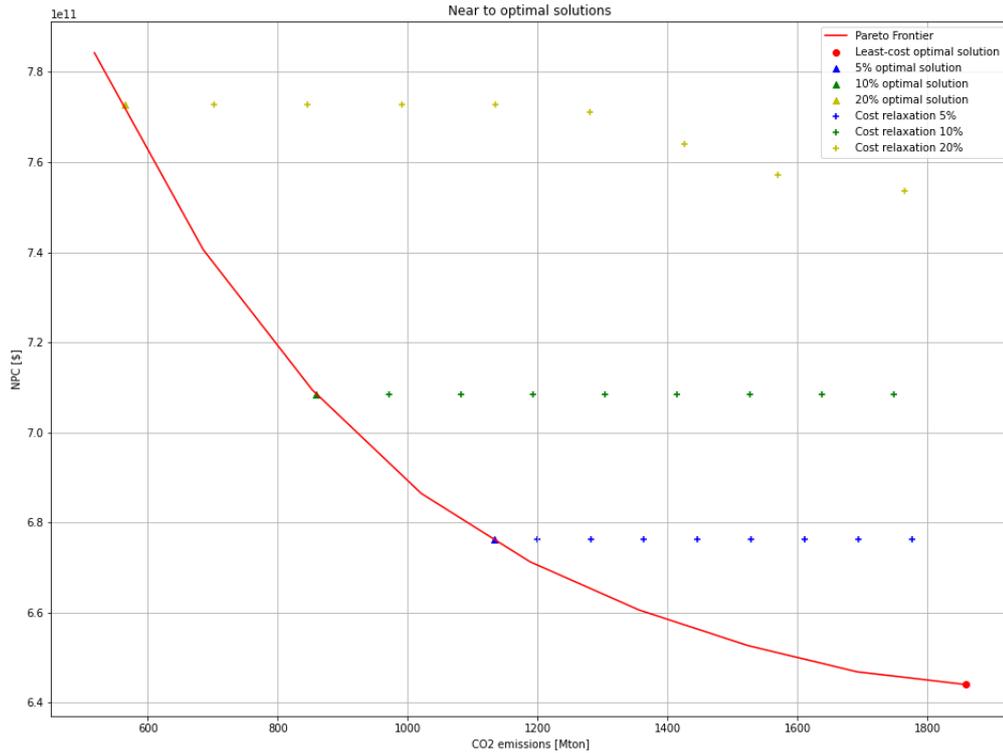


Figure 6: Near to optimal solutions and Pareto Frontier with no maximum costs.

Focusing on the near to optimal solutions, it is first important to mention that, since solution number 10 for each cost relaxation falls on the Pareto Frontier (see Figure 6), it automatically becomes an optimal solution, and hence won't be taken into account for the near to optimal discussion.

One of the first insight provided by the near to optimal solutions, are the so called *must-have* technologies. These are generation and storage technologies for any energy carrier, that are present in all the scenarios, whatever the cost relaxation or the objective function is. Such an analysis, is useful for assisting policy makers when choosing the best energy mix and the investments needed for gaining the country's specific goals.

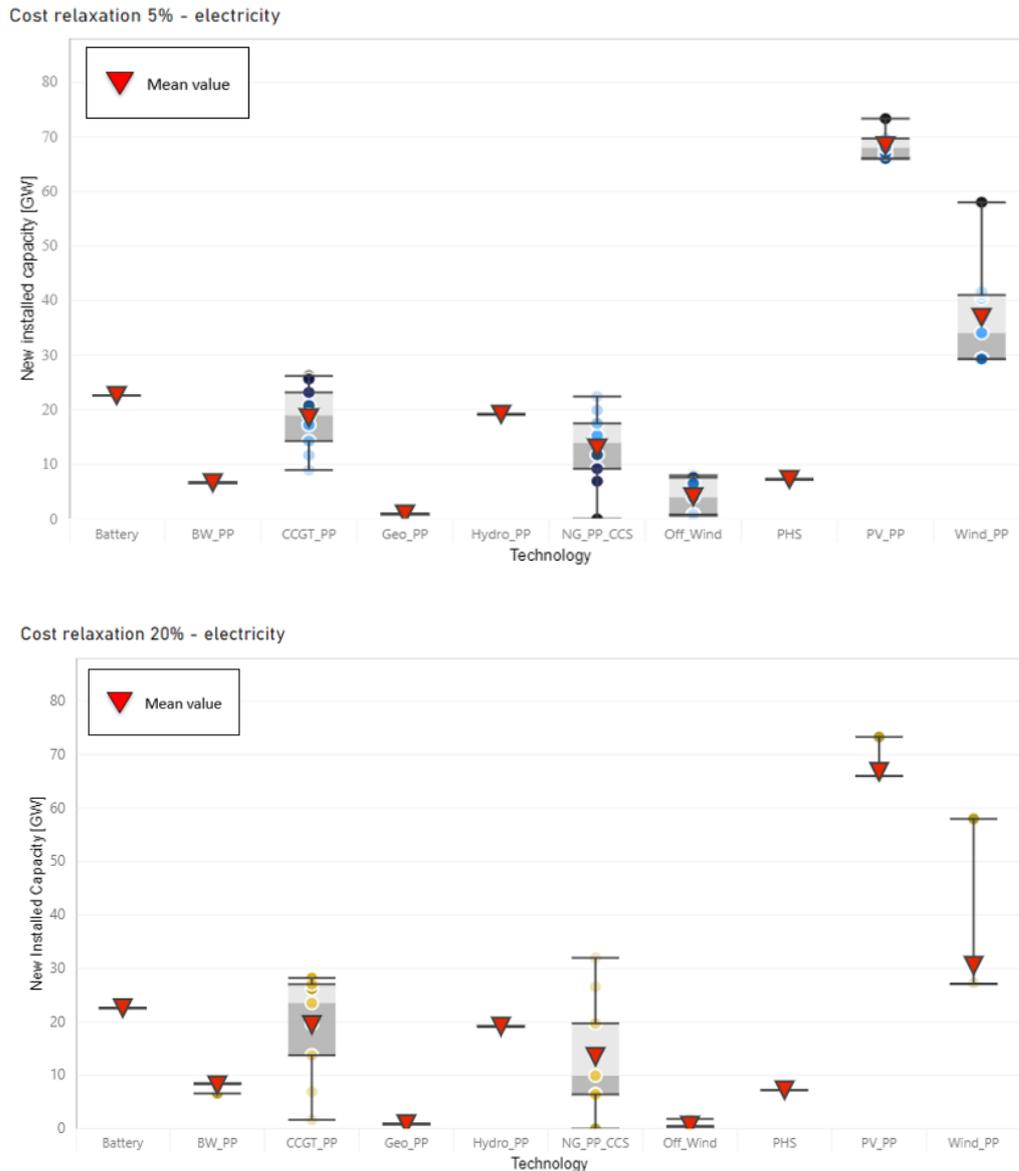


Figure 7: Must-have technologies among near to optimal solutions - electricity.

For this case study, this analysis was carried out considering the dispersion of the new installed capacity, in the period 2020-2050, for each technology in each solution. Figure 7 represents the results for electricity production for a 5% and 20% cost relaxation. Each box represents the dispersion of the values, with a red triangle that shows the median value considering all the near to optimal solutions. Focusing on this latter, the expansion of PV coupled with batteries is a must-have in all the scenarios together with off and on shore wind. However, both technologies face a slight decrease in the new installed capacity when the costs increase. This is related to the objective function chosen, which

benefits other technologies such as natural gas coupled with carbon capture and storage. Additionally, biofuel and waste (BW\_PP), hydro power plants (Hydro\_PP) and and pump hydro storage (PHS), are all must haves since they are present in all the scenarios, being them all key technologies for the Italian energy mix.

Furthermore, the study compared the near to optimal scenarios through the indicators defined in the methodology. Looking at the carbon cost, it decreases going from solution 2 to solution 9. This indicator is essential for understanding how much more is necessary to spend in order to cut more the emissions. This means that, even though the cost increase is quite high, it is still acceptable since are gained great environmental benefits. Overall, all the results follow a reasonable trend and, looking at the table on the right, it is possible to note how spending already 5% more is enough for gaining great environmental benefits.

For what concerns the load factor, the graph shows the trend for the year 2050, defined by Equation 4. The values do not differ a lot, being the overall trend almost steady, even though there is a slight increase in all the near to optimal solutions. This results in a much more efficient resource exploitation with respect to the least-cost solution, making all these alternatives also more attractive for the stakeholders, since would better justify an increase in the costs.

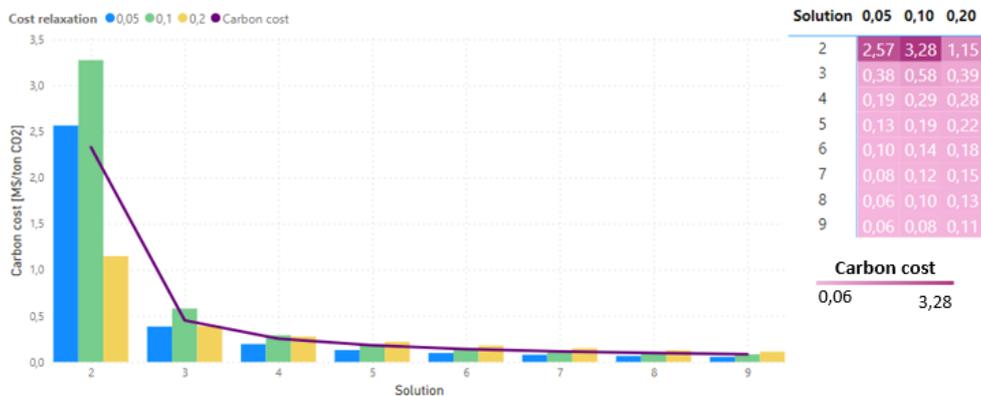


Figure 8: Carbon cost.

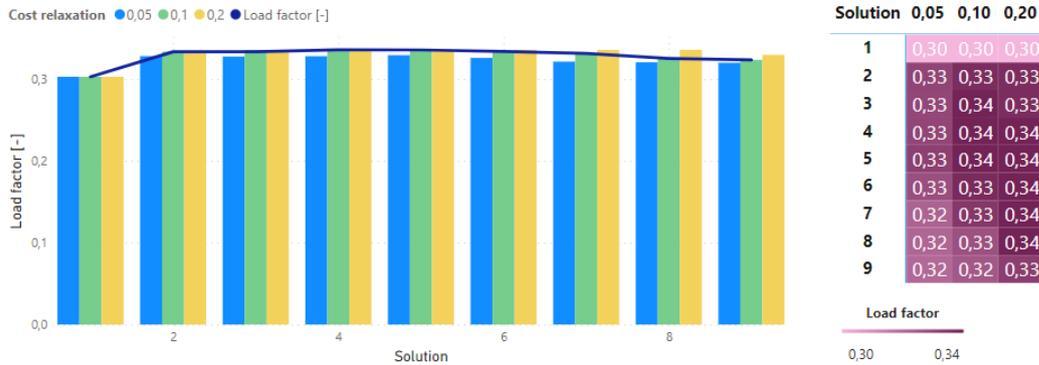


Figure 9: Load factor - year 2050

Finally, the overall results prove how considering near to optimal solutions might result beneficial for assisting policy-makers. The advantages of such analysis consists of understanding how alternative solutions highlight useful insights even though the constraints and the objective functions are arbitrary. For instance, this study proved that if the goal is not strictly correlated to the minimization of the costs (least-cost solution), there might be benefits in terms of emission and land usage decrease, and increase in the load factor. All the alternatives showed indeed how through them is possible to go beyond the technical-economic feasibility, entailing also the often ignored social dimension. Having for example a higher emission decrease and higher load factors coupled with a lower land usage, might result in a lower social resistance since the performances are more effective, the resources can be distributed more efficiently and also a cost increase would be justified.

## 0.5. Conclusions

Using Italy as a case study, was proposed a novel modelling approach for supporting policy-makers in tackling their goals. Through the use of a multi-objective optimization and near to optimal solutions evaluation, was indeed possible to analyze a wide range of alternatives in order to provide maximally different options. Relying only on a cost-optimal solution, proved that the scenarios might suffer of an uneven distribution of the resources, low capacity factors and high land usage.

Starting from the optimal Pareto Frontier, was subsequently applied a new methodology able to find alternative solutions that reach a 5%, 10% and 20% cost increase. The results showed how considering these maximally different options, helps to highlight useful insights such as the *must have* technologies. For the case study of Italy, photovoltaic (PV)

technologies coupled with batteries, and on/off shore wind power plants are must-haves, together with the new cutting-edge carbon capture and storage (CCS) technologies which are present in all the scenarios but the least-cost. Moreover, the study proves that a 5% cost increase is already enough for gaining significant environmental benefits with reasonable carbon costs. Higher cost relaxations are thus feasible and attractive, but they are characterized by higher carbon costs due to the deployment of larger and more expensive technologies which have low specific emissions but are costly to implement.

Finally, this report demonstrated also how crucial can be the system's scale chosen. While multi-region scales are more detailed and hence allow to better represent the system's complexity, single-region scales are more suitable when multiple runs are needed due to their much lower computational costs. Moreover, the study conducted for a multi-region scenario, and the comparison with the single-region one, highlighted how impactful can be the transmission system for both electricity and hydrogen.

Overall, near to optimal are an effective method for supporting policy makers in energy planning at a national level. However, for a matter of time availability and too high computational costs, this study couldn't be conducted on a multi-region scale. The future challenge would thereby be to start from the already developed least cost solutions, and map all the possible optimal or semi optimal alternatives for a disaggregated configuration. The goal is to further highlight the contribution that each Italian region can provide for the energy decarbonization, focusing also on the transmission system. The results showed indeed how the transmission's system load factor changes considering different scenarios, being it strictly correlated to the RES roll out. On the other hand, for what concerns hydrogen, the comparison between a least cost and a least emission scenario, proved how also in this case the transmission system has a key role depending on the objective to be achieved.

In conclusion, the key aspect of this thesis is the use of a new methodology for pointing out the importance of going beyond least cost solutions in energy system optimization models. Modelling to generate alternatives assures to explore different options and strategies. This is indeed decisive, since it should be at the forefront of any energy plan in order to guarantee a transition that has to be just and affordable.



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# Introduction

Over the years the impact of human activity on our planet is no longer negligible as it causes climate change and it is posing a significant risk for our health. With the growing concern about environment, 194 countries have ratified, since 2015, the Paris Agreement [66]. While the agreement stipulates that limiting global warming within 1.5 to 2.0 °C from a pre-industrial level is crucial for preventing damage and preserving global ecological systems, the current commitments aren't sufficient to limit emissions below this threshold [51]. Therefore, further ambition is needed in global decarbonization efforts, and member countries of the Paris Agreement must keep working to renegotiate the National Determined Contributions (NDC) if further emissions reductions need to be reached. That is why, with its ambitious *European Green Deal*, Europe is aiming to cut the emissions by 55%, with respect to 1990 levels, reaching the net zero emissions target by 2050 while ensuring economic growth and a just transition [8].

The plan covers a variety of strategies, decarbonizing different sectors such as agriculture, industry, transport, services and so on. Focusing on the energy sector, which accounts for almost three-quarters of emissions [54], the challenge is to reach the net-zero for transports and for the production of electricity and heat. So far, EU has largely focused on this sector subsidizing renewable energy sources such as wind and solar, being off-shore wind one of the most promising technologies due to its technological development and cost breakdown [56]. The European Union is hence prioritizing renewable energy, energy storage, energy efficiency in buildings and industry, sustainable transportation, and carbon capture and storage. Furthermore, there is a growing recognition of the importance of comprehensive approaches to the entire energy system which include the development of smart grids, innovative solutions for consumers, hydrogen-based systems, and the concept of smart cities [56]. A big challenge stems also from the transport sector, which is the only EU sector that has seen an increase in GHG emissions since 1990 [56]. Thus, electrification is a key strategy for the decarbonization of the vehicle-kilometers that are hard to replace with alternative transportation methods [8]. Electric vehicles can be a key technology, not only reducing hazardous air pollution, but also increasing EU economic competitiveness on the global market [8].

Additionally, due to the war in Ukraine, Europe is trying to intensify its energy security, being its independence from Russian fossil fuels at the forefront of the new ambitious *REPowerEU* plan. The plan has a dual objective: reduce the European Union's reliance on Russian fossil fuels (since they are used as an economic and political weapon and cost European taxpayers nearly €100 billion per year), and tackle the climate change [34]. In order to accomplish these measures, the path to follow consists of enhancing energy savings, diversifying energy supplies, and accelerating the roll-out of renewables [34].

Italy is also among the 27 member states that have made the commitment to make the EU the first climate-neutral continent by 2050. For this reason, in the Italian Integrated National Energy and Climate Plan (INECP) [27] together with the most recent National Recovery and Resilience Plan (NRRP) [11], Italy shares the orientation of the European community aimed at strengthening the commitment of the economy's decarbonization and is therefore willing to promote the aforementioned *Green New Deal*. Its total energy supply, in 2020, consisted of approximately 40% renewable resources, 50% natural gas and the remaining 10% of coal and oil [41].

Italy is indeed the second European country - right after Germany- with the highest natural gas share in the total final energy consumption [40]. This is not only contributing to the emission of GHG, but raises also questions regarding the Italian energy security due to its dependence on socio-politically unstable countries for the natural gas imports. Moreover, gas is still forecasted to be part of the energy supply, coupling future power plants with carbon capture storage systems [27]. Although this might sound contradictory, considering the European effort in lowering its dependence on gas consumption due to the concern of Russia's political and economic threat, in 2022, Italy effectively reduced its dependency on Russia by entering into new agreements with other suppliers, due to the investments made in pipeline and LNG infrastructure over the past ten years[43]. By decreasing the overall demand for natural gas through a faster transition to alternative energy sources and a heightened emphasis on energy efficiency, especially in the construction industry, Italy is thus aiming to enhance energy security and simultaneously align itself with the climate goals.

Being aware of the potential benefits inherent in the widespread diffusion of renewables, together with an improvement of the energy efficiency and the use of new cutting-edge technologies (such as carbon capture and storage), in the Integrated National Plan (INECP), Italy intends to accelerate the transition from traditional fuels to renewable sources. The country will hence implement the necessary policies and measures to achieve GHG reduction targets agreed upon at the international and European levels. The goal is to reach by 2030 a share of renewables for the electric generation of 55% [27] in order to

reach the most ambitious target, stated in the Long-term strategy, of 95% by 2050 [10, 18]. These action, would allow to cut by 55% the emissions by 2030 [60] in order to gradually achieve the final emission benchmark by 2050.

This energy transition, would additionally promote the abandonment of coal -the phase out is planned for 2025- for electricity generation. The urgency of this action, is driven by the extreme harm to health and environment that this source is causing. It is substantially more GHG-intensive than alternative combustion-based energy generation, and this fuel category - together with peat and oil shale- was responsible, in 2021, for 44.4% of global GHG emissions, despite only making up 26.8% of the total global energy supply [42]. Additionally, fossil fuel combustion is responsible for emission of fine particles (PM2.5) – globally, these emissions could be shown to be directly attributable to 1 in 5 deaths in 2018 [48].

In order to afford the essential investments needed to tackle both the climate and - due to Covid-19 pandemic - economic crisis, EU has formulated a response with the launch of the Next Generation EU (NGEU) program in July 2020 [67]. Being part of this program, Italy is going to receive 191.5 billion €, which will be divided in six "missions": digitalisation and culture, green revolution and ecological transition, infrastructure for sustainable mobility, education and research, inclusion and cohesion, and health [11]. Focusing on the green transition, in the *National Recovery and Resilience Plan*[11], Italy is willing to allocate:

- 5.90 billion€: for increasing the share of energy produced by renewable sources;
- 1.10 billion€: for the agri-voltaic development;
- 2.20 billion€: for the renewable energy spread for energy communities and self consumption;
- 0.68 billion€: for promoting innovative installations (e.g. off-shore wind).

For this reason, in the Long-term strategy has been stated the ambitious goal of increasing the installed capacity by renewable resources, reaching by 2050 0,3 GW of the new cutting-edge off-shore wind and 200 GW of photovoltaic installed [10]. Moreover, being renewables non-programmable sources due to their reliability on weather and environment conditions, Italy is willing to address this unpredictability through the spread of storage systems, increasing, by 2050, of 5 GW the pumped hydro storage, and of 30-40 GW the electrochemical one [10, 27].

Finally, also hydrogen is gaining rapid momentum, serving as an energy carrier and storage for multiple sectors and being its development and consumption an additional key factor

for achieving the decarbonization. Indeed, in the EU *Long Term Strategy*, the European Commission has envisaged the spread of hydrogen through three phases [35], from now until 2050 as shown in the following figure:

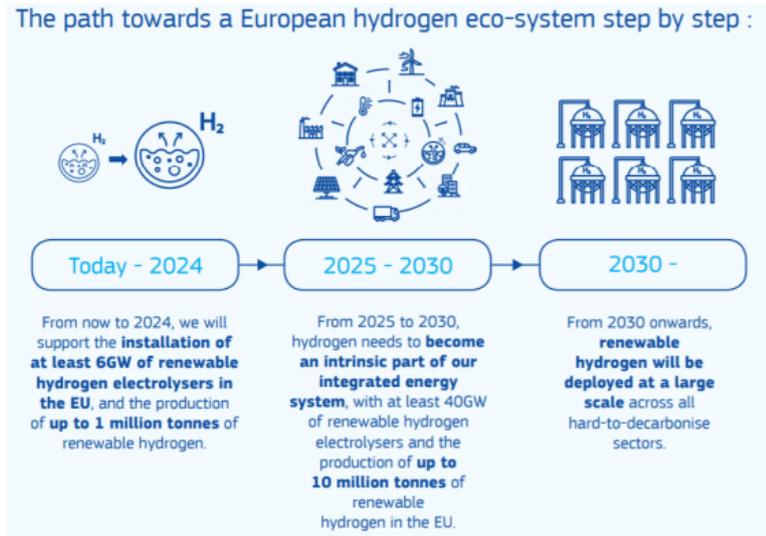


Figure 10: Development stages of the EU long term strategy.

*Source: Confindustria [35]*

The first stage, going from today until 2024, involves the installation of 6 GW of renewable electrolyzers on a European level, followed by the second stage which consists of reaching at least 40 GW of renewable electrolyzers with a minimum production of 10 tons of hydrogen. In this phase, the green carrier, would finally become a key resource for the European energy system, increasing already its demand in the industrial sector (for instance in steel production), expanding its use in heavy transportation, and balancing renewable-based electrical systems, also with the development of the so-called Hydrogen Valleys (specific geographical area where hydrogen supplies more than one end sector or application in mobility, industry and energy) [35]. Finally, the last and most ambitious phase, the technologies for green hydrogen should be mature enough for large-scale development, making a substantial contribution to the EU's decarbonization efforts by 2050 [35]. The production of electricity from renewable sources is, in fact, expected to increase significantly, being approximately a quarter of it used to produce renewable hydrogen [35].

Focusing on Italy, the Italian hydrogen National strategy, has estimated an hydrogen penetration of 2% in the final energy consumption by 2030 (corresponding to approximately 0.7 Mton/year), and of 20% by 2050[37]. Moreover, in order to tackle such ambitious goal, the government foresees the installation of approximately 5 GW of electrolysis capacity by 2050 [37]. Nevertheless, Italy is still debating on which strategy is better to

follow: entirely on-site production, on-site production coupled with energy distribution, or centralized production with hydrogen transport. Pros and cons of these different supply models should be primarily analyzed with a long-term perspective, looking at the cost-benefit of the entire system [37]. Additionally, this assessment should take into account the concentration of consumption and production that could result from the development of the aforementioned 'hydrogen valleys'. From a preliminary analysis, the major advantage of the first option (totally on-site), consists of the absence of transportation for both hydrogen and electricity. However, this could lead to unfeasible solution where space constraints have to be taken into account. On the other hand, centralized production could allow for economies of scale in electrolyzers and benefit from higher load factors of renewable sources located in sunny or windy areas, such as Southern Italy [37].

This study aims at implementing a novel methodology that allows to go beyond a cost-optimal solution, being it technically feasible but often politically or socially undesirable. The objectives are hence twofold. The first one consist on carrying out a technical and economic analysis of all the possible technologies that are needed for achieving the Italian green transition, considering the contribution given by each region. Moreover, a special focus on different system scales is needed, in order to highlight how the scenarios might be affected by an aggregated or a disaggregated system. Finally, in order to make the model more flexible, the second objective consists on finding a new methodology, that enables to map near to optimal solutions applying a cost relaxation of 5%, 10% and 20% starting from the optimal Pareto frontier. This would allow to find a wide range of feasible alternative solutions that bring useful insights for supporting policy-makers.



# 1 | Literature Review

In this chapter is described the systematic literature review that has been adopted based on the techniques explained by Kitchenham [45]. The advantage of conducting a systematic review, is that, if the results are consistent, it offers proof that the phenomenon is robust and can be applied across different contexts since it is characterized by a rigorous scientific approach consisting of five main stages [45] :

- Identification of research
- Selection of studies
- Study quality assessment
- Data extraction and monitoring process
- Data synthesis

For this case study, this process is one of the fundamental aspects, as it enables to address the starting points of the two objectives of the thesis: a detailed overview and characterization of the energy system of the Italian regions, and an understanding of the current state of art of methods used to generate alternative solutions. Moreover, this stages have to be carefully conducted accordingly to the study case of interest. This can be translated into specific key words and filters which allow to find the most suitable data.

## 1.1. Overview and characterization of the Italian energy system

### 1.1.1. Methodology

Figure 1.1 is a schematic representation of the literature research conducted for addressing the first objective. This first stage was composed by two phases: phase I characterized by two parallel researches and phase II which consisted of a final cross-check with the Italian Transmission System Operator (TSO) Terna.

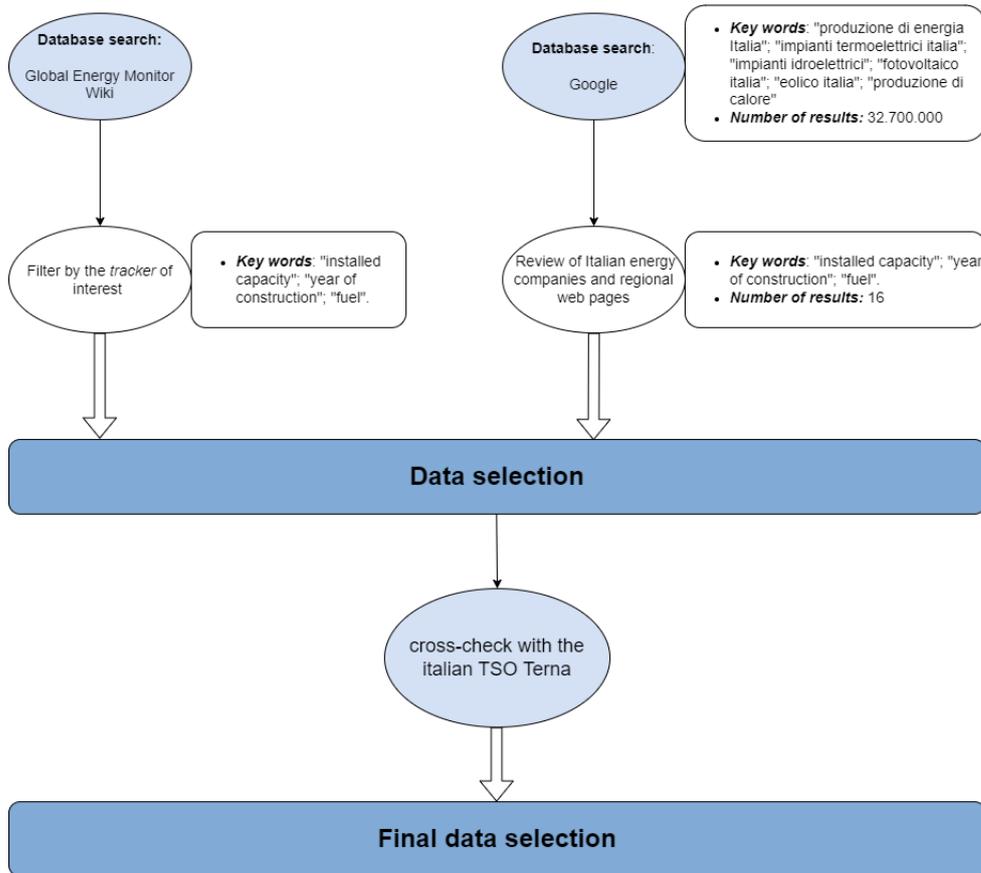


Figure 1.1: Schematic representation of the literature research for the characterization of the Italian energy system

Starting from phase I, the first research was done using a software platform developed by the Wikipedia Foundation: Global Energy Monitor Wiki (GEM Wiki) [6]. This platform is a repository containing numerous pages dedicated to energy initiatives, such as power plants, extraction sites, pipelines, terminals, solar farms, wind farms, and waste sites [6]. Each page functions as a detailed online fact sheet with references, evolving over time to provide information on project size, ownership, location, development status, financing, protests, alternative options, and more. The individual wiki pages serve, indeed, as the basis for GEM's research projects, known as *trackers*. The second step of this first research, consisted thereby in selecting the trackers of interest for this thesis and analyze the extensive datasets, maps, and summary tables for each specific energy projects' category.

The tool used for the second research was Google data base search, entering the specific key words reported in the scheme. The second step consisted in filtering the data reviewing only the official web-sites of all the Italian energy companies or regional official reports. Then the data for each energy power plant (for both researches) were selected

accordingly to the key words "installed capacity", "year of construction", and "fuel" (for non renewable power plants). Once these two parallel researches were concluded, the data selection was done cross-checking the results provided by both researches.

Finally, was done an extra validation between the final data gathered during the first phase of the research and the total installed capacity of each technology in each region provided by Terna, in order to further ensure the consistency of the data needed for the characterization of the energy system.

Finally, for what concerns the transmission system, was conducted a separate research considering only the data provided by Terna.

### 1.1.2. Results and discussion

Result	Reference	Result	Reference
A2A	[19]	Statistiche regioni 2020	[61]
Acea	[1]	Statistiche regioni 2021	[63]
Alperia	[20]	Statistiche regioni 2022	[64]
Alpiq	[21]	Produzione di calore	[16]
ARPAT	[22]	Piano di sviluppo 2021	[60]
Biopower Sardegna	[2]	Executive summary	[57]
CVA	[3]		
Edison	[23]		
Enel	[4]		
Enel Green Power	[24]		
Eni	[5]		
Fonti rinnovabili - Regione Toscana	[13]		
Iren	[25]		
Risorse idriche, Regione Abruzzo	[14]		
Rizziconi Energia	[15]		
Tirreno Power	[26]		

Table 1.1: Review of regional and energy companies' official web-sites (left side) and cross-check with Terna (right side).

Table 1.1 is a list of all the Italian energy companies and regional web-sites that were consulted and finally cross-checked with the data provided by Terna. Focusing solely on the data of the TSO, wouldn't have been sufficient since the phase I of the literature review was essential for gaining a more detailed overview of all the technologies present in each region, gathering data for the installed capacity and the year of installation. This latter data is indeed needed for the characterisation of the *residual capacity* of each power plant, that allows to build the model described in the second chapter of this report. Finally, for each bidding zone was considered an average value and the total installed capacity for the group of the regions of interest - go to Appendix A for the data gathered.

Finally, for the transmission system was enough to analyze all the available data provided by Terna [58, 59, 62].

The following table shows the maximum capacity set for the transmission lines, taking into account that in case of different seasonal capacities, has been considered an average value:

	<b>NORD</b>	<b>CNORD</b>	<b>CSUD</b>	<b>SUD</b>	<b>SICI</b>	<b>SARD</b>
NORD	-	5.869	-	-	-	-
CNORD	5.869	-	4.476	-	-	0.325
CSUD	-	4.476	-	6.136	-	1.064
SUD	-	-	6.136	-	2.859	-
SICI	-	-	-	2.859	-	-
SARD	-	0.325	1.064	-	-	-

**Table 1.2:** Capacities of existing transmission lines [GW]-reference year 2022.

*Elaboration from Terna [59]*

For what concerns the future development of the transmission net, also Terna is aligned with the international willingness of cutting the emissions by 55% by 2030. Being the Transmission System Operator (TSO), Terna has to align the grid's development to the national and international plans presented in the Introduction, being able to design a grid that can handle the progressive decarbonization of the energy system, with the consequent integration of renewable power plants. Because of that, in order to ensure a high stability and reliability of the transmission system, in 2023 has been published the Company's Grid Development Plan [58], which foresees an investment of over €21 billion from 2023 to 2032. Due to the need of guaranteeing a just, affordable, inclusive, and resilient transition, Terna launched the innovative Hypergrid project, in charge of boosting the HVDC (High Voltage Direct Current) transmission system doubling the exchange capacity between market zones from the current 16 GW to over 30 GW [58, 62]. Additionally, it has stated five new electricity backbones designed to integrate the renewables, minimising the land usage and the impact on the landscape [58].

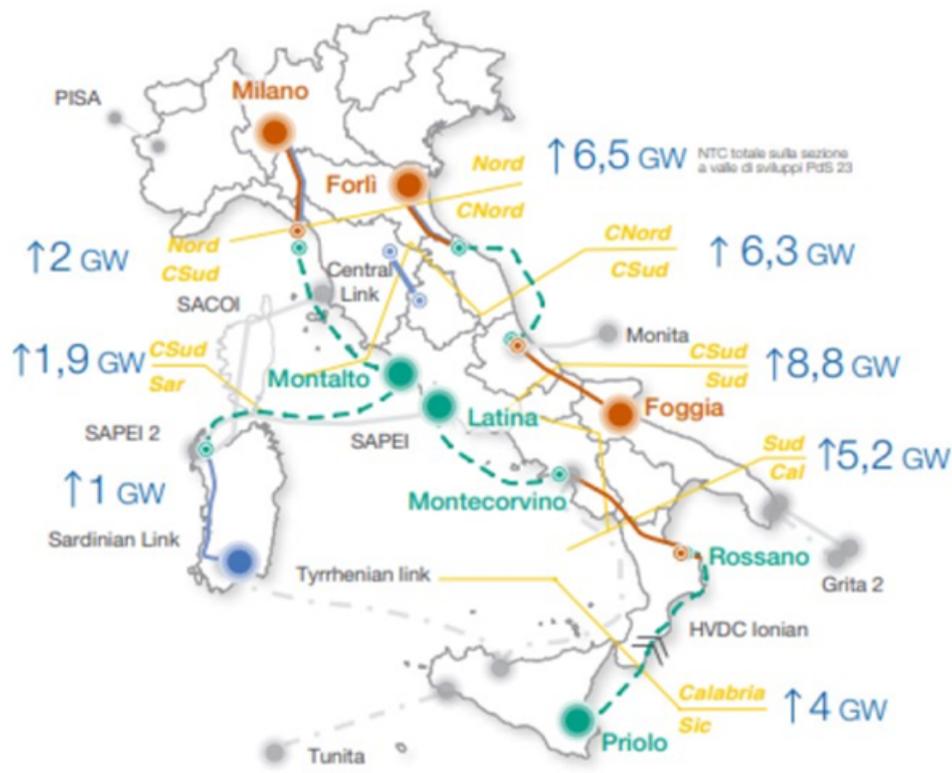


Figure 1.2: Representation of the future development of the transmission system.

*Source: Integrated report [62]*

Figure 1.2, is a schematic representation that summarizes Terna's development plan. The forecasted increased capacity by 2032, is divided among the transmission lines between the Italian bidding zones. The green lines represent the future marine HVDC in accordance to the previously mentioned Hypergrid project, whereas the orange and the blue ones are the future modernization of respectively AC/DC and AC connections [62].

## 1.2. Modelling to generate alternatives

### 1.2.1. Methodology

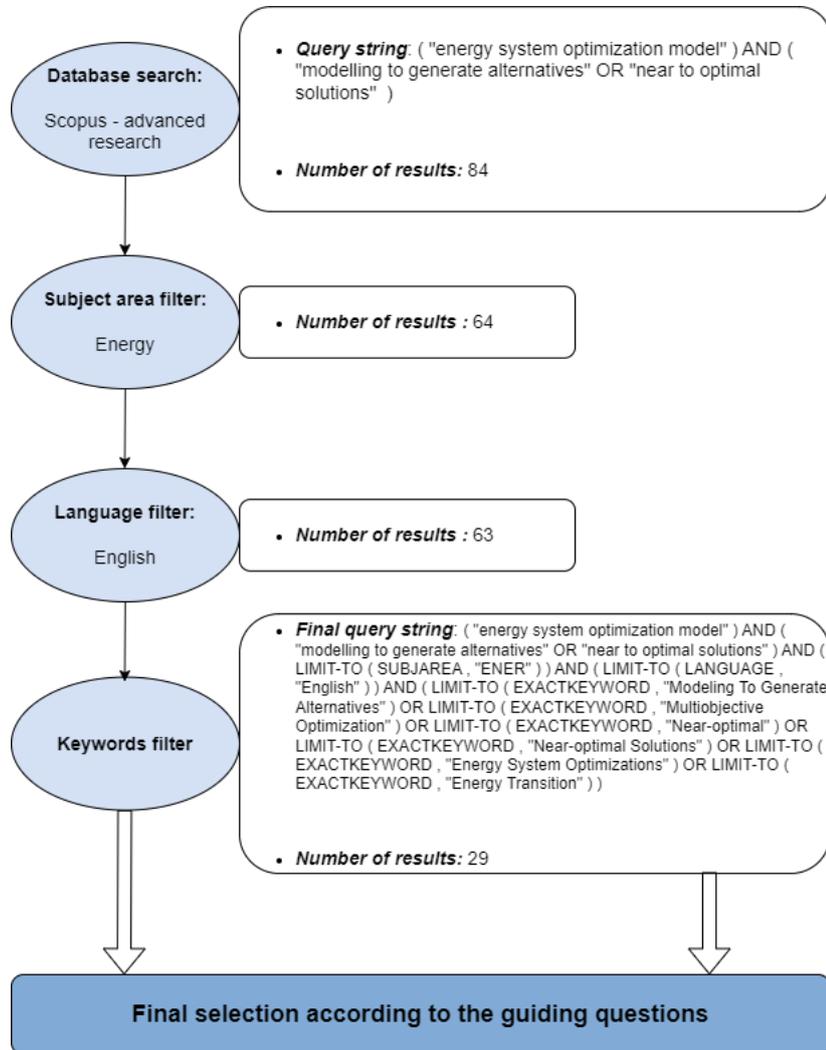


Figure 1.3: Schematic representation of the selection process

For the second objective of the thesis, was also performed a systematic literature review due to its rigorous scientific approach in finding relevant articles. Figure 1.3 represents the selection process carried out in order to ensure reproducibility and minimize the bias.

The database search was *Scopus-Advanced research*, using a series of filters and keywords for selecting the relevant articles. The search was not restricted to a specific time and produced an initial result of 84 papers. Then two filters were applied: one limiting the subject area to energy and the second one for the language - English. Afterwards, were selected the key words present in the *final query string* obtaining a final result of 29 articles. Finally, for selecting the final papers, was carried out an analysis of the abstracts in order to select the studies inherent to the scope of the thesis. The selection was

narrowed accordingly to the four guiding questions as shown in the following table:

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<b>Guiding questions</b>
What are the advantages of the modeling to generate alternatives?
How can near-optimal solutions be implemented?
What is the contribution that MGA can provide for energy planning?
How can alternative energy system scenarios support policy makers?

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Table 1.3: Guiding questions for the final data selection

### 1.2.2. Results and discussion

Author	Year	Method	Model	Scope
Lombardi et al. [46]	2020	MGA with SPORES	Calliope	Investigation of the possible configurations for the full decarbonization of the Italian energy system by 2050.
Pfenninger et al. [52]	2014	-	-	Challenges related to the models relevant to national and international energy policy.
Yue et al. [69]	2018	-	-	Uncertainties in ESOMs.
De Carolis [36]	2011	MGA	-	Introduction of MGA for producing insights that might not be realized with the standard least-cost optimality.
Chen et al. [32]	2022	MGA	Balmorel	Balance of GHG mitigation and land-use conflicts accepting higher system costs.
Trutnevyte [65]	2016	MGA	D-EXPANSE	How energy optimization models manage to simulate the real World energy transition.
Pedersen et al. [50]	2021	MGA and Mapping All Alternatives (MAA)	European electricity system model	Map a near-optimal region with solutions that are slightly more expensive than the optimum but better in terms of equality, land use, and implementation time.

Author	Year	Method	Model	Scope
Prina et al. [53]	2023	MGA	EnergyPLAN	Application of the methodology to the Italian case to support policymakers in evaluating energy system scenarios from a selection of optimal and near-optimal solutions.
Neumann et al. [47]	2021	MGA	PyPSA	Exploration of diverse technology mixes for the European power system.
Berntsen et al. [30]	2017	MGA	EXPANSE	Achievement of future possibilities and uncertainties of Swiss electricity supply scenarios.

Table 1.4: Literature review final data selection

The results provided by the literature review, can be divided into two groups: qualitative and quantitative. Studies such as the ones carried by De Carolis, Pfenninger and Yue et al., are more focused in describing what modelling to generate alternatives (MGA) is and what are the main challenges and contributions that they can provide to assist policy-makers and energy planning, whereas all the other researches quantitatively apply MGA with a specific method and model.

The first paper in Table 1.4 is: *"Policy Decision Support for Renewables Deployment through Spatially Explicit Practically Optimal Alternatives"*, 2020, Lombardi, F., Pickering, B., Colombo, E., Pfenninger, S. This has been used as the benchmark for this thesis, since the main scope is the investigation of the possible configurations for the full decarbonization of the Italian energy system by 2050, finding near-optimal solutions. In order to analyze these alternatives, Lombardi et al. [46], have developed a method to generate spatially explicit, practically optimal results called SPORES. The way through which they have been able to relax all the system cost, is through the creation of a new objective function that aims at minimizing decision variables, such as the new installed capacity of renewable technology, multiplying it by a weight accordingly on the theoretical maximum capacity for each technology that could be installed in each region. Through this method

they were finally able to prove what are the essential technologies for the decarbonization of the Italian system (photovoltaic and storage), while others have a larger flexibility of choice such as wind power. A similar approach was also carried by Trutnevyte [65], with the exception of adopting a randomized approach since the weights were sampled from a uniform distribution of set  $(-1,1)$ , bringing new insights as it enables to obtain also a uniform distribution of close to optimal solutions.

Another paper analyzed was the one by Chen et al. [32], which focuses more on a qualitative way of investigating near-optimal solution. In this case they implement a new objective function coping with the renewable technologies land use. On the contrary, Pedersen et al. [50] adopt a completely different approach, seeking in "Mapping All Alternatives" (MAA). Starting from the single least-cost solutions, they first define a tetrahedron of near-optimum with a constrain on the total cost of the system, and then the area is populated of all the possible near-to-optimal solutions. This is not solely a quite robust way of finding new solutions, but is also an interesting analysis done through the introduction of a new coefficient: the *Gini-coefficient*. In that study, it has been adopted in order to compute the energy produced in a certain region compared to what is actually consumed by the population.

Finally, the last paper analyzed, is the one by Prina et al. [53]. In the research, they adopt a heuristic method through an equality and a sharing function. The study is carried through the EnergyPLAN model, starting from a multi-objective optimization that enables to define the Pareto frontier in a total annual cost -  $CO_2$  emissions diagram [53]. Then they apply the two aforementioned functions: an equality function for preventing individual solutions from converging into a single optimal solution and a sharing function to ensure diversity [53]. Also in this case, the solutions found (8434 in total), aim at supporting policymakers in energy planning. The results proves indeed that it is possible to gain a reduction in the emissions, improving simultaneously the diversity of the energy system.

### 1.3. Conclusion

With the growing concern about environment and climate change, together with the willingness of increasing the energy security and analyze the impact of new cutting-edge technologies, energy policy has gained, in the last century, an incredible importance. There is indeed a growing interest in the use and study of energy models, since they are essential for providing insights to decision makers on climate and energy policy [69]. Long-term strategic energy planning, has hence gained importance especially for both industry

and policymakers, as it is crucial for making forecasts, cost analysis and investments [52]. Pfenninger et al. [52] group all the existing models in four main families: energy system optimization models, energy system simulation models, power system and electricity market models, and qualitative and mixed-methods scenarios. Accordingly to the scope of the research, these families can be then divided in two main categories: simulation/forecast and optimization/scenarios [52]. The main problem with these distinctions is that there is not one single model able to capture all the dimensions of interest for making a complete analysis of such a complex system. Many models can be based on narrow assumptions, generating often scenarios that can't be reproduced for finally failing to capture the fundamental changes in real-world transitions [65]. The main challenges summarized by Pfenninger et al. [52] include: resolving time and space, balancing uncertainty and transparency, addressing the growing complexity of the energy system, and integrating the human behaviour and social risks.

Especially nowadays, the development of the less polluting renewable technologies require a higher spatial and temporal resolution. Their reliability on weather and time, makes it essential to consider the variability of the capacity factor in time. It has been indeed proven, that models that do not consider the importance of time resolution, do not take into account both the variability of the demand and the supply, at the risk of overestimating the amount of demand met by the renewables [52]. Moreover, their unpredictability, variation through time and weather, and different capacity factors, make also the definition of the system's boundaries a core aspect of the model's implementation. For instance, for the Italian case, the southern regions are more suitable for the deployment of PV and wind power plants, due to higher capacity factors and land availability. The way in which the region of interest is divided, has thereby an impact on the results and hence on the different scenarios and forecasts analysed. The question then is, when defining the "scale" of the system, whether it is better to have a large-scale, that covers an entire region with a low resolution missing important aspects, or a small-scale, that covers a smaller portion of that location with a higher resolution but an increased complexity [52].

Due to these factors, the projection to 50 or even 100 years into the future is intrinsically uncertain [69]. When dealing for example with the most important family of energy models, which is the Energy system optimization models (ESOMs), Yue et al. [69] identify two main causes of uncertainty: parametric and structural. Most of the times, indeed, the modeler has to face difficulties in gathering the required data needed for implementing the model, and has to make assumptions referring to how some parameters might change in the future (e.g the energy demand or the costs) or also how some technologies, that are not present yet, might be characterized. Furthermore, there is the intrinsic uncertainty

of the *structural* equations that characterize the model, that could be linked also to the impact that politics, society, and culture might have in the real world [69].

Being costs the fundamental drivers of the energy transition, cost-optimal solutions do not take into account the human behaviour, public opinion, and social or political acceptance, which are all key factors that determine the final application or implementation of the forecasted policies [52]. This happens because, even though the real-world transition could be close to the cost-optimal scenario, it does not have to strictly follow it [65]. Studies have indeed so far proven, that stakeholders would accept a cost-relaxation up to 30%, meaning that they would accept this deviation from a cost-optimal solution paying more, if the system would reach other objectives [65]. For this reason, the modelling world has started to ensure diversity of scenarios, in order to include also the less likely real-world developments [30]. This task is one of the most critical challenges that modellers have to face, since most of the research studies focus on increasing the accuracy in order to have a better representation of the intrinsic complexity of the system [36]. However, in order to tackle this problem and make the models more flexible, new techniques have been adopted such as the modeling to generate alternatives (MGA) [36]. This method includes both a multi-objective optimization which leads in finding a set of optimal solutions that constitute the so called Pareto front, and the possibility of analyzing also the feasible *near-optimal* solutions, in order to develop alternatives that consider also the previously mentioned dimensions [36]. Therefore, employing this methodology addresses the requirements of policymakers to explore alternative solutions, even if they entail higher monetary costs. The MGA's methodology, proves beneficial when considering various paths that countries may choose in addressing the challenges of climate change. However, it's crucial to note that applying this method alone is insufficient when examining individual case studies. This is because there are numerous options for selecting new constraints, defining new objective functions, and adjusting parameters, leading to a consequent increase of complexity [52]. Consequently, it is essential to conduct a comprehensive study, analysis, and comparison of various MGA applications with the optimal single solution case, seeing how it affects the results.

One of the main problems related to Italy, is the discrepancy of the energy balance withing each regions and bidding-zones. For instance, just from a deeper analysis of the data gathered in section 1.1 , it is possible to note how northern regions are the ones with the highest energy demand, whereas the south is more suitable for the exploitation of renewable resources, having higher capacity factors and more room for hosting these power plants. Therefore, the north is usually forced to import electricity, implying that the other regions have a production that is higher than the one needed for meeting their

demand.

The problem is hence twofold. The first issue lies in the transmission system. A high import/export between regions, might create congestion along the line, stressing the infrastructure and putting at risk the regional energy security. The second problem is related to the land use, followed by a local backlash of the citizens.

When pursuing a cost-optimality, the risk is to accentuate this mismatch, as proven also by the results provided by Lombardi et al. [46]. For instance, when looking at Sardinia or Sicily, the least-cost scenario, features a great deployment of wind energy, higher than the local electricity demand, and consequently involving a high land usage, which might cause social resistance and territorial unfeasibility, being finally undesirable from a policymaking prospective.

For these reasons, policymakers are increasingly more interested in new scenarios, that are able to entail also other factors and consider sustainability in all its dimensions: economic, technical, social and environmental. As previously mentioned, having a higher number of solution can take into account several aspects that might be missing in the least-cost scenarios, together with the diverse real world nature.

Starting from the current Italian Reference Energy System, the aim of this thesis will be hence to consider the current state of art of the different methodologies for generating alternatives, in order to investigate further the contribution that each Italian region can provide for the national decarbonization. The methodology adopted will be carefully explained in the next chapter.



# 2 | Methodology

## 2.1. Italy as a case study

A Reference Energy System -Res- is the framework of the energy system used in an optimization model. When building it, the target, is to schematically represent as much as possible the real energy system of the case study under analysis. The Res must thereby include all the existing - and also stated- energy technologies, taking into account their costs and all parametric constraints in the period of analysis.

For this case study, was defined a Res for each Italian bidding-zone defined by Terna [57], thanks to the in-depth literature review described in Chapter 1 , gathering both economic and technical data for each technology. Being the renewables at the forefront of the Italian energy plan, it was essential to characterize them also through their capacity factor which varies accordingly to time and weather. It was addressed for on and off shore wind, and PV, through the use of the tool *Renewable ninja*[12], where the tilt and azimuth parameters for the PV were chosen accordingly to *Global solar Atlas*[7], whereas the turbine model selected, for wind power plants, was the most advanced one, assuming that it will be the one used by 2050: Vastas [68]. On the contrary, for what concerns hydro power-plants, the capacity factor was obtained as:  $cf_{hydro} = \frac{Gross\ annual\ energy\ production}{8760 \cdot Installed\ capacity}$ . This was done for a five years span -from 2017 to 2021- consulting the data provided by the Italian TSO Terna, and the final capacity factor in each region was finally given by an average value within the five years.

For what concerns heat production, due to the impossibility of mapping the existing heating power plants, the methodology followed consisted in converting the gross heat production [16], into the installed capacity considering a capacity factor of 1. Moreover, in order to take into account also renewable heat plants, the total heat installed capacity was divided considering the share of natural gas and bioenergy heat plants, according to EUROSTAT Italian energy balance for 2022 [39].

Finally, were considered also new cutting-edge technologies that haven't been implemented yet, but that are gaining a rapid momentum as they are essential for the Italian decar-

bonization. These include off-shore wind, steam methane gas reforming, steam methane gas reforming with CCS, natural gas power plants with CCS, methane pyrolysis, electrolysis and hydrogen storage.

The following figure, provides a scheme of the final Italian reference energy system:

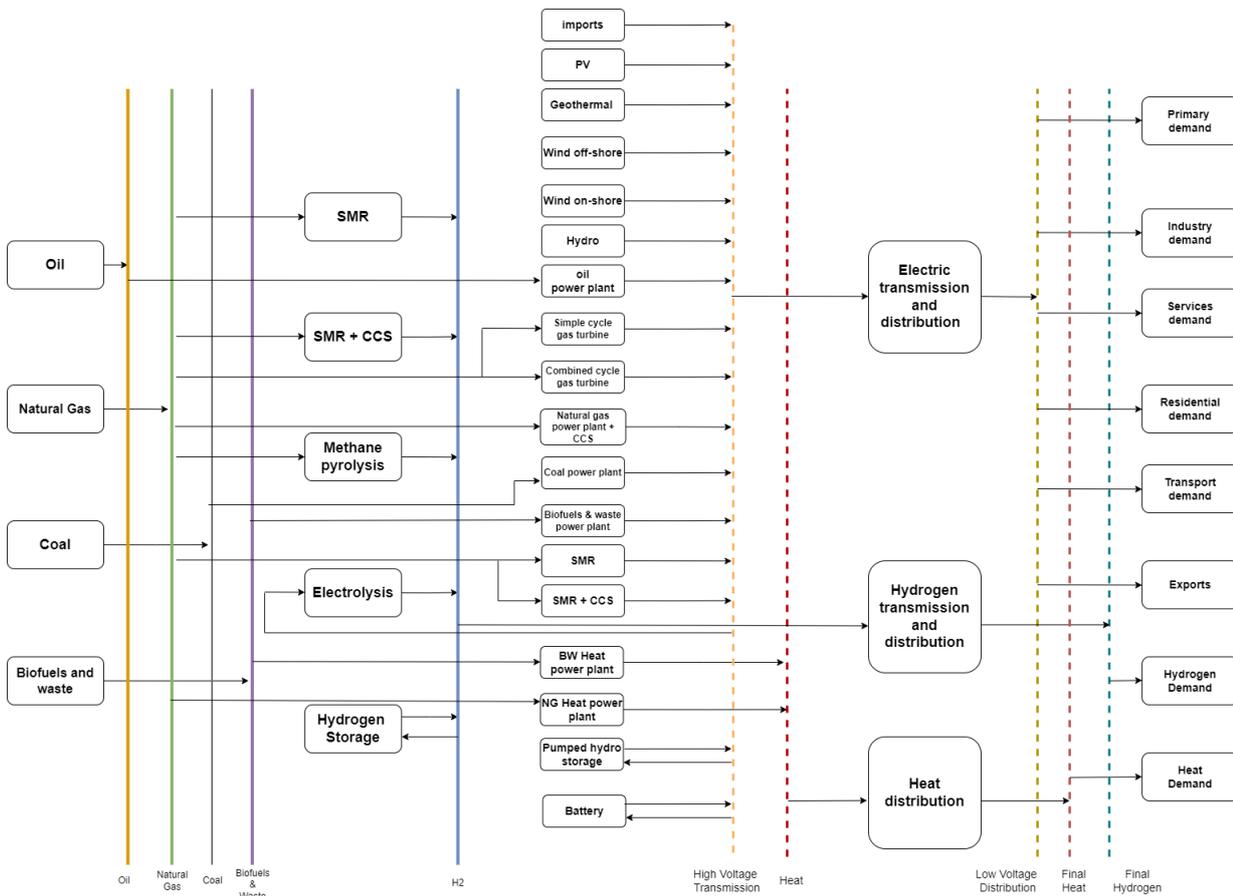


Figure 2.1: Italian Reference Energy System

Starting from the left side, at the beginning is possible to see the primary energy, consisting of: oil, natural gas, coal and bio-energy. Each of these resources, is then connected to its specific *carrier* (represented by the vertical lines), that supplies each so called *conversion* technologies (go to the List of symbols ?? for the acronyms used for each technology in all the scenarios) . On the contrary, for what concerns the renewable ones, since they do not have a *carrier in*, they are directly connected to the output of most of the technologies: electricity. This carrier has been modelled twice: first there is the high voltage transmission, connected to the corresponding *transmission technology* -in charge of transmitting and distributing electricity in order to allow also the import/export between regions- and finally there is the low voltage distribution, connected to the transmission

and in charge of satisfying the electricity demand divided in: primary, services, residential, transport, and export. Focusing on the latter one, this was coupled with the technology "imports", since they both model imports/exports with foreign countries. For a matter of simplicity, not every region has an export demand, since the connections with the external nations were modelled based on Lombardi et al. [46] article:

- Piemonte - France;
- Lombardia - Switzerland;
- Trentino Alto-Adige - Austria;
- Friuli Venezia Giulia - Slovenia;
- Abruzzo - Montenegro;
- Puglia - Greece;
- Sicilia - Malta.

Finally, the last part of the Res consisted in modelling the demand. Still referring to the electricity, for this case study it was divided into five main sectors: primary, residential, industry and services. Moreover, when the bidding zone exchanges electricity with foreign countries, also exports are considered in the demand. From year 2020 to 2022, the data were taken from Terna's regional statistics [61, 63, 64], whereas the forecast by 2050, follows the trend defined by the European reference scenario 2020 for Italy [33].

For what concerns heat, it was modelled as electricity -one heat carrier and one final heat that satisfies the final demand- with the only difference that there is no heat transmission, but only distribution -meaning that there are no imports/exports between regions.

Finally, considering the previously defined Italian stated policies, also hydrogen was included. This, is hence produced by steam methane reforming, steam methane reforming coupled with carbon capture and storage, methane pyrolysis, electrolysis and hydrogen storage. In this case, for what concerns transmission and distribution, the costs and the connection between regions were assumed to be the same of the current gas pipelines, as they are forecasted to be converted into hydrogen ones [27]. In 2020, the final consumption of hydrogen in Italy was of approximately 16 TWh, equivalent to the 1% of the final energy consumption at the national level and corresponding to around 480,000 tons per year [37]. Since the specific hydrogen demand for each bidding zone was not available, the division of the total was done accordingly to the share of the final electric consumption of each region according to the previously reported Terna data.

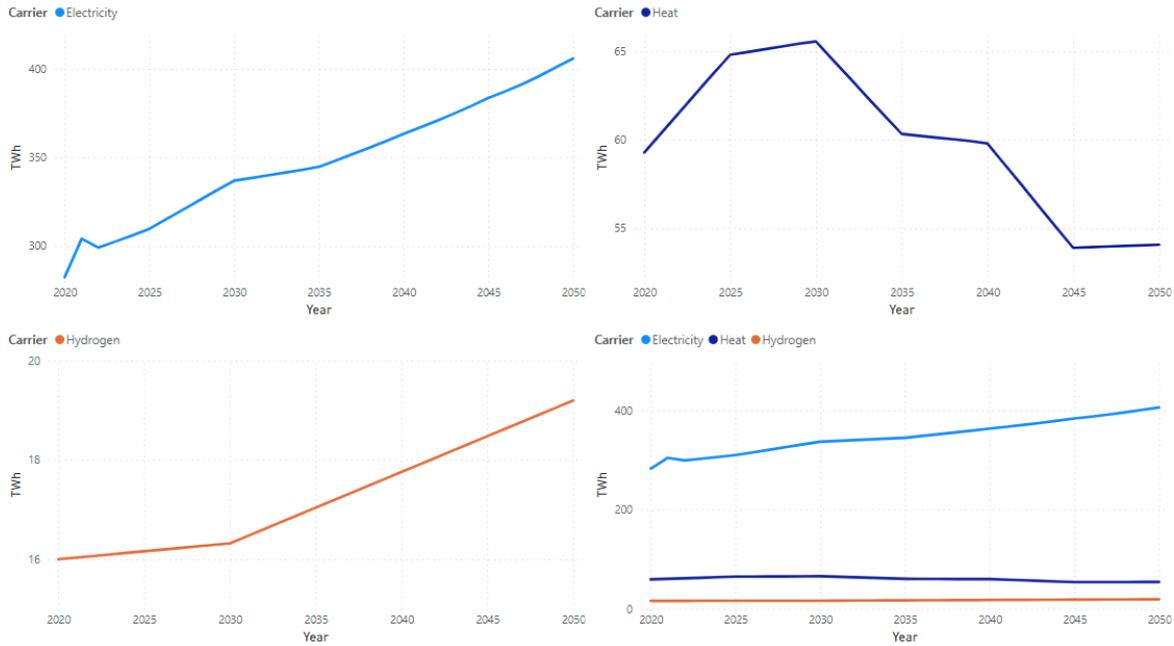


Figure 2.2: Final energy consumption forecast.

*Elaboration from: EU Reference scenario 2020 [33]*

## 2.2. Different system scales

As stated in Section 1.3, one of the most important challenges when defining the reference energy system, lies in the space resolution [52]. Especially for the Italian case, the location of the growing deployment of renewables, can have a great impact on the costs and on their generation potential [52]. In order to highlight this aspect and prove further the contribution that the Italian regions can provide to the decarbonization, a part of the study consisted in comparing a single region scenario to a multi region one.

Starting from the latter one, it was modelled dividing Italy into six bidding zones defined by Terna [57]:

- NORD: Valle d'Aosta, Piemonte, Lombardia, Trentino, Veneto, Friuli, Emilia Romagna, Liguria;
- CNORD: Toscana, Umbria, Marche;
- CSUD: Lazio, Abruzzo, Campania;
- SUD: Molise, Puglia, Basilicata, Calabria;
- SICI: Sicilia;
- SARD : Sardegna.

This allowed to specify in a more detailed way the capacity factor for each zone together with the specific energy demand. Moreover, having a *multi-node* scale, means also to consider the transmission system and the benefits that it brings especially when addressing land usage, and the energy supply and demand mismatch between regions. Starting from the capacity of the transmission lines defined in Table 1.2, the maximum capacity by 2050 was estimated accordingly to Terna’s Development Plan described in Section 1.1.2. First was estimated the capacity reached by 2032, then between 2023 and 2032 was done a linear interpolation between the two values, and then, from 2032 on, was considered the final maximum capacity reached in 2032.

Connection	Increased capacity	Max total capacity by 2032	Unit of measure
NORD-CNORD	+8.5	14.369	GW
CNORD-CSUD	+6.3	10.776	GW
CNORD-SARD	-	0.325	GW
CSUD-SUD	+8.8	14.936	GW
CSUD-SARD	+1.9	2.964	GW
SUD - SICI	+9.2	12.06	GW

Table 2.1: Maximum capacity of the transmission system by 2032 [62].

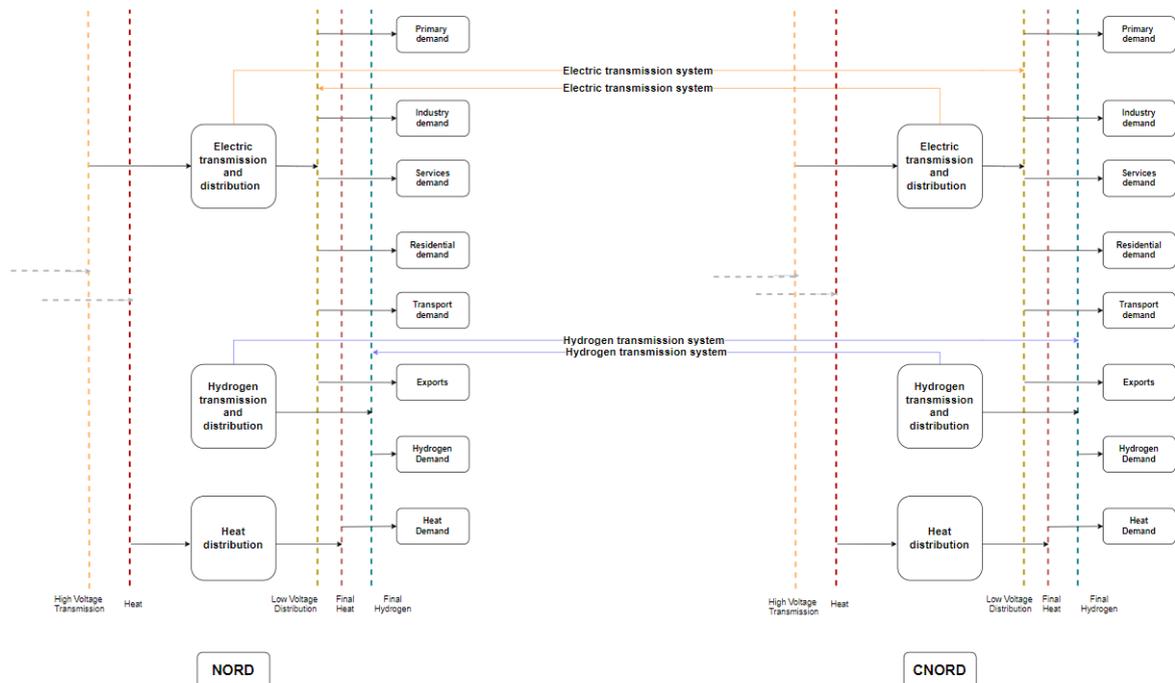


Figure 2.3: Schematic representation of the transmission system between regions.

Figure 2.3, represents schematically how the connections between regions were modelled. In this case, is reported only the interlink between two regions, NORD and CNORD,

since the logic is the same for all the others. Through the connection, each region can benefit from the surplus of the energy production coming from another region. This is possible since, whenever it is needed, the overproduction is directly connected to the *Low voltage distribution* of the neighboring bidding zone. Finally, in the figure is also shown the hydrogen transmission system. However, for this part, was not possible to carry out such a detailed study as for the case of electricity, since the infrastructure hasn't been developed yet. Since the capacity exchanged is forecasted to reach still quite low values, there was no need of setting a cap for the capacity, whereas, for what concerns the costs, were adopted, as previously mentioned, the same as the current gas transmission system based on the data provided by Lombardi et al. [46].

On the other hand, for what concerns the single region scenario, it was modelled summing up the data of each bidding zone and considering an average value for the capacity factor of the renewable resources. Moreover, there is no need of considering the transmission system having a single node.

The two systems have, thereby, a different size due to the different "boundaries" considered: the single-region with a larger scale and lower resolution, and the multi-region with a more detailed scale and a higher resolution. In Chapter 3, will be carefully analyzed the consequences and the benefits of adopting one scale instead of another one.

### 2.3. Hypatia

Hypatia is an open source energy system optimization modelling framework written in Python and developed by the Politecnico di Milano research group SESAM [9]. This model is suitable for optimizing both the operation and planning mode of energy systems in short-term and long-term time horizons. In the first, the model optimizes for the operational analysis in one year, while in the second, Hypatia optimizes for continuous capacity deployment analysis over a wider years span. However, for the aim of this thesis - decarbonization of the Italian energy system by 2050- only the Planning mode is of interest. Hypatia is inspired by other energy system optimization models such as Calliope and OSeMOSYS. It is based on CVXPY Domain-Specific Language , which is a Python-embedded modeling language for convex problems [9], since it enables writing the optimization problem in a natural way following plain mathematical rules.

Hypatia is thereby designed with the following main objectives [9]:

- It uses excel-based input data in order to ensure an easy interaction with the model.
- Entails different categories of technologies such as supply, conversion, conversion-

plus, transmission and storage.

- It is possible to consider different sectors of the energy system such as electricity, heat, hydrogen and others.
- Resolution in space through the possibility of following both a single-node or multi-node approach, with the possibility of implementing interconnection among different regions.
- Resolution in time determining "Years" and "Timesteps" tables.

For what concerns the structure of the model, it is divided into different modules, which are Python files that define the functions of the model itself. The main ones are:

- *Build.py*

It contains the core of the model, entailing the definition of the problem in CVXPY for planning and operation modes, the objective functions and the optimization required. The latter one can be chosen at the will of the user, and it can be either *Single* or *Multi*. The first one has been used for the least-cost scenarios, whereas the second one is implemented by a function called "solve\_MO" which takes as an input the number of solutions required and the path where to display the Pareto curve in case of a multi-objective optimization - see Section 2.4.

- *ModelVariables.py*

It defines all the problem variables.

- *Main.py*

This is Hypatia's interface module. It has the model's class with all the methods needed to create, solve and save the results.

Furthermore, being an optimization model, there are so far two possible objective functions that can be used accordingly to the goal of the research. They are both defined in the "Build.py" file under the name *final\_global\_objective* and *final\_emission\_objective*. The first one is an economic objective function which minimizes the overall costs and is usually used for the base case or stated policies scenarios. On the contrary, the second one minimizes the overall emissions and enables to conduct more interesting optimizations such as a multi objective one, where the combination of the two enables to explore the set of optimal solutions in the Pareto Frontier carefully explained in Section 2.4.1.

In order to build the scenarios, is essential to start from the Reference Energy System described in Section 2.1. This can be modeled starting from defining the sets on a global and then regional level (the number of regions varies at will of the users). In this first

step is thereby required to define all the already existing or stated technologies, the unit of measures, the emissions, the years, the time-steps, and the carriers used. For this application, the technologies and the carriers are the ones defined in the Italian Res in Section 2.1, whereas the years span go from 2020 to 2050 with a 24-h time-step resolution.

Once the sets have been defined, it is possible to have a first run of the model which will automatically generate a parameter folder, containing the global and the regional parameter excel files together with the additional connection excel file if it has a multi-node space resolution. In each excel file, there is the possibility to specify all the other parameters that are essential for building the model: specific costs (investment, fixed, variable, taxes and subsidies), specific emissions, carbon tax, min/max/new total capacity, min/max production, technology capacity factor, resource capacity factor, technology efficiency, annual emission limit, economic and technical lifetime, discount rate, interest rate, demand and finally the residual capacity for each already existing technology.

## 2.4. Modelling to generate alternatives

The starting point of the research consisted in running the least-cost base case. For this application have been considered, as stated policies, the Italian Integrated National Energy and Climate Plan 2019 (PNIEC2019), the PNIEC2019 coupled with the Long Term strategy [10] and the most recent Integrated National Energy and Climate Plan 2023 (PNIEC2023) coupled with the Long Term strategy [29] - the values for the minimum total installed capacity and the renewables' share are reported in Appendix B.

After carefully exploring MGA methods in Chapter 1, this study follows a multi-objective evaluation in order to find the Pareto Frontier optimal solution curve and then is defined a new methodology that allows to map the *near to optimal* area which spans from the maximum emissions (corresponding to the minimum costs) and the maximum costs accordingly to the cost-relaxation chosen.

### 2.4.1. Multi - objective optimization

The Pareto Frontier is a set of optimal solutions, found through a "compromise" between different objectives. For this application, the two objective functions taken into account were the minimization of the Net Present Cost (NPC) and the minimization of  $CO_2$  emission. The study seeks at finding 10 solutions that span from the least-cost optimal solution with minimum NPC and maximum emissions, and the emission optimal with minimum  $CO_2$  emissions and maximum NPC. Based on the formulation reported by

Stevanato et al. [55], the problem can be expressed as follows:

$$\begin{aligned}
 & \text{minimize} \quad \mathbf{f}(x) = [f_1(x), f_2(x), \dots, f_j(x)], \\
 & \text{subject to} \quad y_i(x) \leq 0, \quad i \in 1 \dots m, \\
 & \quad \mathbf{x} = [x_1, x_2, \dots, x_n].
 \end{aligned} \tag{2.1}$$

where  $\mathbf{x}$  represents the decision variables and hence  $f(x)$  is the  $j$ -dimensional vector of the objective functions subjected to the  $\mathbf{m}$  inequality constraints.

Also the algorithm is the same presented in [55], which enables to transform the multi-objective optimization into several single-objective ones. In this case, calling  $f_1(x)$  the NPC and  $f_2(x)$  the emission objective function, was first optimized  $f_1(x)$ , maximizing  $f_2(x)$  and then was performed the optimization of  $f_2(x)$  maximizing  $f_1(x)$ . At this point, the Pareto Function was built accordingly to the number of the solutions  $p$  required by the user. Each interval, going from the previously described two optimal points, was characterized by  $step = \frac{(Max\_emissions - Min\_emissions)}{(p-1)}$ , which allowed to obtain a  $p$ -dimensional vector  $F_2$ . Then, a single objective iteration cycle was performed, with  $f_1(x)$  as an objective function and  $f_2(x)$  as a constraint which changed its value for each iteration as shown in Eq. 2.6 [55]:

$$\begin{aligned}
 & \text{minimize} \quad \mathbf{f}_1(x) \\
 & \text{subject to} \quad f_2(x) = F_2(it), \quad it \in 1 \dots p, \\
 & \quad \mathbf{x} = [x_1, x_2, \dots, x_n].
 \end{aligned} \tag{2.2}$$

Combining an economic and an emission objective function, can bring interesting insights, being especially the latter crucial for focusing also on environmental aspects, often leading to more complete and accurate results and evaluations [55]. In order to highlight the pros and the limitations of a multi objective optimization for the case of Italy, was carried out a comparison within all the 10 optimal solutions, considering the NPC increase, the emission decrease and the carbon cost estimated as:

$$Carbon\ cost = \frac{\Delta\ Costs[\$]}{\Delta\ emissions\ [tonsofCO_2]}. \tag{2.3}$$

This is a very useful indicator since it quantifies how much is necessary to pay for reducing the emissions, being the  $\Delta Costs$  the difference between the costs of solution  $x$  (with  $x$  spanning from 2 to 10 in this case) and solution 1 (which is the min NPC), and  $\Delta emissions$  the difference between the emission in the solution 1 (being the most polluting) and

solution  $x$ .

### 2.4.2. Near to optimal solutions

After exploring the Pareto Frontier for this case study, it is possible to further investigate the region between the curve and the maximum NPC allowed. This latter value is obtained increasing the NPC of the least cost solution accordingly to the cost-relaxation  $\epsilon$  as shown in Eq.2.4

$$NPC_{n2o} \leq NPC_{least\_cost}(1 + \epsilon) \quad (2.4)$$

As stated also in the literature review, each study seeks indeed near optimal solutions accordingly to a new objective function, which is arbitrary. For this application, the new objective function  $f_3(x)$  minimizes the land usage defined as:

$$Total\_land\_usage = \sum_r^R \left( \sum_n^N P_n l u_n \right)_r \quad (2.5)$$

where  $P_n$  is the installed power of source  $n$  times the specific land usage  $l u_n$ , in the Italian region  $r$ . The input data adopted with the related references are reported in Appendix A. It is important to note, that these values have been obtained assuming that space and installed capacity follow the same linear trend. However, despite the objective function changes, this can be still considered a cost optimization that differs from the least-cost due to the cost relaxation  $\epsilon$  that defines the *range* of the optimization allowing to find solutions that are near to optimal.

In order to implement a new *optimization mode* into the model, was necessary to bring some changes into the main modules described in Section 2.3 - see Appendix E for the algorithms. First, was added a new function in the "ModelVariables.py", as it was necessary for the final calculation of the land objective. Then was added the most important function called "solve\_n2o" in the core module of Hypatia: "Build.py". The function is similar to the multi-objective one previously explored, with the exception that the user has to define also the cost relaxation. The starting point consists in finding the two optimal extremes: the least-cost and the least-emission (which has to be constrained to the maximum NPC allowed). Then, accordingly to the number of solutions required by the user, is first generated an "emission\_list", which stores all the emission values that span from the two optimal solutions previously found with the same *step* described in the multi-objective optimization. Then, once the emission list is found, follows the core part of the near to optimal optimization.

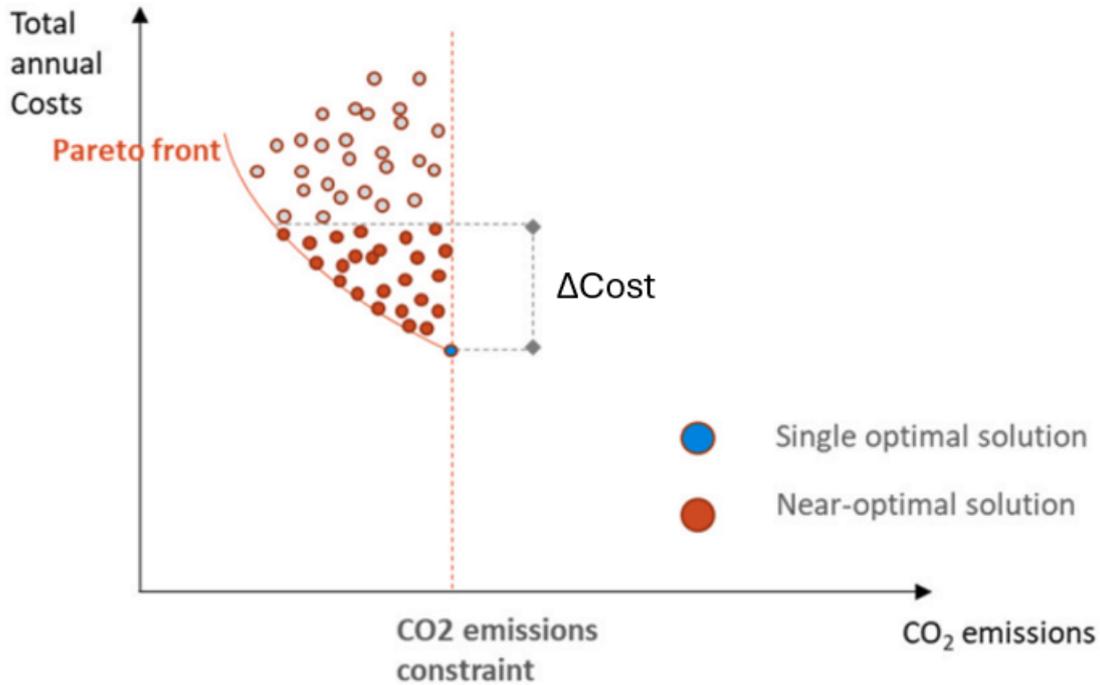


Figure 2.4: Near to optimal area.

*Adapted from [53]*

Figure 2.4, shows the area of interest for the investigation of the near to optimal solutions, which goes from the optimal Pareto front and the maximum NPC accordingly to  $\Delta$ Costs that varies based on the cost relaxation. As previously mentioned, the objective function becomes the minimization of the land usage subjected to the costs constrain, which cannot be higher than the maximum net present cost. However, since the willingness is to find maximally different solutions, was set also another constrain on the emissions. Through a *for* loop, is possible to make sure that each solution is different from the others as it has a higher emission cap compared to the previous one.

$$\begin{aligned}
 & \text{minimize} && \mathbf{f}_3(x) \\
 & \text{subject to} && f_2(x) \leq F_2(it), \quad it \in 1 \dots p, \\
 & \text{subject to} && f_1(x) \leq Max\_NPC, \\
 & && \mathbf{x} = [x_1, x_2, \dots, x_n].
 \end{aligned} \tag{2.6}$$

Additionally, for the near to optimal solutions, were selected 10 solutions for each cost relaxation. Accordingly to Trutnevte [65], the cost relaxation can rarely reach a maximum value of 30% only if "the system would reach other goals, e.g. related to environmental

concerns or energy independence." Because of this, the cost relaxation values were set in this case to 5%, 10% and 20%, which is also in accordance to the study of Lombardi et al. [46], being it the benchmark of this thesis.

Finally, the comparison between the different scenarios was done based on three parameters: cumulative emissions, system's load factor for year 2050 and carbon cost (already defined in Equation 2.3).

$$Load\ factor_{2050} = \frac{Total\ Energy\ Production_{2050}}{Total\ Installed\ Capacity_{2050} \cdot 8760} \quad (2.7)$$

# 3 | Results and discussion

This chapter will carefully explore the results obtained by applying the methodology explained in Chapter 2. It will first start from analyzing the Stated policy scenarios least-cost solution, followed by the multi-objective optimization analysis. Moreover, for both sections, there will be an additional analysis in charge of highlighting pros and cons of considering different system scales (multi-region vs single-region).

## 3.1. The stated policies

The first three least-cost scenarios analysed, are the ones based on the Italian intended policies: PNIEC2019 [27] and PNIEC2019&longterm [10, 27]. Additionally, has been studied also the *possible* future stated policy, which is the latest PNIEC2023&longterm [29], since it is still under the evaluation of the European Commission.

The following figures show the results for the installed capacity for each carrier -electricity, heat and hydrogen - and scenario:

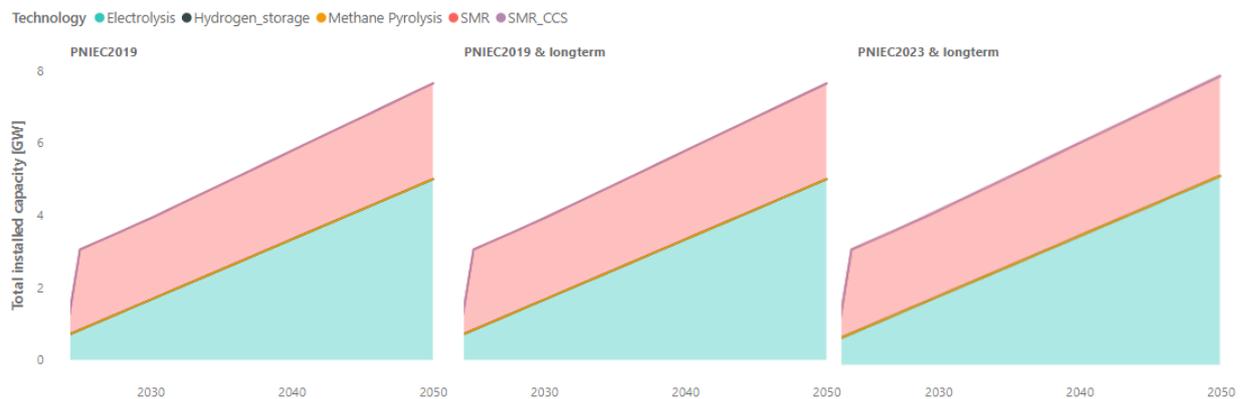


Figure 3.1: Total installed capacity - hydrogen.

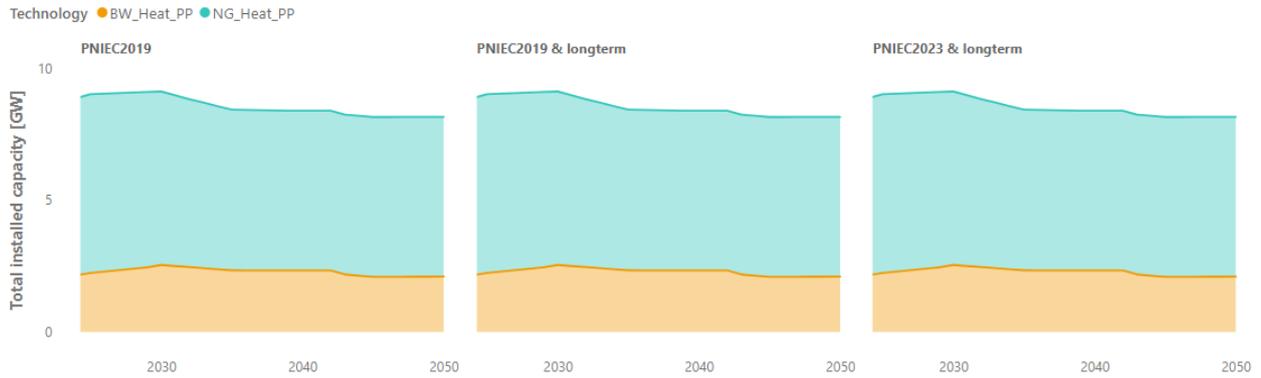


Figure 3.2: Total installed capacity - heat.

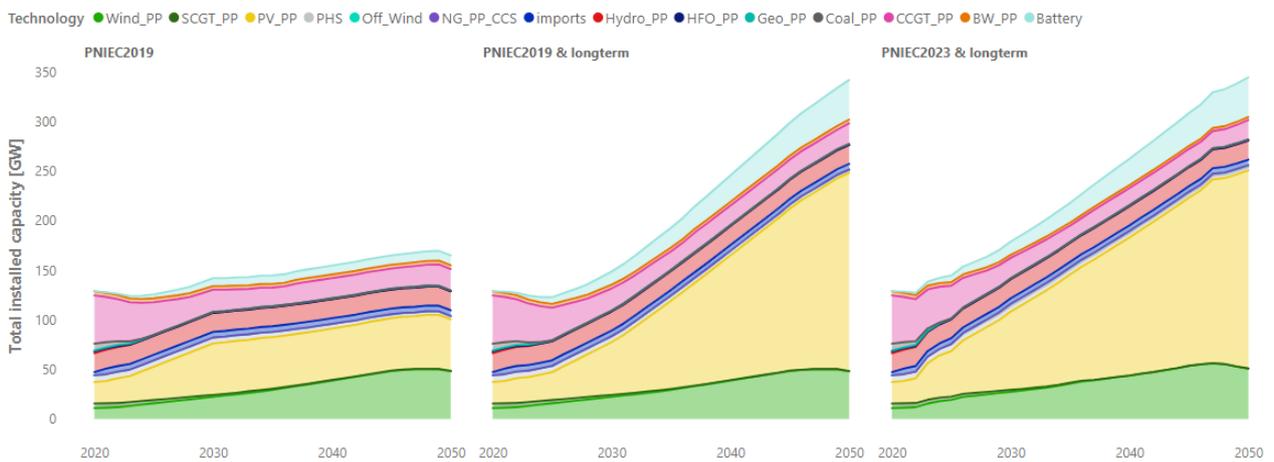


Figure 3.3: Total installed capacity - electricity.

Focusing first on Figures 3.1 and 3.2, it is possible to note that on a global level, the forecasted total installed capacity is the same within all the scenarios for heat and hydrogen. That is due to the fact that the stated policies for these two carriers are the same.

On the contrary, there is a great change in the total installed capacity of electricity. Because of that, this part of the study will focus more on this carrier - see Figures C.1, C.2 and C.3 for the installed capacity for each bidding zone. Starting from Figure 3.3, on a global scale, the main changes occur in the total PV power plants installed and electrochemical storage. The reason lies mostly in the addition of the Long term strategy plan [10], which intends to install a minimum capacity for the electrochemical storage (that is fourfold with respect to the PNIEC2019), and 200 GW for the PV power plants by 2050. All these considerations, are also reflected in the installed capacity for each bidding zone.

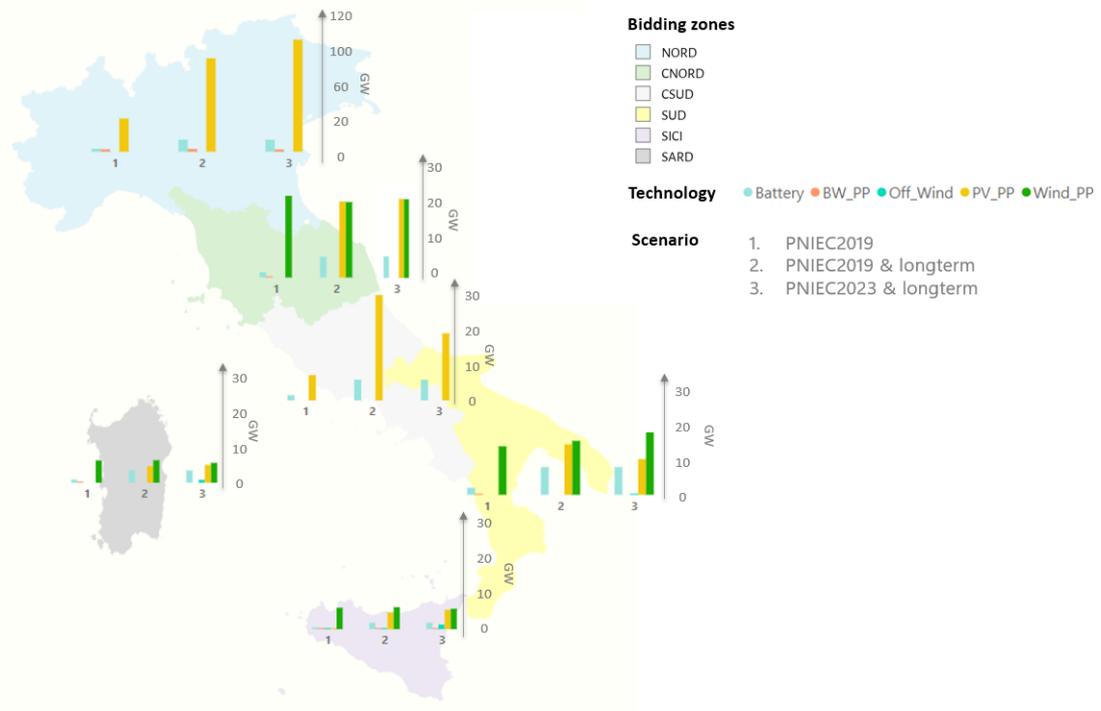


Figure 3.4: Installed capacity - year 2050.

Simply looking at Figure 3.4, in all the zones there is quite a huge change in the installed capacity of these two technologies. The one with the highest values is always NORD, due to the highest energy demand and the lack of other renewable resources such as wind power plants. Then, also in regions where in the original PNIEC2019 there isn't a great development of PV power plants such as SICI, SARD, SUD and CNORD, is possible to assist in an increase of the installed capacity. The same can be said about wind. Only in two regions there is the total absence of this technology by 2050: NORD and CSUD. For the first it is related to a lack of high capacity factors and for the second because it is preferable to keep installing it in other regions instead of CSUD - see Figures C.1, C.2 and C.3. Also in this case, the overall capacity is slightly higher in PNIEC2023&longterm than in the other scenarios due to higher targets by 2030 for the installed capacity (28.14 instead of 19.3 GW) and the RES share (65% instead of 55%). Finally, all the intended policies state also the development of a new cutting-edge technology: off-shore wind power plants. For PNIEC2019 and PNIEC2019&longterm, the results are the same since the minimum total global capacity was set to 0.3 GW [27] and the model was free to choose which bidding zones are the most suitable for its development: in this case SICI. However, with the newest PNIEC23, the minimum capacity has to reach 2.1 GW from 2030 on. Because of that, it is possible to assist on a forecasted potential development of off-shore wind not only in SICI, but also in SARD and SUD, being the ones with the highest

capacity factors.

Furthermore the study has allowed to analyse also the contribution given by the transmission system thanks to the multi-region configuration.

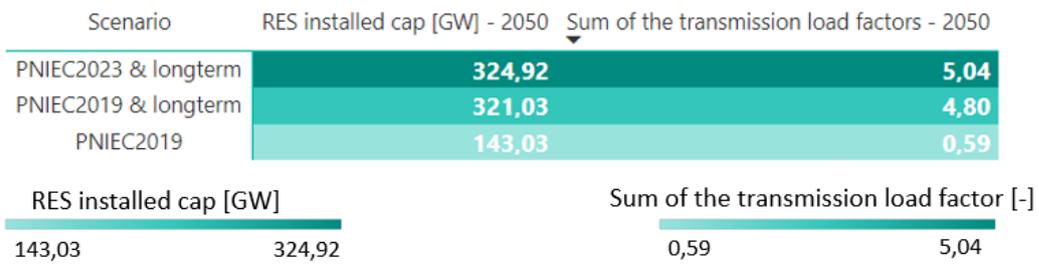


Figure 3.5: Total RES installed capacity and sum of the transmission load factor - year 2050.

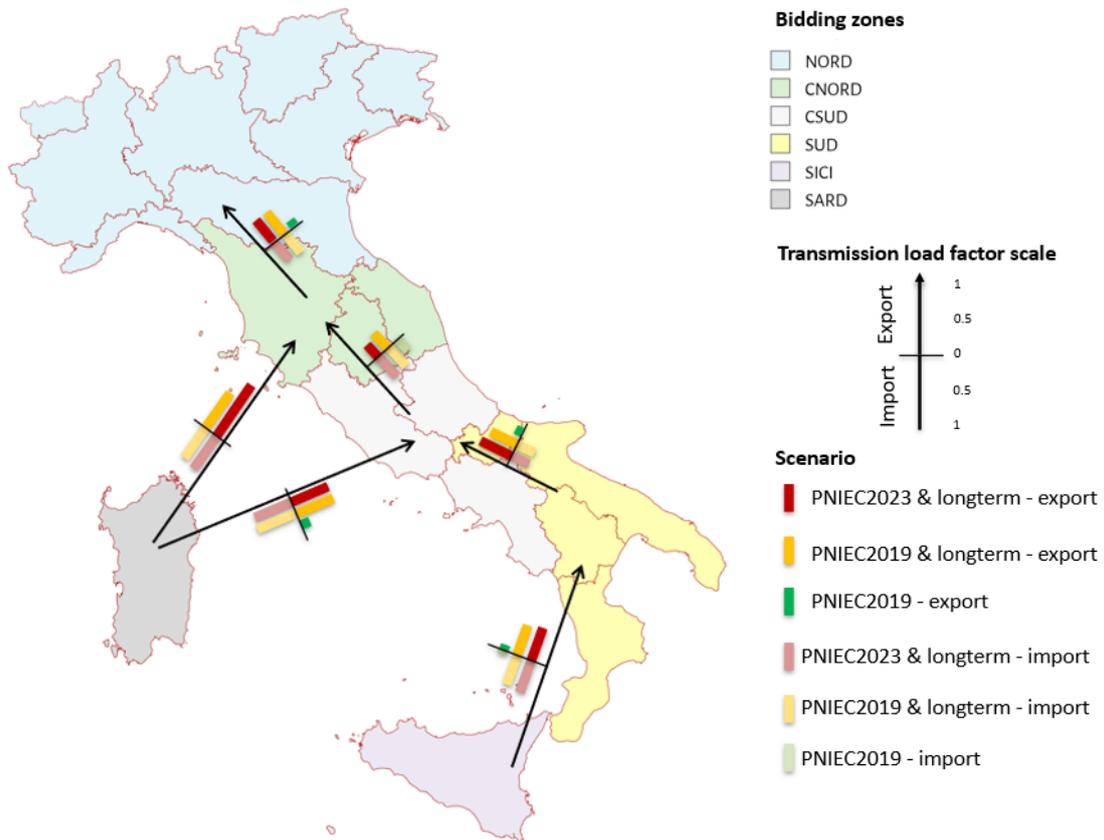


Figure 3.6: Transmission load factor - year 2050.

Figure 3.5 shows that a higher development of renewables, results also in a higher load fac-

tor from the transmission system which benefits the RES exploitation and reduces the land usage. This is related to the different capacity factors, and hence technology availability, that changes across the regions: whenever there is an overproduction, each region is able to export it to the neighbouring one if needed. In its newest development plan 2023, Terna has indeed pledged a great increase of the transmission system to be reached by 2032 (see Table 2.1), as it has taken into account the RES roll-out, with the intention of "promoting the integration of renewable sources, develop international interconnections, increase the security and resilience of the electricity system, and invest in grid digitalisation" [58]. Being indeed the maximum transmission system total capacity fixed, the only factor that changes within the three scenarios is the effective transmission line capacity exploited, reflected by the load factor, estimated as:  $Load\_factor = \frac{Capacity\ exploited}{Maximum\ Potential\ Capacity}$ . Figure 3.6, shows how the transmission system is exploited throughout the Italian regions. Each line represents the interlink between the bidding zones, being the peak of the arrow the maximum load factor equal to 1. Then, each bar represents the effective load factor exploited for each scenario by 2050, considering both the imports and the exports. Being the most ambitious possible future stated policy scenario PNIEC2023&longterm, the one with highest RES installed capacity, it is also the one with the highest values. Moreover, it is possible to note also the problem already mentioned in Section 1.3: being the NORD the zone with the highest demand, it still keeps being one of the major importers, while Sardina, Sicily and SUD keep being the major exporters due to their great resource availability and low energy demand.

Furthermore, although accordingly only to the results of PNIEC2019, this huge increase of the installed capacity of renewable power plants is not needed for reaching the climate goals and respecting the emission constraints, this would allow to decrease further the need of natural gas power plants as shown in the following Figure:

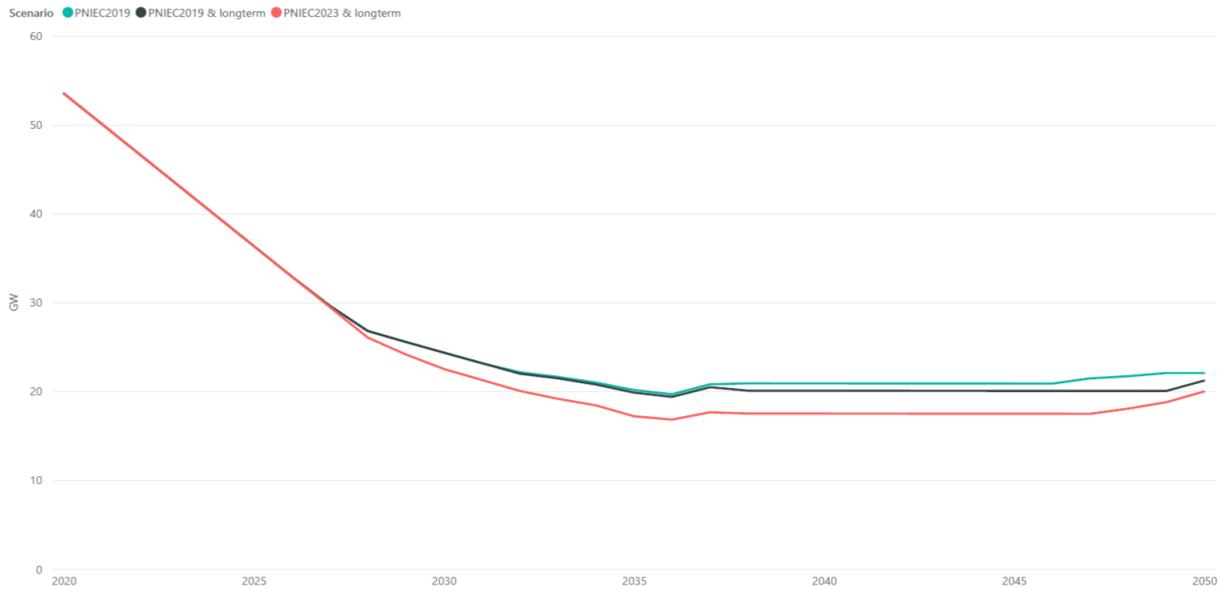


Figure 3.7: Total installed capacity of natural gas power plants.

All the scenarios face indeed a decrease in the total installed capacity, but the highest change is seen in PNIEC2023&longterm, due to the roll-out of renewables. This benefits not only the environmental impact, but also the Italian energy security, being even more aligned to the REPowerEU plan [34] that aims also at reducing the European Union's reliance fossil fuels that might come from politically unstable countries.

Moreover, even though the last possible scenario states the greatest RES expansion, the cumulative costs are not the highest and do not differ so much from the cheapest PNIEC2019.

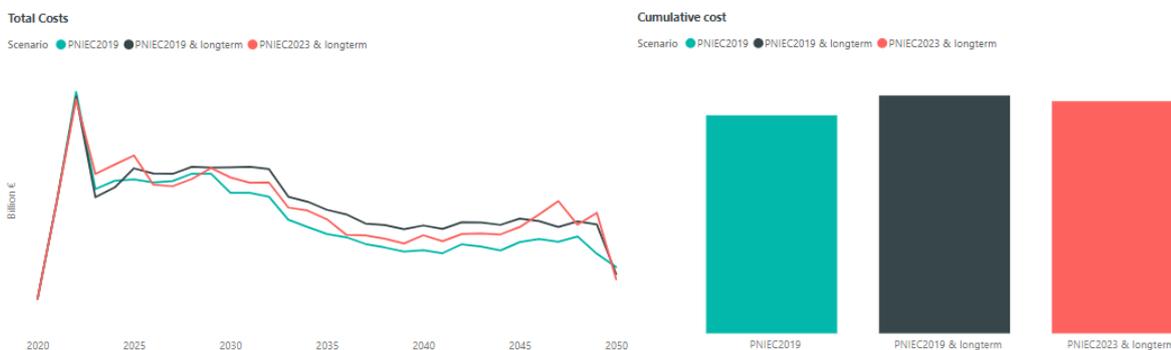


Figure 3.8: Costs comparison - stated policy scenarios.

For the first two years (2020-2022) the trend is the same for all the scenarios, since have been provided the historical data accordingly to the literature review presented in Section

1.1. Then they start to differ and as previously stated the cheapest one is the first scenario due to the much lower installed capacity. However, the difference is not that high since, even though the installation of new power plants (especially renewables), means higher investment costs, then it is compensated by much lower variable costs (close to 0 for RES) compared to the traditional thermal power plants.

Finally, the cost-optimal results for the three scenarios are all feasible on a techno-economic and environmental level, but might be problematic on a social and political one. First of all, it is possible to assist on an uneven distribution of the renewables especially for what concerns PV and Wind power plants (having a too high concentration in the north for the first and in the south for the second technology). This might indeed lead to a social backlash and resistance against the effective development and installation of these technologies. Secondly, this leads also to an uneven distribution of the use of the transmission system. It is true that the transmission load factor increases almost linearly with the RES installed capacity, but it still presents an uneven trend, making some regions more dependent from the energy imports and causing problems related to the reliability and the energy security of the specific zone.

### 3.1.1. Multi-region vs Single-region for the least-cost solution

As stated in the introduction, and also in the methodology, part of the study consisted also in analyzing the effective contribution that each region can provide to the Italian decarbonization, and the pros and cons of considering a multi-region model instead of a single-region one. One of the main challenges in modelling is indeed "balancing model resolution with data availability and computational tractability" [52]. This study was conducted considering only the PNIEC2019&longterm stated policy. The two scenarios compared are then *Multi* and *Single* which represent respectively the multi-region and the single-region scale.

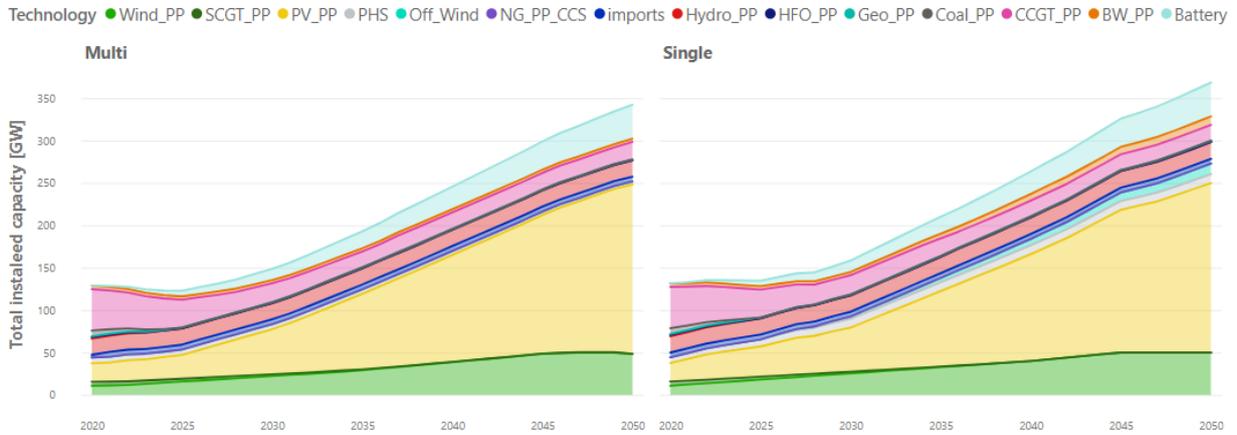


Figure 3.9: Total installed capacity for electricity.

Starting from a comparison of the total installed capacity, it is possible to see in Figure 3.9 a slight difference in its value. Being the minimum PV installed capacity quite constrained due to the long-term plan, the main differences between the two scenarios are related to on shore and off shore wind power plants. Although the constraints and the minimum stated capacities are the same on a global level for both scenarios, when considering a single region there is a higher installed capacity for both technologies. This is mostly related to the different capacity factor considered. For the Multi scenario, each zone has indeed its own capacity factor, allowing to have a more detailed and precise estimation with respect to the Single one where there is only one global average value. This leads indeed to not fully exploit the regional potential that each RES technology can globally provide. For instance, the southern regions such as SICI, SARD and SUD, have the highest on shore and off shore wind capacity factors, but when considering an average value, this is influenced also by the lowest ones such as the northern capacity factor which is close to zero. This results in a higher installed capacity, needed for meeting the energy demand (which is the same for both scenarios). Moreover, the whole system in Single, misses the potential benefit provided by the transmission system, which enables to reduce the local installed capacity if the electricity can be imported from the neighbouring region.

However, while from a technical point of view the single node might result too compact for representing such a complex system, when analyzing the pros and cons of different system's scales, is important to consider in an optimal trade-off also the computational power required.

	Variables	Constraints	Time
Multi	697314	6233	7 hours
Single	41044	590	5 minutes

Table 3.1: Multi vs Single scenario computational requirements.

Table 3.1, shows the variation in the number of variables, constraints and running time required for each scenario. For this application, a disaggregated scenario results in a number of variables and constraints of respectively sixteen and ten times as much the Single region. The growth of the time required for a single run <sup>1</sup> then grows almost exponentially, reaching 7 hours instead of 5 minutes. This might have a great impact especially when building the scenarios making sure that all the constraints are feasible and lead to acceptable results.

In conclusion, when limiting the study on a single cost-optimal scenario, it is feasible and also more interesting to consider larger system boundaries, in order to better represent possible demand fluctuations, different capacity factors, potential of the renewables and the benefits of the transmission lines of such a complex system. However, when the aim is to entail also more complex analysis such as multi-objective optimization or near to optimal solutions which need multiple runs, it is crucial to take into account also the computational power required and the related problems that it might bring when it is underestimated. For this reason, the study will apply a multi-objective optimization considering only the first stated policy scenario, modelled as a single node: PNIEC2019. It is indeed the one that requires the lowest running time and it is more suitable for studying the Pareto Function and perform multiple runs. Subsection 3.2.2 will highlight the issues and challenges in trying to carry out a multi-objective optimization with a multi node system, while Section 3.2 will present the results from the single-node optimization.

## 3.2. Multi-objective optimization

As stated in the methodology, a multi-objective optimization consists of generating an optimal finding between more objective functions, in this case the minimization of the costs and the emissions. The results consist on 10 optimal solutions based on the *single-region* PNIEC2019, which all together generate the Pareto Frontier curve.

### 3.2.1. The Pareto frontier

For this application, the Pareto frontier follows the trend shown in Figure 3.10 :

<sup>1</sup>All the runs were made with the same solver (Gurobi Optimization) on a 32 gb RAM computer.

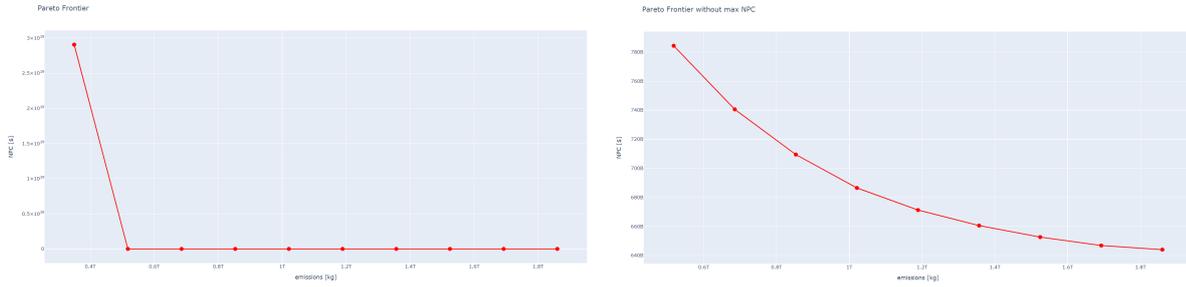


Figure 3.10: Pareto Frontier for PNIEC2019 Single-region with Max NPC (left) and no Max NPC (right).

From this result is possible to understand even more the concept described in the methodology. The two extreme points represent indeed the two extreme optimal solutions: one with minimum costs and maximum emissions and the other one with maximum costs and minimum emissions. The solutions in between are the optimal trade-offs among the two. The following table reports the NPCs increase and emissions decrease with respect to the least-cost optimal solution.

n.solution	NPC increase	Emission decrease
2	0.44%	9%
3	1.34%	18%
4	2.57%	27%
5	4.23%	36%
6	6.59%	45%
7	10.16%	54%
8	14.98%	63%
9	21.77%	72%
10	242.50%	81%

Table 3.2: Optimal Pareto Frontier solutions.

In order to achieve such a great reduction for the cumulative emissions, the total installed capacity by 2050 increases, peaking its value for the least-emission scenario.

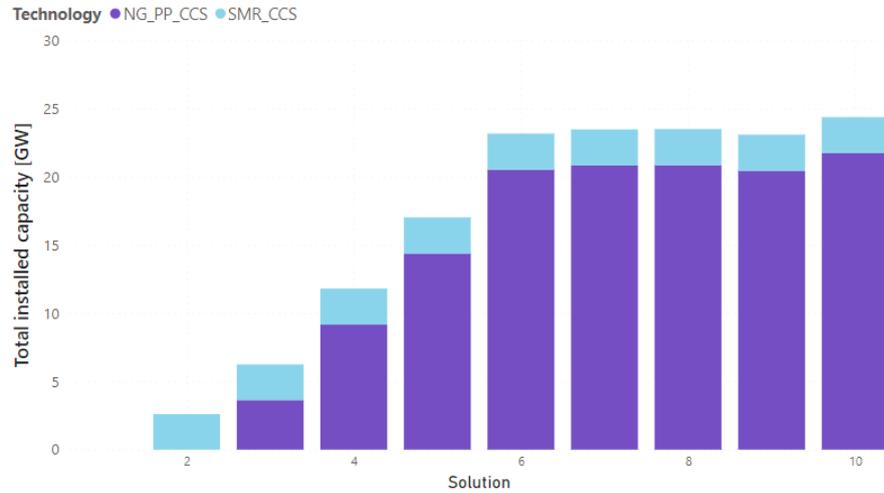


Figure 3.11: Total installed capacity for CCS technologies installed capacity - year 2050.

Moreover, there are two additional technologies which are not exploited in the least cost scenarios: natural gas and steam methane reforming with carbon capture and storage. These technologies have the advantage of guaranteeing a stable base load energy supply, while capturing the emissions with an efficiency assumed to be 0.9. Additionally, while the SMR reaches the same value for all the scenarios starting from the second solution, natural gas power plants with CCS increase their installed capacity, peaking at the least emission scenario. For all the carriers -electricity, heat and hydrogen- is possible to note a difference in the installed capacity, being always the least emission scenario the one with the highest RES share and carbon capture and storage technologies - see Appendix D for the installed capacities. Moreover, it is the only solution which considers the installation of hydrogen storage, being the most expensive technology.

However, despite the huge environmental benefits reached especially by the least-emissions scenario, the single optimal solutions does not necessarily have to be considered as the most feasible and the best trade-off to accept.

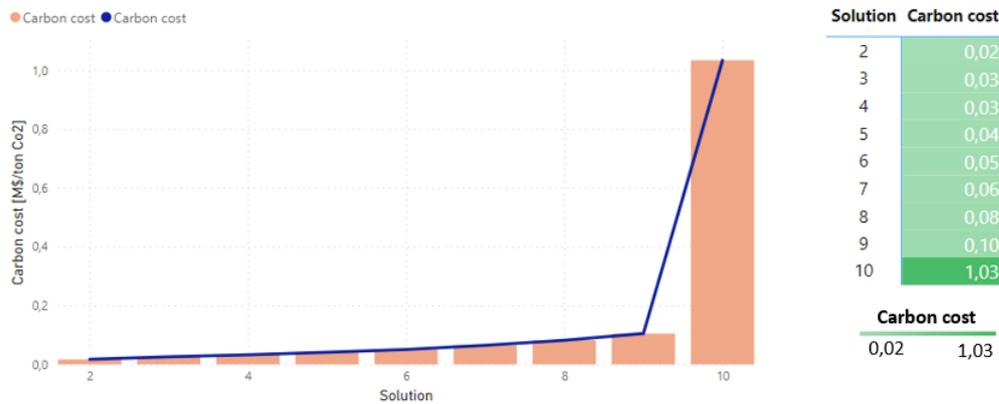


Figure 3.12: Carbon cost comparison.

Figure 3.12, shows the comparison among the scenarios of the carbon cost indicator defined in the methodology. This indicator is essential for understanding how much more is necessary to pay in order to cut more the emissions. Overall the results have a steady trend, with just a slight and reasonable variation going from solution 2 to number 9. This means that, even though the cost increase is quite high, it is still acceptable since are gained great environmental benefits, reaching an emission decrease of 72% ( Table 3.2). However, as emissions are further reduced, there's a significant rise in costs due to the deployment of larger and more expensive technologies which have low specific emissions but are costly to implement. This trend is evident when comparing the incremental changes in emissions and cost between solution 9 and the minimum emission solution 10.

Finally, all these optimal solutions are thus feasible, but are still potentially problematic for the political and social dimension. The least-emission solution proved that it might lead to problems related to the installed capacity and the unreasonable cost increase. Moreover, in all the scenarios is forecasted the deployment of technologies which haven't been installed yet and that are still under technical evaluation such as carbon capture and storage. Despite this technology has been considered in the last COP28 essential for the transition [44], especially for the highest energy intensive industries, could still entail unwanted trade-offs such as the reliance on natural gas imports together with huge investments in a technology that from a long-term perspective can't assure zero emissions - being the capture efficiency not higher than 0.9.

### 3.2.2. Multi-region vs Single-region with minimum emissions

As stated in Section 3.1.1, a multi-node configuration has a higher computational cost and might nullify all the benefits that such analysis could bring if multiple runs are needed. The initial goal of this report was to conduct a study considering a disaggregated configuration, but due to high computational costs, the results took too long to run presenting traces of unfeasibility.

However, in order to be able to analyse the regional contribution at least for the least-emission solution, was performed a single run with an objective function that minimizes the costs with an additional constraint on the emissions.

Solution	NPC increase	Emission decrease
Multi	367.18%	82%
Single	215.17%	76%

Table 3.3: Least-emission solution results.

As in Section 3.1.1, the two scenarios will keep the same name: Multi and Single.

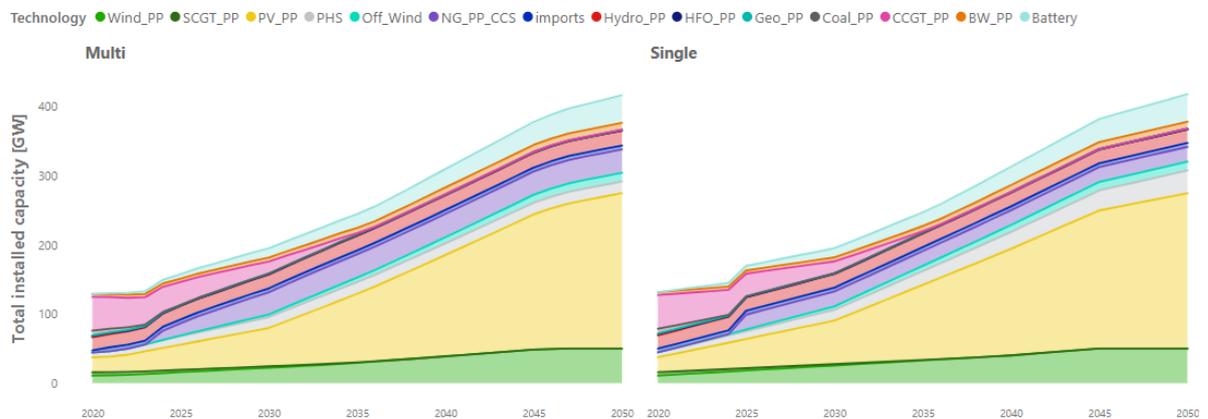


Figure 3.13: Total installed capacity for electricity.

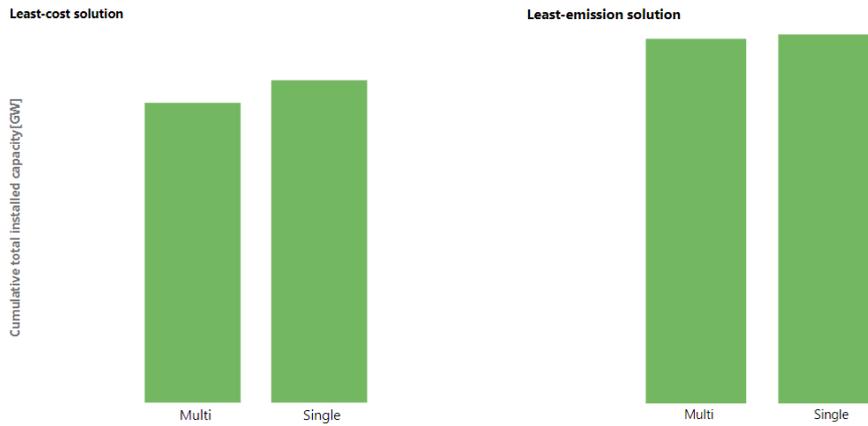


Figure 3.14: Cumulative total installed capacity - electricity.

For the least-emission solution, the differences are almost irrelevant for electricity, being the cumulative total installed capacity much higher than the least-cost solution and hence the system is not really influenced by a multi region or single region configuration.

In Appendix D, Figure D.1 shows how each region can contribute if the objective is to minimize the emissions. In order to gain an 82% decrease in the emissions (see Table 3.3), a boost in natural gas and CCS and off-shore wind power plants is needed. The first technology is indeed installed in each region, whereas off-shore wind is present especially in SICI and SARD. The reason is due to the very high capacity factors, that make it a much more attractive technology if there are no cost constraints. Because of that, in both regions there is a slight concavity of the curve in 2049, due to the on shore wind technical lifetime that comes to an end and is replaced by off shore wind.

On the other hand, a great change can be seen in hydrogen technologies, which, for the same heat and -almost- electricity total installed capacity, have the highest contribution in the emissions reduction.

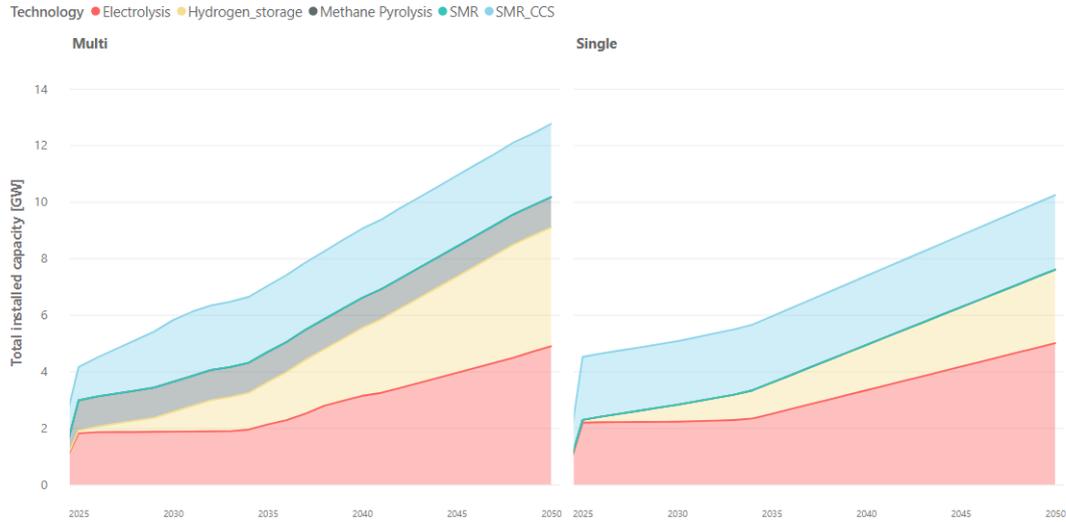


Figure 3.15: Total installed capacity for hydrogen - least emissions.

In the least-emission solution there is the deployment of an additional technology: methane pyrolysis.

This is a technology which hasn't been implemented yet within the Italian energy system, but is gaining quite a great interest worldwide due to its potential to reduce GHG emission [49]. The hydrogen produced, comes from the pyrolysis of natural gas:  $CH_4 \rightarrow C + 2H_2$ , which is known as *turquoise* hydrogen, with respect to the gray one produced through SMR or blue via SMR and CCS [49]. Being this technology more expensive than SMR and electrolysis, it is not present in the least-cost scenario, but due to its beneficial environmental impact, it is installed in a least-emission solution. Figure D.2, shows that methane pyrolysis is installed only into NORD, being the region with the highest hydrogen demand and having peaked the maximum new capacity for the other technologies. For a least-emission configuration, results indeed more beneficial to minimize the imports/exports of hydrogen with respect to a least-cost solution.

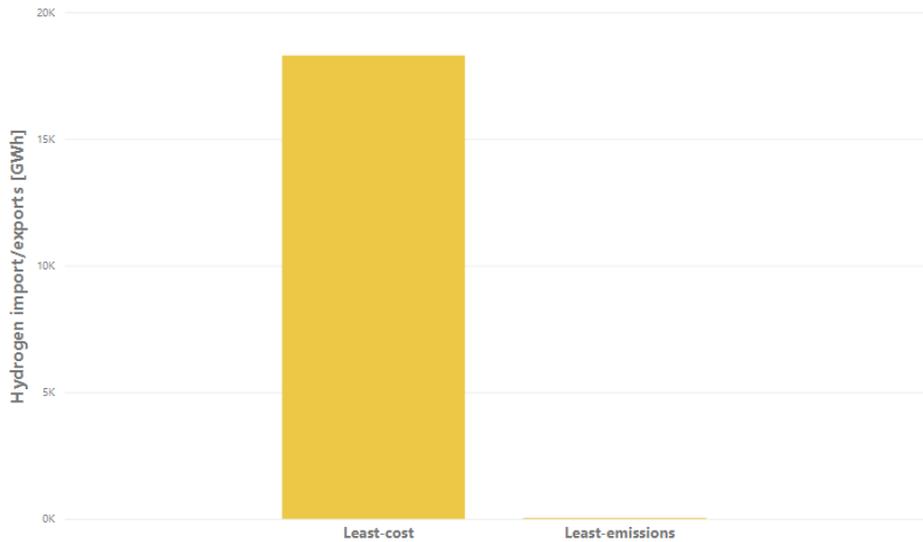


Figure 3.16: Average imports/exports of hydrogen per year - least cost vs least emissions.

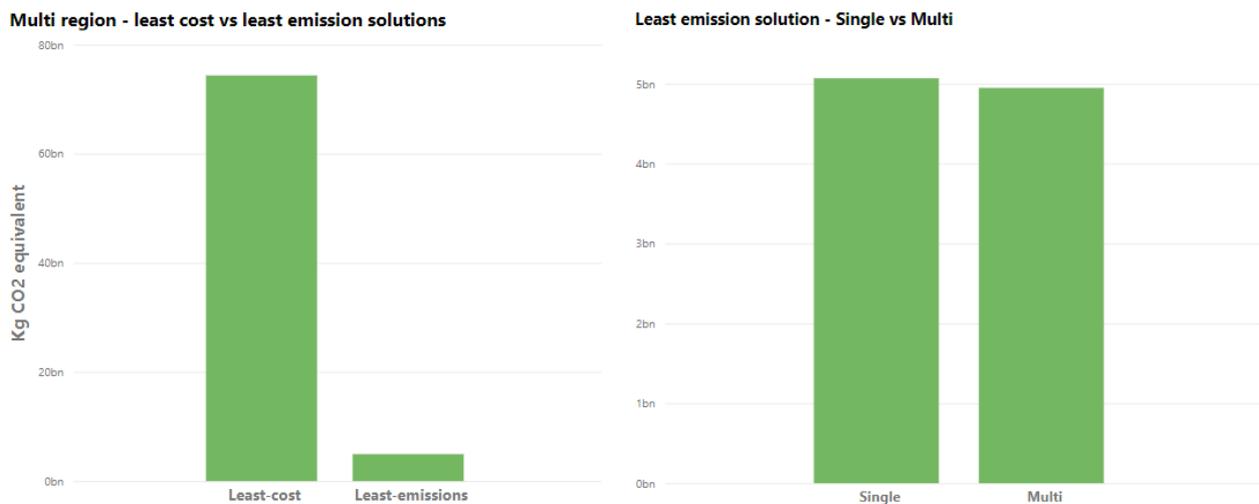


Figure 3.17: Cumulative emissions from hydrogen technologies.

Looking at the cumulative emissions produced only by hydrogen technologies, there was no doubt that the least-cost solution would have had a much higher value. The reason lies mostly in the replacements of the most polluting SMR with the aforementioned more sustainable technologies. However, looking on a comparison between a multi-node and a single-node setting for a least-emission solution, the Multi configuration still looks more environmentally friendly. This proves further how considering also a disaggregation of the constraints (for example as in this case for the installed capacity), brings benefits in

terms of possible solutions and overall benefits that could be brought on an environmental dimension.

Additionally, the study led also to another interesting result. As aforementioned in the Introduction, Italy is still debating on which strategy is better to follow in order to tackle the great forecasted hydrogen penetration [37]: entirely on-site production, on-site production coupled with energy distribution, or centralized production with hydrogen transport. The comparison between the least-cost and the least-emissions scenarios, can be seen as a first answer to this question. The results show how in order to minimize the costs, it is preferable to have an on-site production coupled with energy distribution. This is proven by the least-cost solution, where there is a much higher exploitation of the transmission system also due to a total lack of hydrogen storage. On the contrary, if the goal consists of minimizing the emissions, it is better to favor an entirely on-site production as proven by the least-emission solution where the benefits of having a transmission system are almost totally nullified. Moreover, the feasibility of this configuration is due to the presence in each region - see Figure D.2 - of hydrogen storage, which would allow to store hydrogen and use it when needed without the need of a transmission system.

### 3.3. Near to optimal solutions

As stated in Chapter 3, in order to map the near to optimal solutions, were considered three different cost relaxations (5% , 10% and 20%) running 10 solutions each, where the first one corresponds always to the optimal one. The figure below shows graphically the results provided by the application of this methodology:

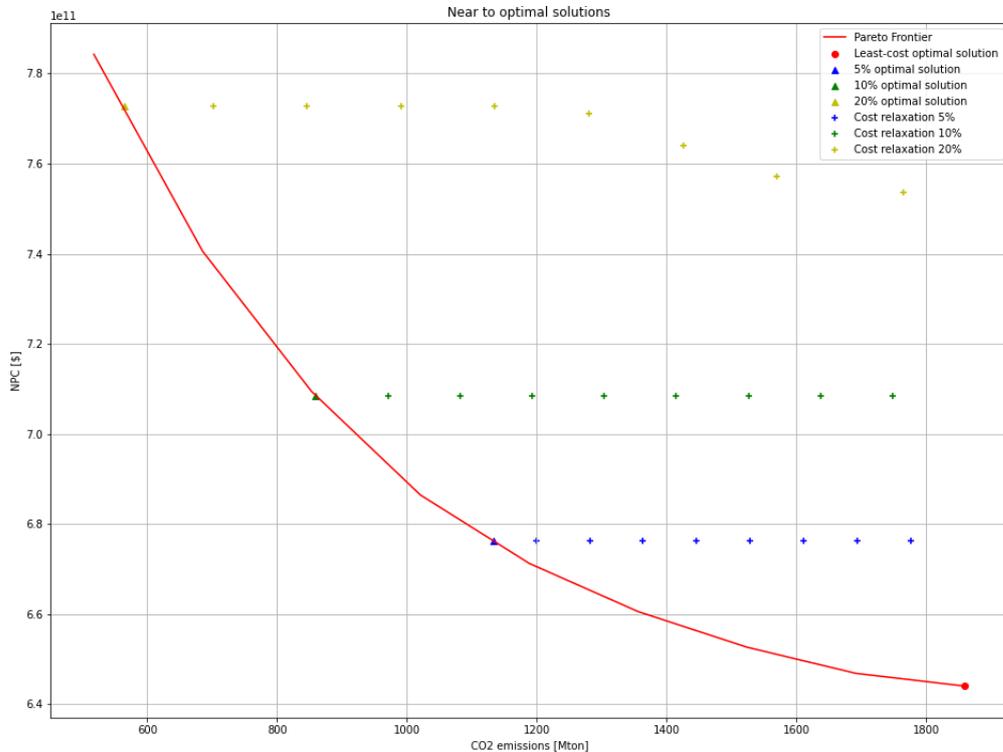


Figure 3.18: Near to optimal solutions and Pareto Frontier with no Max costs.

All the crosses represent all the near to optimal solutions for each cost relaxation with respect to the Pareto frontier (with no Max NPC, Min emission solution). It is important to note how solution number 10 lies on the front, being it an optimal solution. This is related to the methodology: the additional emission constrain considered, as explained in Section 2.4.2, was set accordingly to the emission value corresponding to the optimal solution found through the same *step* used for the multi-objective optimization - see Section 2.4.1. Because of that, the last solution, corresponds to the optimal solution that minimizes the emissions spending up to the maximum costs allowed depending on the cost relaxation. Because of this, from now on the discussion will follow analyzing only the real near to optimal, not considering solution number 10.

### 3.3.1. Must-have technologies

The methodology was able to map the region in between the optimal Pareto Front and the maximum cumulative emissions of the least-cost solution, in order to find maximally

different alternatives for each cost relaxation. One of the first insight provided by the near to optimal solutions, are the so called *must-have* technologies. These are generation and storage technologies for any energy carrier, that are present in all the scenarios, whatever the cost relaxation or the objective function is. This kind of analysis, inspired by Lombardi et al. [46], is useful for assisting policy makers when choosing the best energy mix and the investments needed for gaining the country's specific goals. Additionally, this study highlights which are the technologies that cannot be substituted and which are the ones, on the contrary, that can be replaced by others since they are not essential.

For this case study, this analysis was carried out considering the dispersion of the new installed capacity, in the period 2020-2050, for each technology in each solution. Figures 3.19 and 3.20 represent the results for respectively electricity production, and hydrogen and heat production. Each box represents the dispersion of the values, with a red triangle that shows the median value considering all the near to optimal solutions. Focusing on this latter, the expansion of PV coupled with batteries is a must-have in all the scenarios together with off and on shore wind. However, both technologies face a slight decrease in the new installed capacity when the costs increase. This is related to the objective function chosen, which benefits other technologies such as natural gas coupled with carbon capture and storage. This latter one, even though cannot be considered a real must have since it is not present in a lest-cost solution, it could be considered a must have considering only near to optimal solutions since it is installed in all of them. The reason lies in its higher efficiency in terms of energy production, land use and emission decrease: the more the costs increase and the emissions decrease, the more this technology substitutes the traditional natural gas power plants or the more land consuming renewables. Additionally, focusing also on the other technologies, biofuel and waste (BW\_PP), hydro power plants (Hydro\_PP) and and pump hydro storage (PHS), are all must haves since they are present in all the scenarios, being them all key technologies for the Italian energy mix.

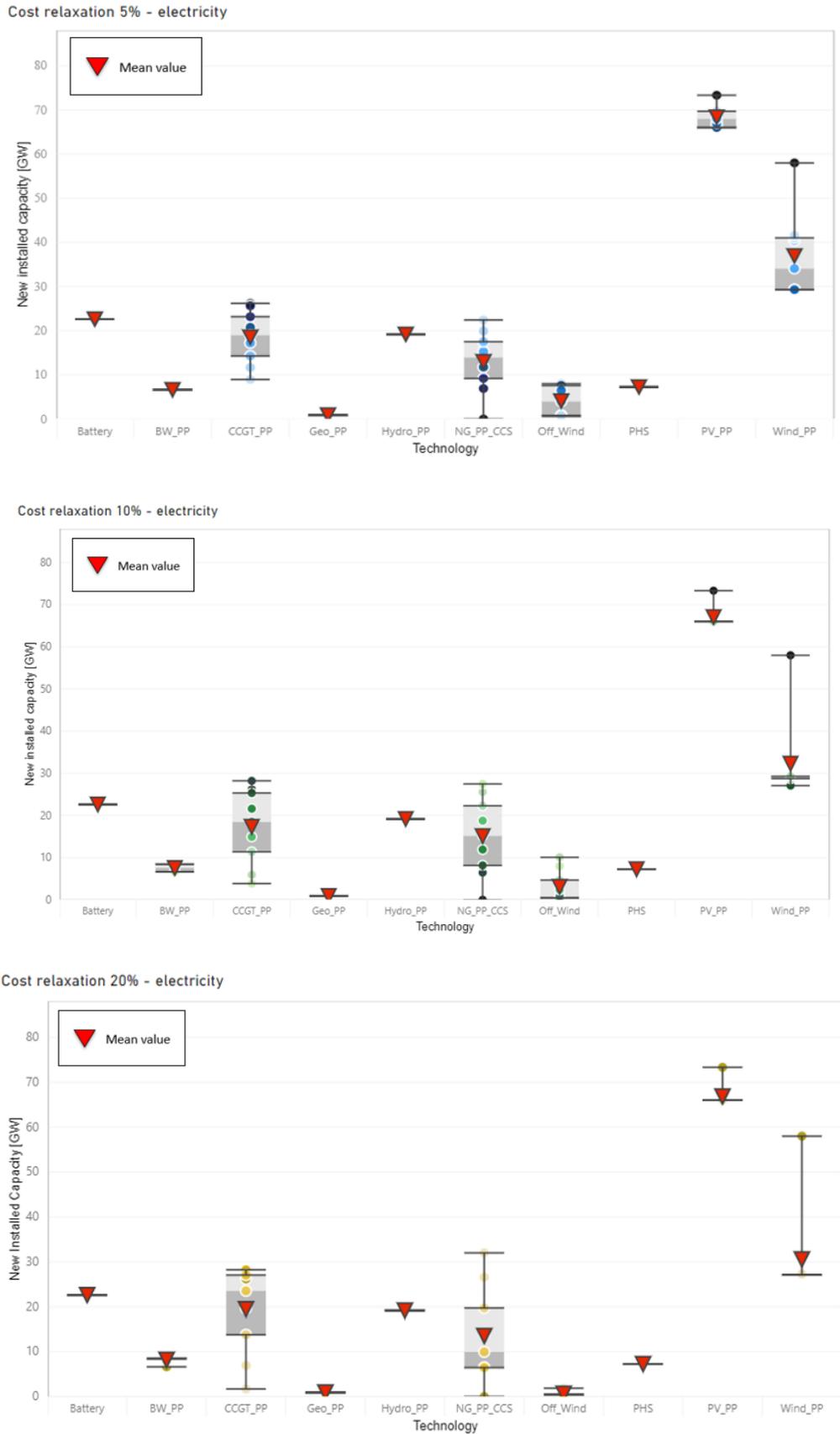


Figure 3.19: Must-have technologies among near to optimal solutions - electricity.

Moreover, these results are almost the same as for the case of Lombardi et al. [46], strengthening even more the *must-have* concept. As stated in the methodology, when dealing with near to optimal solutions, since the costs become a constrain, it is essential to implement a new objective function which is *arbitrary* at the will of the user. Comparing the results of two different methodologies and objective functions - this case study with the minimization of the land use, and Lombardi et al. [46] with the minimization of the installed capacity - proves even further how these must-have technologies are always present and are not influenced by a specific objective function or methodology (and hence optimization algorithm) adopted. Finally, focusing on the scenarios, another interesting insight, is that with this methodology, the more the costs increase, the more the new installed capacity for wind and PV power plants decreases. This proves how considering alternative solutions in addition to the least cost single solution, makes the research more feasible for a real case application since it entails also the social dimension. These scenarios are indeed feasible for a technical, economical and environmental level, but might be more interesting also for a social one. Even though this is a single-region scenario, a slight decrease in the new installed capacity of on/off shore wind and PV power plants, might hypothetically be beneficial for the previously explored uneven development of the renewables among the different regions, and the social resistance that might arise due to higher land usage in some regions.

Looking at the other technologies in Figure 3.20, also in this case is possible to make the same observations. Hydrogen storage and methane pyrolysis, having a null new installed capacity in all the scenarios aren't must have technologies and can hence be replaced by cheaper technologies such as steam methane reforming coupled with carbon capture and storage. Also in this case, CCS technologies become must-haves focusing only on the near to optimal solutions, since they are present in all the scenarios but the least-cost. Moreover, for what concerns heat, there are no significative changes a part from the highest cost relaxation which has also a higher emission constrain and has indeed a slightly higher new installed capacity for biofuels and waste heat power plants.

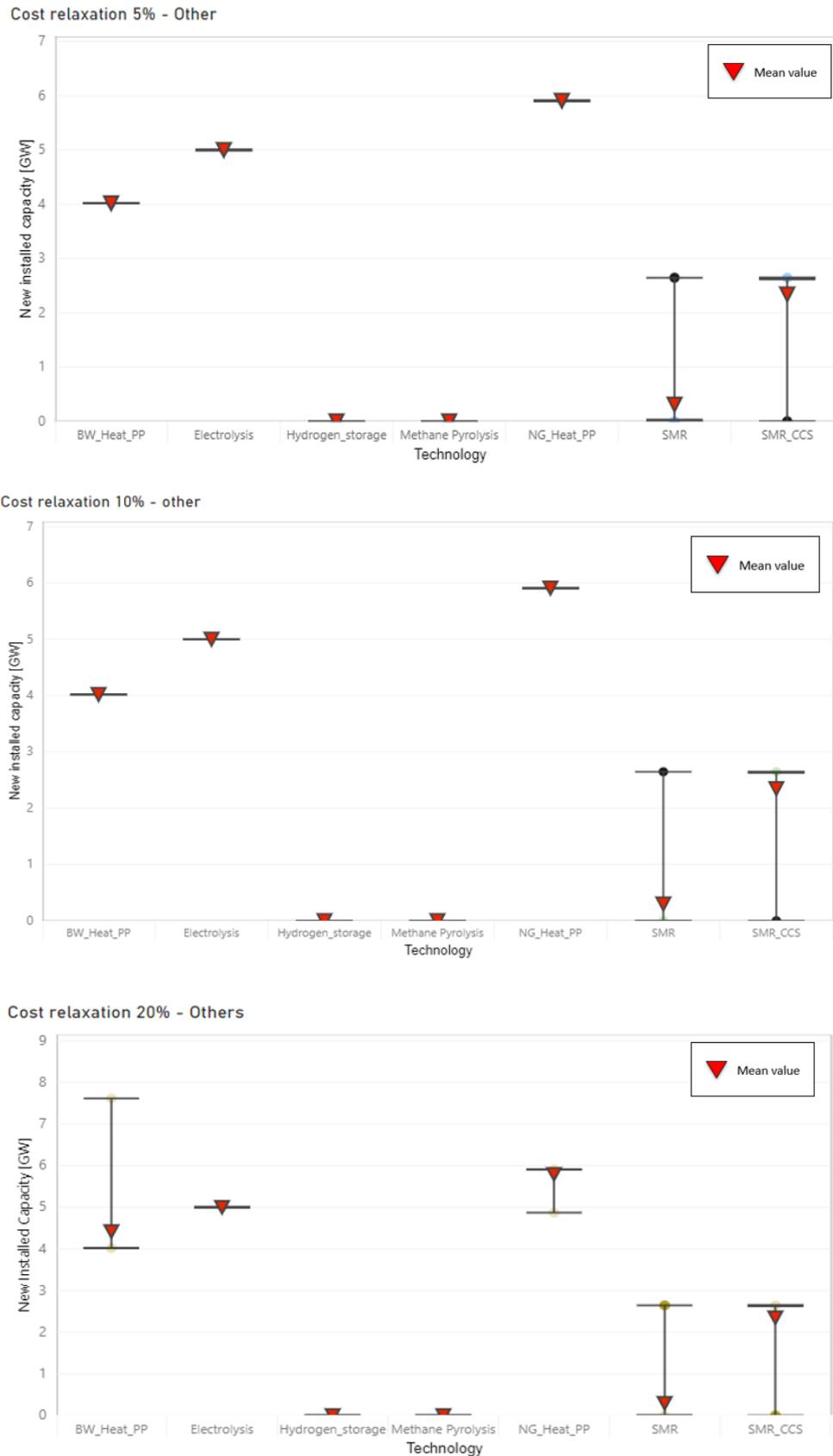


Figure 3.20: Must-have technologies among near to optimal solutions - heat and hydrogen.

### 3.3.2. Scenarios comparison

As stated in the methodology, the investigation will follow through a comparison within the near to optimal scenarios, in order to highlight the main insights provided by the application of this methodology. Also in this case, solution number 10 won't be taken into account since it cannot be considered a near to optimal due to the fact that falls on the Pareto Front. The three indicators used for this analysis are: the emission reduction, the carbon cost and the overall load factor for year 2050.

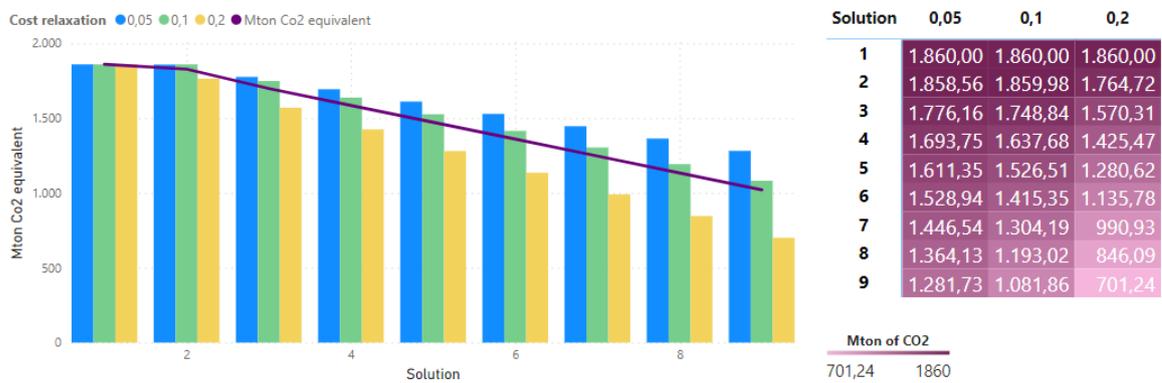


Figure 3.21: Emission reduction

Although the objective function adopted for this case study is the minimization of the land usage, the additional constrain on the emissions resulted in a decrease of the cumulative emissions of the system. The emission trend is indeed consistent with the methodology adopted since a higher cost increase results in a higher emission reduction as proven by Figure 3.21 and Table 3.4.

n.solution	5%	10%	20%
2	0.08	0.1	5.12
3	5	6	15.6
4	9	12	23.36
5	13	18	31.15
6	18	24	38.94
7	22	29.8	46.72
8	27	36	54.51
9	31	41.8	62.30

Table 3.4: Emission decrease [%] for each cost relaxation with respect to the least-cost solution.

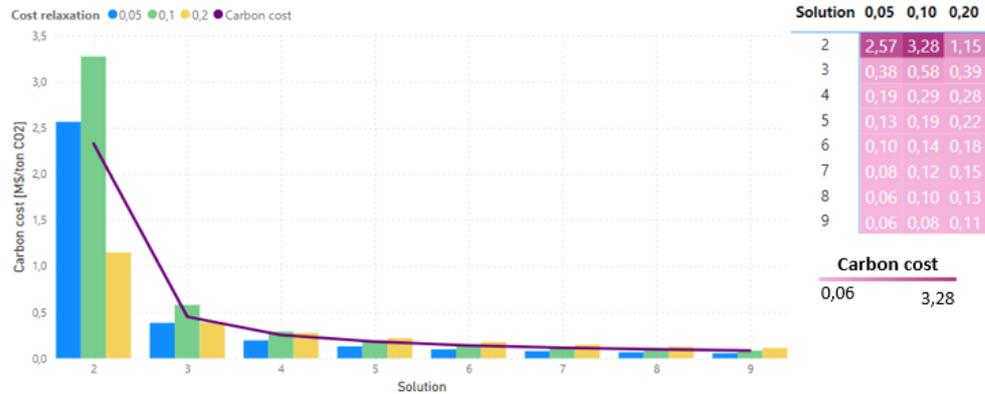


Figure 3.22: Carbon cost.

For what concerns the carbon cost, this decreases going from solution 2 to solution 9. Overall, it is possible to note how spending already 5% more is enough for gaining great environmental benefits. For instance, cross-checking Figure 3.22 and Table 3.4, with a cost increase of 5% is possible to gain a 31% of emission decrease, which are gained also in solution number 5 of a 20% cost relaxation with a carbon cost of 0,22. This proves that it is not always necessary to increase further the costs, since the more the relaxation is high, the more there's a significant rise in costs due to the deployment of larger and more expensive technologies which have low specific emissions but are costly to implement.

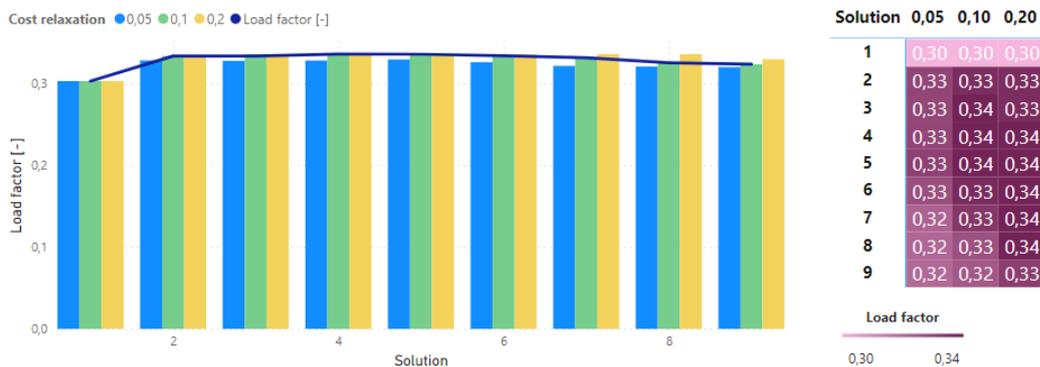


Figure 3.23: Load factor - year 2050

For what concerns the load factor, the graph shows the trend for the year 2050, entailing energy produced and the total installed capacity of the overall energy system by 2050. The values do not differ a lot, being the overall trend almost steady, even though there is

a slight increase in all the near to optimal solutions. This results in a much more efficient resource exploitation with respect to the least-cost solution, making all these alternatives also more attractive for the stakeholders, since would better justify an increase in the costs.

Additionally, being the objective function the minimization of the land usage, also a comparison within the cumulative values of this parameter was worth to be done.

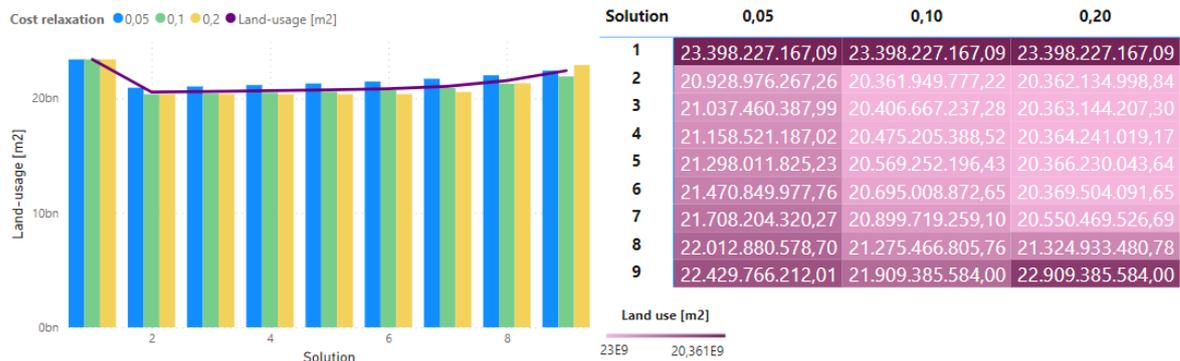


Figure 3.24: Land use

The results prove how, also in this case, all the near to optimal solutions are more advantageous in terms of land usage. The most "land-consuming" solution is indeed the least-cost solution, whereas all the others gain a lower value. However, the decrease does not follow a linear trend since the values tend to increase going from solution 2 to 9. This is because, for this specific optimization, the additional constrain has a great influence: the closer the solution to the optimal Pareto, the lower are also the emissions and hence are required more RES technologies responsible of the land usage increase.

Finally, the overall results prove how considering near to optimal solutions might result beneficial for assisting policy-makers. The advantages of such analysis consists of understanding how alternative solutions highlight useful insights even though the constraints and the objective functions are arbitrary. For instance, this study proved that if the goal is not strictly correlated to the minimization of the costs (least-cost solution), there might be benefits in terms of emission and land usage decrease, and increase in the load factor. All the alternatives showed indeed how through them is possible to go beyond the technical-economic feasibility, entailing also the often ignored social dimension. Having for example a higher emission decrease and higher load factors coupled with a lower land usage, might result in a lower social resistance since the performances are more effective, the resources can be distributed more efficiently and also a cost increase would be justified.



## 4 | Conclusions and future developments

Using Italy as a case study, was proposed a novel modelling approach for supporting policy-makers in tackling their goals. Through the use of a multi-objective optimization and near to optimal solutions evaluation, was indeed possible to analyze a wide range of alternatives in order to provide maximally different options.

Relying only on a cost-optimal solution, proved that the scenarios might suffer of an uneven distribution of the resources, low capacity factors, high land usage and low social acceptance. Also when considering a multi-objective optimization, the optimal set of solutions in the Pareto Frontier, led to problems related to the installed capacity and an unreasonable cost increase. However, this study was essential for addressing the core part of the research.

Starting from the optimal Pareto Frontier, was subsequently applied a new methodology able to find alternative solutions that reach a 5%, 10% and 20% cost increase. The results showed how considering these maximally different options, helps to highlight useful insights such as *must have* technologies, which are conversion or storage systems that cannot be substituted and are essential for the future energy mix by 2050. Furthermore, the analysis of the various scenarios developed in this study, proved how going beyond optimal solutions, allows to improve the system's performances, making the alternatives more suitable for real case applications since they are all characterized by higher load-factors, lower emissions and lower land usage.

For the case study of Italy, photovoltaic (PV) technologies coupled with batteries, and on/off shore wind power plants are must-haves, together with the new cutting-edge carbon capture and storage (CCS) technologies which are present in all the scenarios but the least-cost. Moreover, the study proves that a 5% cost increase is already enough for gaining significative environmental benefits (31% of emission decrease) with reasonable carbon costs. Higher cost relaxations are thus feasible and attractive, but they are characterized by higher carbon costs due to the deployment of larger and more expensive technologies

which have low specific emissions but are costly to implement.

Finally, this report demonstrated also how crucial can be the system's scale chosen. While multi-region scales are more detailed and hence allow to better represent the system's complexity, single-region scales are more suitable when multiple runs are needed due to their much lower computational costs. Moreover, the study conducted for a multi-region scenario, and the comparison with the single-region one, highlighted how impactful can be the transmission system for both electricity and hydrogen.

Overall, near to optimal are an effective method for supporting policy makers in energy planning at a national level. However, for a matter of time availability and too high computational costs, this study couldn't be conducted on a multi-region scale. The future challenge would thereby be to start from the already developed least cost solutions, and map all the possible optimal or semi optimal alternatives for a disaggregated configuration. The goal is to further highlight the contribution that each Italian region can provide for the energy decarbonization, focusing also on the transmission system. The results showed indeed how the transmission's system load factor changes considering different scenarios, being it strictly correlated to the RES roll out. On the other hand, for what concerns hydrogen, the comparison between a least cost and a least emission scenario, proved how also in this case the transmission system has a key role depending on the objective to be achieved: if the goal is to minimize the costs, it is preferable to have an on-site production coupled with energy transmission, whereas if the goal consists of minimizing the emissions, it is better to favor an entirely on-site production due to the presence in each region of hydrogen storage which allows to store hydrogen and use it when needed without the need of a transmission system. Because of these considerations, considering that Italy will undergo significant development in RES and hydrogen technologies, applying this method to a multi-regional scenario would be worthwhile.

In conclusion, the key aspect of this thesis is the use of a new methodology for pointing out the importance of going beyond least cost solutions in energy system optimization models. Modelling to generate alternatives assures to explore different options and strategies. This is indeed decisive, since it should be at the forefront of any energy plan in order to guarantee a transition that has to be just and affordable.

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# A | Appendix A

Region	Hydro	Wind	Geo	PV	BW	Coal	CCGT	SCGT	BW heat	NG heat
V. D'Aosta	1990	2012	-	2011	2013	-	2013	-	2013	2013
Piemonte	1959	2012	-	2011	2013	-	2005	2004	2013	2005
Lombardia	1969	-	-	2011	2001	-	2005	1982	2001	2005
Trentino	1969	2011	-	2011	2013	-	2008	-	2013	2008
Veneto	1972	2011	-	2011	2010	1974	2007	-	2010	2007
Friuli	1964	2007	-	2011	2010	1984	2014	2022	2010	2014
Emilia Romagna	1990	2007	-	2011	2009	-	-	2004	2009	2004
Liguria	1972	2017	-	2011	2019	-	2000	-	2019	2000
Toscana	1938	2011	2014	2018	2008	-	2006	2018	2008	2006
Umbria	1971	2021	-	2018	2008	-	1999	-	2008	1999
Marche	2012	2005	-	2018	2005	-	2001	-	2005	2001
Lazio	1992	2012	-	2011	2011	2010	2003	-	2011	2003
Abruzzo	1966	2001	-	2011	2011	-	2005	-	2011	2005
Campania	1979	2009	-	2011	2009	-	2005	-	2009	2005
Molise	1999	2005	-	2017	2012	-	1998	-	2012	1998
Puglia	2006	2007	-	2017	2012	1992	2008	-	2012	2008
Basilicata	1983	2013	-	2017	2001	-	2008	-	2001	2008
Calabria	1985	2012	-	2012	2003	-	2009	1996	2003	2009
Sicilia	1970	2010	-	2012	2008	-	2008	1988	2008	2008
Sardegna	1949	2009	-	2016	2009	1994	2008	-	2009	2008

Table A.1: Average year of installation of existing power plants

Bidding zone	Hydro	Wind	Geo	PV	BW	HFO	Coal	CCGT	SCGT	PHS	BW heat	NG heat
NORD	14.54	0.15	-	9.65	2.57	-	0.98	25.74	4.19	4.64	1.58	2.83
CNORD	1.16	0.16	0.82	2.48	0.25	0.016	-	3.8	0.1	-	0.24	0.43
CSUD	1.78	2.08	-	3.05	0.44	-	1.98	6.93	-	1.54	0.13	0.23
SUD	1.01	5.5	-	4	0.66	-	2.64	8.11	0.4	-	0.19	0.32
SICI	0.15	1.93	-	1.5	0.07	1.27	-	3.9	0.22	0.53	0.18	0.33
SARD	0.47	1.09	-	0.97	0.11	0.58	1.23	0.36	0.22	-	0.11	0.19

Table A.2: Capacities of existing power plants [GW] reference - year 2020

Bidding zone	PV	Wind	Off-shore Wind	PHS	Electrolysis
NORD	185.769	27.9323	12.3351	5.0643	143.617
CNORD	46.7889	26.4524	5.2239	1.4	50.2001
CSUD	66.3039	13.3249	5.4127	4.0816	53.2987
SUD	54.8058	25.5251	10.3562	3.6	54.487
SICI	33.1655	14.4854	10.1938	1.5737	36.1534
SARD	24.5943	16.8287	12.2044	1.2369	34.2514

Table A.3: Max total capacities of existing power plants [GW] [46]

Technology	$m^2/MW$	Reference
Coal	40	[32]
HFO	40	[32]
CCGT	25	[32]
SCGT	30	[32]
NG_CCS	40	[32]
ON_Wind	4207.381	[68] <sup>1</sup>
OFF_Wind	2916.133	[68]
BW_PP	295	[32]
PV	6340	[28] <sup>2</sup>
GEO_PP	18211	[17]
Hydro	13994.2	[38]
NG_heat	5	[32]
BW_heat	295	[32]
Battery	6.25	[32]
PHS	12	[31]
Electrolysis	25	[53]
SMR	18.29	[32]
SMR_CCS	18.29	[32]
Hydrogen storage	43800	[53]

Table A.4: Specific Land usage

<sup>1</sup>The value for on shore and off shore wind, was estimated manually dividing the rotor size by the installed capacity. The model considered was Vestas since it is the same adopted in Renewable Ninja [12] web-site for determining the wind capacity factor.

<sup>2</sup>This value was obtained considering an average value from Tab.5 at pag.22, which involves also agrivoltaic technology.

# B | Appendix B

	<b>Target</b>	<b>Target to</b>
ON_Wind	19.3 GW	2030
OFF_Wind	0.3 GW	2030
BW_PP	3.76 GW	2030
PV	52 GW	2030
GEO_PP	0.95 GW	2030
Hydro	19.2 GW	2030
Electrolysis	5 GW	2050
RES share	55%	2030

Table B.1: Stated policy PNIEC2019 [27]

	<b>Target</b>	<b>Target to</b>
ON_Wind	28.140 GW	2030
OFF_Wind	2.1 GW	2030
BW_PP	3.052 GW	2030
PV	79.921 GW	2030
GEO_PP	1 GW	2030
Hydro	19.172 GW	2030
Electrolysis	5 GW	2050
RES share	65%	2030

Table B.2: Stated policy PNIEC2023 [29]

	<b>Target</b>	<b>Target to</b>
PV	200 GW	2050
Battery	40 GW	2050
RES share	95%	2050

Table B.3: Stated policy Long term strategy [10]



# C | Appendix C

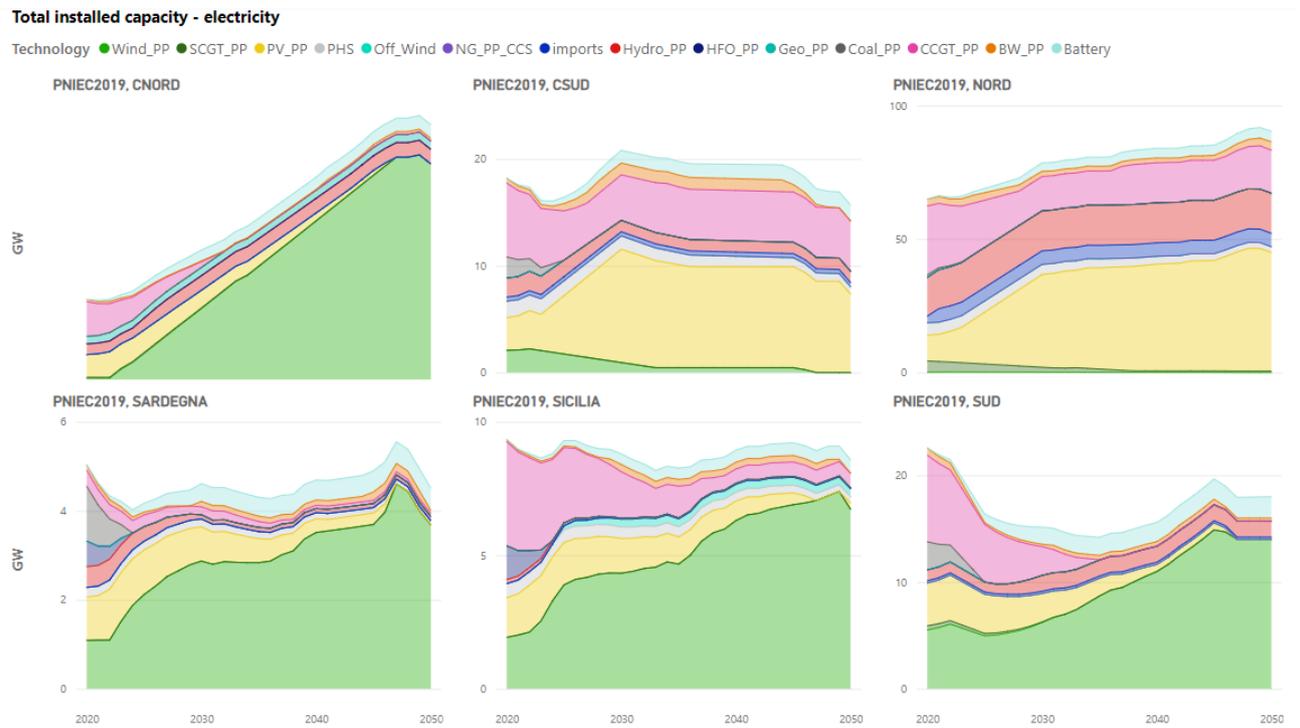


Figure C.1: Total installed capacity for each bidding zone - PNIEC2019.

**Total installed capacity - electricity**

Technology ● Wind\_PP ● SCGT\_PP ● PV\_PP ● PHS ● Off\_Wind ● NG\_PP\_CCS ● imports ● Hydro\_PP ● HFO\_PP ● Geo\_PP ● Coal\_PP ● CCGT\_PP ● BW\_PP ● Battery

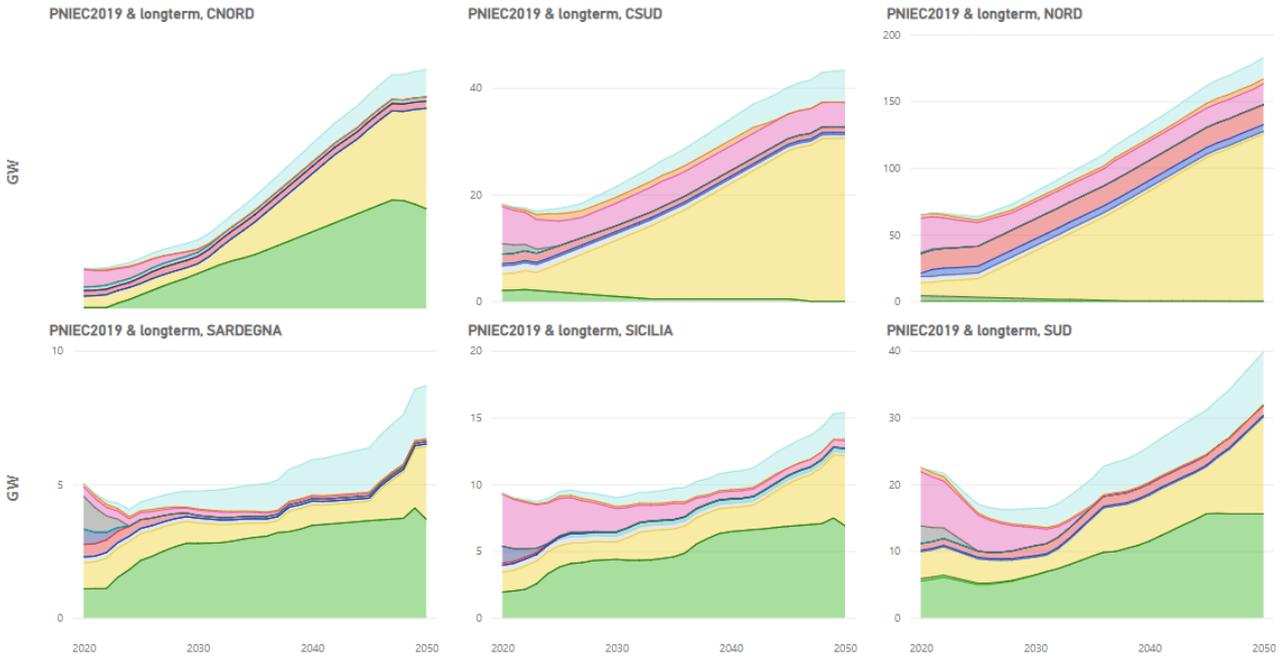


Figure C.2: Total installed capacity for each bidding zone - PNIEC2019&longterm.

**Total installed capacity - electricity**

Technology ● Wind\_PP ● SCGT\_PP ● PV\_PP ● PHS ● Off\_Wind ● NG\_PP\_CCS ● imports ● Hydro\_PP ● HFO\_PP ● Geo\_PP ● Coal\_PP ● CCGT\_PP ● BW\_PP ● Battery

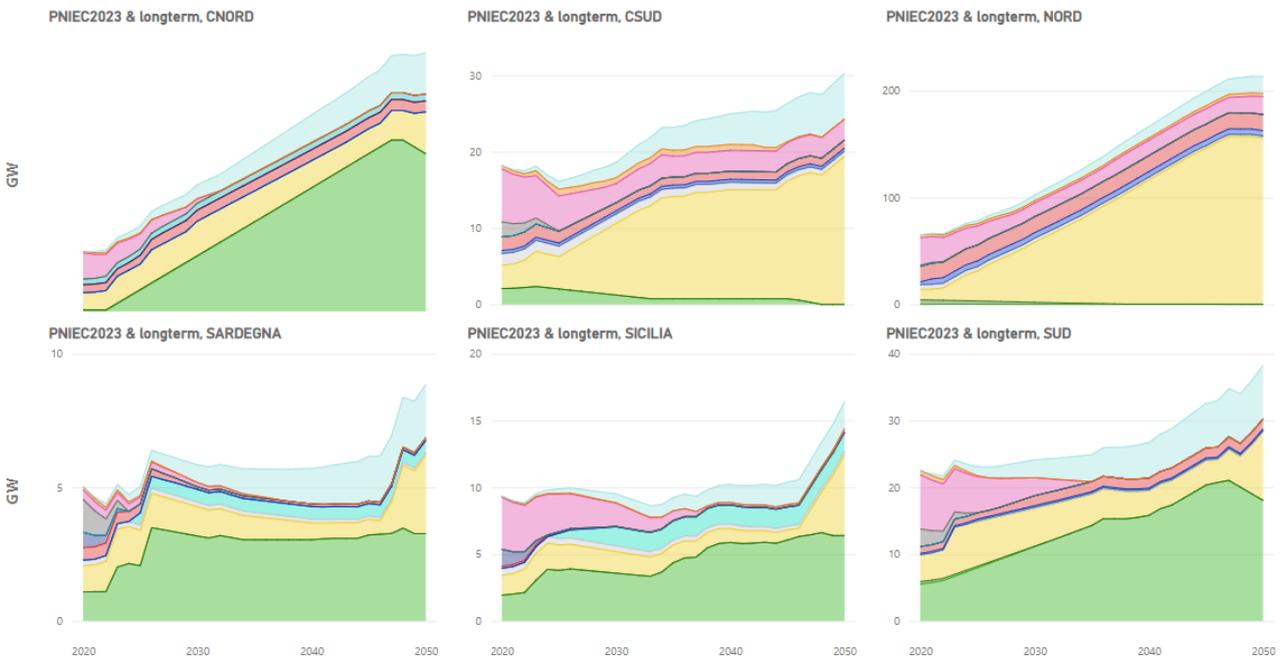


Figure C.3: Total installed capacity for each bidding zone - PNIEC2023&longterm.

# D | Appendix D



Figure D.1: Total installed capacity of electricity- Multi, least-emission scenario.

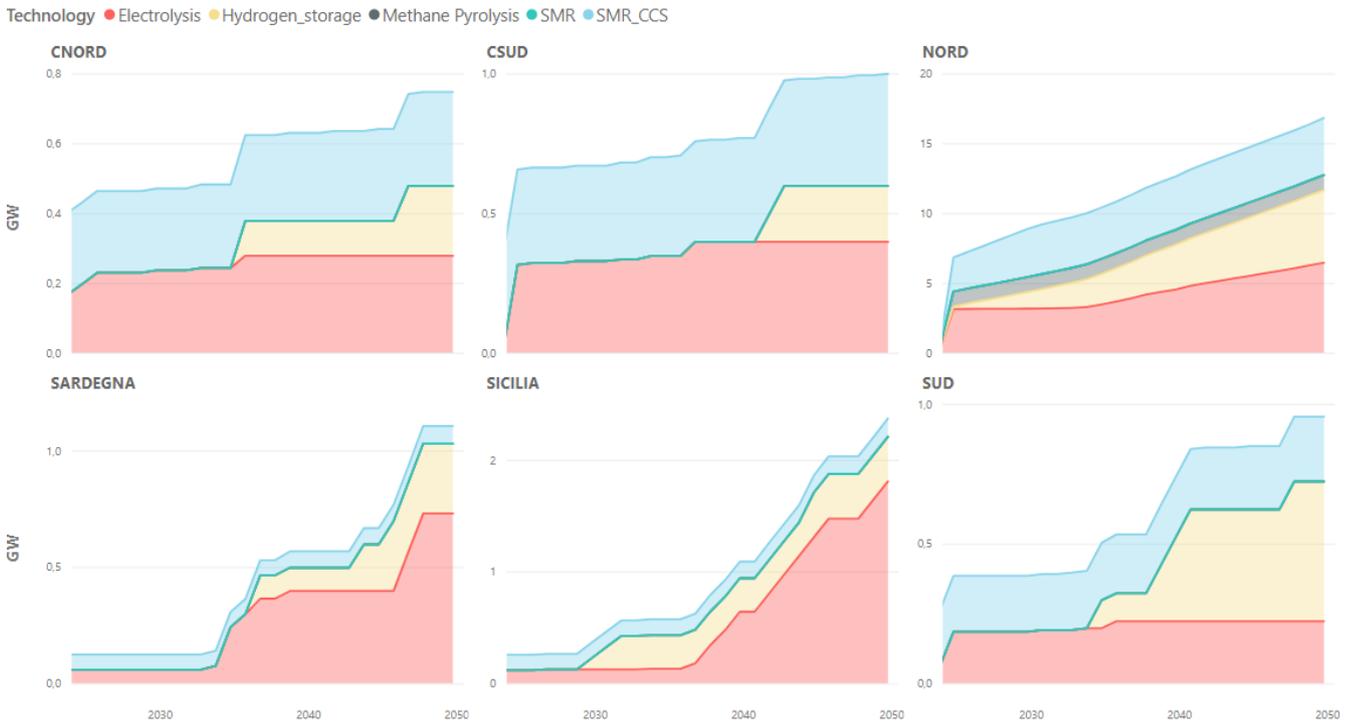


Figure D.2: Total installed capacity of hydrogen - Multi, least-emission scenario.

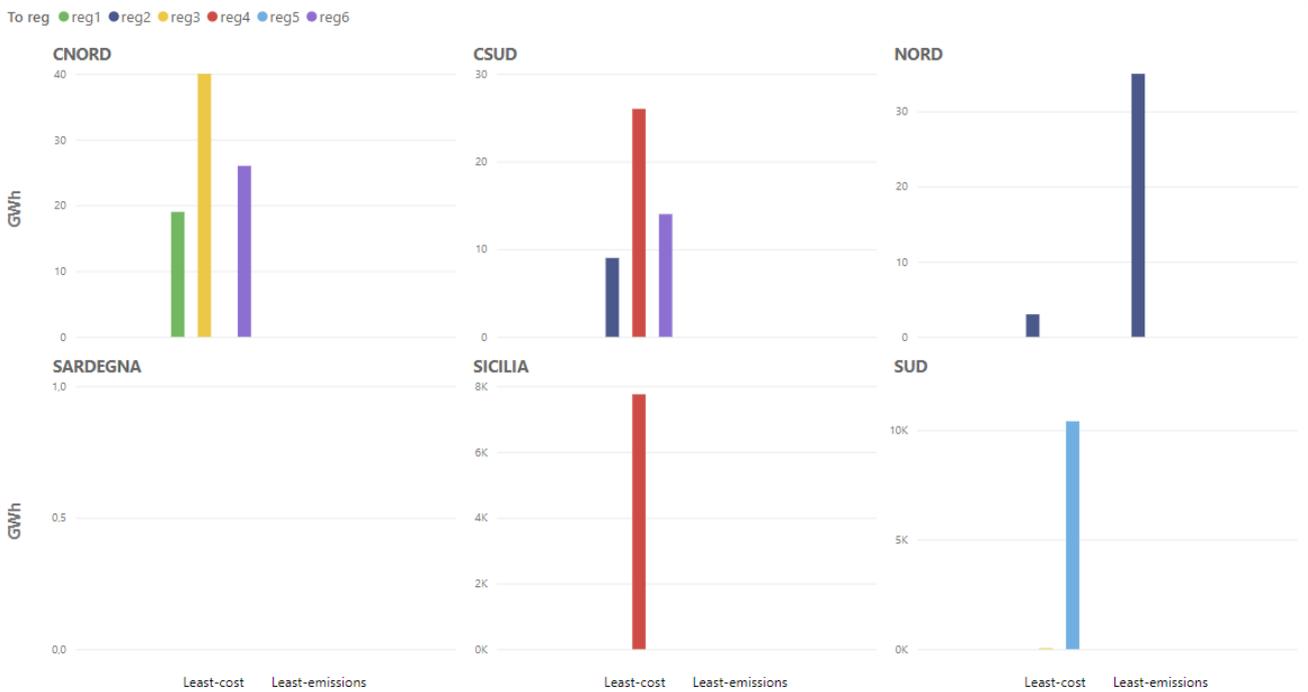


Figure D.3: Hydrogen exports - Multi, least-emission scenario.

# E | Appendix E

---

Algorithm E.1 Land calculation in "ModelVariables.py"

---

```

1 def _calc_regional_land(self):
2     """
3     Calculates the regional land objective function
4     """
5     self.total_land_allregions = np.zeros((len(self.model_data.
6     settings.years), 1))
7
8     for reg in self.model_data.settings.regions:
9
10        total_land_regional = np.zeros((len(self.model_data.
11        settings.years), 1))
12
13        for ctgry in self.model_data.settings.technologies[reg].
14        keys():
15
16            if ctgry != "Demand" and ctgry != "Transmission":
17
18                total_land_regional += cp.sum(
19                    self.vars.land_usage[reg][ctgry], axis=1
20                )
21
22            self.total_land_allregions += total_land_regional
23
24 def _calc_total_land(self):
25     """
26     Calculates the overall land objective function
27     """
28     if self.model_data.settings.mode == ModelMode.Planning:
29         self.total_land = cp.sum(self.total_land_allregions)

```

```

27
28     elif self.model_data.settings.mode == ModelMode.Operation:
29         self.total_land = cp.sum(self.total_land_allregions)

```

---

Algorithm E.2 Near to optimal Operation mode in "Build.py"

---

```

1 def _solve_n2o(self, number_solutions, cost_relaxation, path,
2     verbosity, solver, **kwargs):
3
4     """
5     Creates a CVXPY problem instance, if the output status is
6     optimal, returns the results to the interface.
7     """
8
9     print("\n ----- NEW RUN ----- \n")
10
11    if self.model_data.settings.optimization == OptimizationMode.
12    Single:
13        return print(
14            "Wrong run function. Use run"
15        )
16
17    if self.model_data.settings.optimization == OptimizationMode.
18    Multi:
19        return print(
20            "Wrong run function. Use run"
21        )
22
23    """
24    First optimal solution: least-cost.
25    """
26
27    objective = cp.Minimize(self.global_objective)
28    problem = cp.Problem(objective, self.constr)
29    problem.solve(solver=solver, verbose=verbosity, **kwargs)
30
31    if problem.status == "optimal":
32
33        res = RESULTS.copy()
34        to_add = []
35        if self.model_data.settings.multi_node:

```

```
31         if self.model_data.settings.mode == ModelMode.Planning
32             :
33                 to_add = [
34                     "line_totalcapacity",
35                     "line_new_capacity",
36                     "real_new_line_capacity",
37                     "line_decommissioned_capacity",
38                     "cost_inv_line",
39                     "cost_fix_line",
40                     "cost_decom_line",
41                     "cost_variable_line",
42                     "tot_cost_multi_node"
43                 ]
44             else:
45                 to_add = [
46                     "line_totalcapacity",
47                     "cost_fix_line",
48                     "cost_variable_line",
49                     "tot_cost_multi_node"
50                 ]
51         else:
52             to_add = [
53                 "tot_cost_single_node"
54             ]
55
56         if self.model_data.settings.mode == ModelMode.Planning:
57             to_add.extend(PLANNING_RESULTS)
58         if self.model_data.settings.multi_node:
59             to_add.extend(MULTI_NODE_RESULTS)
60
61         res.extend(to_add)
62         result_collector = namedtuple("result", res)
63         results = result_collector(
64             **{result: getattr(self.vars, result) for result in
65             res}
66         )
67
68         Min_NPC = self.global_objective.value
```

```

68     if self.model_data.settings.mode == ModelMode.Operation:
69         Min_NPC = self.global_objective.value[0]
70         emissions_Min_NPC = results.tot_emissions.value
71         Max_NPC = Min_NPC*(1+cost_relaxation)
72         land_Min_NPC = self.global_land_objective.value
73
74     else:
75         print(
76             "No solution found and no result will be uploaded to
the model",
77             "critical",
78         )
79
80     print("\n ----- NEW RUN ----- \n")
81
82     """
83     Second optimal solution:  minimum emissions and costs =
Max_NPC allowed.
84     """
85
86     cost_constr = [self.global_objective <= Max_NPC]
87     objective = cp.Minimize(self.global_emission_objective)
88     problem = cp.Problem(objective, self.constr + cost_constr)
89     problem.solve(solver=solver, verbose=verbosity, **kwargs)
90
91     if problem.status == "optimal":
92         [Same as above]
93
94     print("\n ----- NEW RUN ----- \n")
95
96     """
97     Steps as in the multi-objective optimization in order to find
the emission list that reaches only the Max_NPC.
98
99     """
100
101     step = (emissions_Min_NPC-emissions_Max_NPC)/(number_solutions
-1)
102

```

```

103     i = 1
104     emission_list = []
105     while i < (number_solutions-1):
106         emission_list.append(emissions_Min_NPC-i*step)
107         i += 1
108     emission_list = [emissions_Min_NPC] + emission_list[1:
number_solutions-1] + [emissions_Max_NPC]
109
110     """
111     Near to optimal solutions
112     """
113     Emission_n2o = []
114     Costs_n2o = []
115     land_list = []
116     for emis in emission_list:
117         print("\n ----- NEW RUN -----
\n")
118         new_constr1 = [self.vars.tot_emissions <= emis]
119         new_constr2 = [self.global_objective <= Max_NPC]
120         objective = cp.Minimize(self.global_land_objective)
121         problem = cp.Problem(objective, self.constr + new_constr1
+ new_constr2)
122         problem.solve(solver=solver, verbose=verbosity, **kwargs)
123
124         if problem.status == "optimal":
125             [Same as above]
126
127             if self.model_data.settings.mode == ModelMode.
Operation:
128                 land_list.append(self.global_land_objective.value
[0])
129                 Emission_n2o.append(self.global_emission_objective
.value[0])
130                 Costs_n2o.append(self.global_objective.value[0])
131             else:
132                 land_list.append(self.global_land_objective.value)
133                 Emission_n2o.append(self.global_emission_objective
.value)
134                 Costs_n2o.append(self.global_objective.value)

```

```
135
136
137     new_constr1 = []
138
139
140     else:
141         print(
142             "No solution found and no result will be uploaded
to the model",
143             "critical",
144         )
145
146
147     land_list = land_list[0:number_solutions-1] + [land_Max_NPC]
148     Emission_n2o = Emission_n2o[0:number_solutions-1] + [
emissions_Max_NPC]
149     Costs_n2o = Costs_n2o[0:number_solutions-1] + [Max_NPC]
150
151
152     fig = go.Figure()
153     fig.add_trace(go.Scatter(
154         x= Emission_n2o,
155         y=Costs_n2o,
156         mode='markers',
157         marker=dict(
158             size=10,
159             color='red',
160             symbol='circle'
161         )
162     ))
163
164     fig.update_layout(
165         title='Near to optimal solutions',
166         xaxis_title='emissions [Kg]',
167         yaxis_title='NPC [Euro]'
168     )
169
170     fig.write_html(path + "N2o.html")
171
```

```

172     print("\nEmissions = " +str(Emission_n2o))
173     print("NPCs = " +str(Costs_n2o))
174     print("Land = "+ str(land_list))

```

---



---

Algorithm E.3 Near to optimal interface in "Main.py"

---



---

```

1 def run_n2o(self, solver, number_solutions, cost_relaxation, path,
2     verbosity=True, force_rewrite=False, **kwargs):
3
4     # checks if the input parameters are imported to the model
5     if self.__model_data == None:
6
7         raise DataNotImported(
8             "No data is imported to the model. Use " " '
9             read_input_data' function."
10        )
11
12    if self.results != None:
13
14        if not force_rewrite:
15            raise ResultOverWrite(
16                "Model is already solved."
17                "To overwrite the results change "
18                "'force_rewrite'= True"
19            )
20
21        self.backup_results = deepcopy(self.results)
22
23        self.results = None
24
25    # checks if the given solver is in the installed solver
26    package
27    if solver.upper() not in installed_solvers():
28
29        raise SolverNotFound(
30            f"Installed solvers on your system are {

```

```
31     model = BuildModel(model_data=self.__model_data)
32
33     self.constr_backup = model.constr
34
35     results = model._solve_n2o(number_solutions, cost_relaxation,
36     path, verbosity=verbosity, solver=solver.upper(), **kwargs)
37     self.check = results
38     if results is not None:
39         self.results = results
```

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## List of Symbols

<b>Technology</b>	<b>Description</b>
Coal	Coal
HFO	Heavy Fuel Oil
CCGT	Combined cycle gas turbine
SCGT	Simple cycle gas turbine
NG_CCS	Natural gas and carbon capture and storage
Wind	On-shore wind
OFF_Wind	Off-shore wind
BW_PP	Biofuels and waste power plant
PV	Photovoltaic
Geo_PP	Geothermal power plant
Hydro	Hydro power plant
NG_heat	Natural gas heat plant
BW_heat	Biofuels and waste heat plant
Battery	Electrochemical storage
PHS	Pumped Hydro storage
Electrolysis	Electrolysis
SMR	Steam Methane Reforming
SMR_CCS	SMR and carbon capture and storage
Hydrogen storage	Hydrogen storage

<b>Name</b>	<b>Description</b>
$f_1(x)$	cost objective function
$f_2(x)$	emission objective function
$f_3(x)$	land objective function
$\epsilon$	cost relaxation
$p$	number of solutions
reg1	NORD
reg2	CNORD
reg3	CSUD
reg4	SUD
reg5	SICI
reg6	SARD

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