SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

Beyond optimal cost in energy models: overview of methodologies and application to the Italian energy system as a case-study

TESI MAGISTRALE IN Energy ENGINEERING – INGEGNERIA Energetica

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ACADEMIC YEAR: 2024-2025

1. Introduction

The escalating impact of human activities on the environment has intensified concerns over climate change and its associated risks. With rising global temperatures and deteriorating ecological systems, the urgency for effective climate action has never been greater. Italy, as a key member of the EU, is deeply involved in these initiatives. The Italian Integrated National Energy and Climate Plan (INECP) and the National Recovery and Resilience Plan (NRRP) outline Italy's commitment to the EU's climate goals. Italy's strategy includes ambitious targets for renewable energy adoption and energy efficiency improvements.

Energy System Optimization Models (ESOMs) have long been a cornerstone in the planning and analysis of energy systems, providing crucial insights into the most cost-effective ways to meet energy demands while minimizing environmental impact.

In recent years, energy modelling research has increasingly focused on finding alternative solutions beyond the least-cost options. Traditional single-optimal solution ESOMs often fail to account for social issues that cannot easily be quantified in a mathematical model. These issues range from public acceptance of certain technologies to the regional overuse of a technology compared to actual energy consumption. These factors significantly influence policy decisions and should not be overlooked. Consequently, policymakers are willing to accept higher costs to address these issues, a point that will be further discussed in this thesis. Recently, a new methodology called "Modelling to Generate Alternatives" (MGA), introduced by DeCarolis, has been applied in energy modelling. [1]

This thesis aims to address these limitations by incorporating methodologies that explore near-optimal solutions. The first objective has been addressing the lack of user-friendly automated alternative generation methods in open-source models, specifically Hypatia. Current open-source energy models lack simple automated methods to generate alternative solutions. Existing MGA implementations are often complex, hardly replicable, and difficult to interpret for nonexperts. Additionally, previous attempts to generate alternative solutions in Hypatia required excessive manual intervention, limiting the efficiency and scalability of decision-space analysis. The second objective of this study has been the application of the method to the Italian energy sector and analysing the decision-space for Italy's energy planning. Application of near-optimal solutions to the Italian energy sector provides alternative pathways to achieve the same goal and offers insights about existing trade-offs in the multi-criteria problem of energy planning.

2. Literature Review

2.1 Characterization of the Italian Energy System

Italy's energy transition is marked by a rapid shift towards renewable energy sources (RES) and modernization of the electricity grid to accommodate increasing shares of intermittent renewables. Italy's electricity generation relies on a diverse mix of energy sources, including renewable energy, natural gas, and limited coal and oil-based production.

2.2 Modelling to Generate Alternatives (MGA)

The transition to a sustainable energy system requires not only cost-optimal solutions but also the exploration of near-optimal alternatives that consider social, environmental, and political factors. A systematic literature review was performed using Scopus Advanced Research, applying multiple filtering steps to ensure relevance and minimize bias. The final dataset includes 34 peer-reviewed articles, selected based on keywords related to MGA, multi-objective optimization, near-optimal solutions, and energy transition modeling.

The diverse range of MGA methodologies highlights multiple ways to explore alternative energy transition pathways. The key takeaways for this thesis are:

1. Incorporating cost-relaxation MGA methods: Following Lombardi et al. [2], the thesis will explore how different slack values impact near-optimal solutions.
2. Randomization techniques: Inspired by Trutnevyte [3], randomized weight sampling will be tested to diversify solution sets.
3. Resilience analysis: Zhang et al.'s [4] MGR methodology will be evaluated to ensure solutions remain reliable under uncertain renewable conditions.
4. Policy implications: Integrating constraints other than cost and emissions will enhance the applicability of near-optimal results for real-world decision-making.

Building on these findings, the thesis will focus on adapting and implementing MGA methodologies to Italy's energy transition, particularly for achieving decarbonization by 2050. The key methodologies chosen for implementation include:

1. Cost-relaxation MGA methods: Inspired by Lombardi et al. [2], this approach will assess how different slack values impact near-optimal solutions.
2. Randomized weight assignment: Following Trutnevyte [3], a uniform distribution-based approach will be tested to explore a broader solution space.
3. Resilience-based alternative generation: The insights from Zhang et al. [4] will be incorporated to ensure energy security and system adaptability.

For this study, the crossover technique of the heuristic method has been selected as the method to generate the near optimal solutions. The conclusion has been achieved as the result of the following characteristics of this method:

1. Enhanced Solution Diversity & Decision Space Quality

Unlike Lombardi et al. [2], this method Incorporates randomization, ensuring a broad range of high-quality alternative solutions.

2. More Realistic Representation of the Energy System

Unlike Lombardi et al. [2], this approach does not impose modified weights on all technologies, making it a closer reflection of reality. It is also simpler & more intuitive to implement, reducing complexity without compromising accuracy.

3. Optimal Balance Between Feasibility & Diversity

This technique avoids the high computational costs of Monte Carlo or extensive scenario-based methods, while still capturing diverse outcomes.

4. Adaptability to Italy’s Complex Energy System

3. Methodology

3.1 Hypatia

Hypatia is an open-source energy system optimization framework developed in Python by the SESAM research group at Politecnico di Milano. It is designed to optimize both the operation and planning of energy systems over different timeframes. In short-term scenarios, it focuses on optimizing system operations within a single year, while in long-term planning, it manages continuous capacity expansion over an extended period.

3.2 Heuristic Method – Crossover Technique

For this study, an innovative approach inspired by the crossover technique of the Heuristic method, originating from genetic algorithms, has been chosen as the method to generate the alternative solutions in this study. This method has advantages over other approaches to generate near optimal solutions, especially the Lombardi et al. [2], by incorporating randomization, using a more realistic representation of the reality and balancing between feasibility and diversity of the solutions.
To achieve a diverse decision space, we need to have solutions that are maximally different from each other. One way to achieve this is to limit the most dominant technologies in the optimal solution and encourage the underutilized technologies. This way we will end up with the new solutions that use a very different energy mix. We also would like to have unique solutions, so we can have high quantities of the solutions, increasing the quality of the decision space. Hence, some randomized value is appreciated.

The concept of the used approach is to iteratively impose additional capacity constraints to the original problem by blending dominant and random technologies. The idea is to suppress the dominant technologies and encourage underutilized technologies in alternative solutions to increase the diversity and flexibility of the decision space.

Figure 1 - Alternative Solution Generation Process Chart

Starting from the original problem, the optimal solution is obtained. In this optimal solution, one single technology is the most dominant one, in terms of the new installed capacity throughout the years. Other than this dominant technology, there are other technologies that are involved (or could have been involved) in the energy mix of the optimal solution for energy planning. The idea is to impose a limiting constraint to the most dominant technology (Max_TotalCapacity limit), and to impose an encouraging constraint to a random technology among other technologies. (Min_TotalCapacity)
After the identification of the two technologies, we combine these two technologies. (crossover) In this study, we have used a simple arithmetic average as a way to combine these two values, for the sake of simplicity. This combined variable is used as the basis for imposing the additional constraint in the sequential near-optimal problems. The way of crossing over can make some differences but does not change the main concept of combining and imposing the constraints.

Now, we have a variable based on the most dominant technology and a random technology. This variable is now used to impose the additional constraints in the next optimization run. In the new optimization problem, we use all the parameters of the original optimization problem, with two new constraints: A new maximum capacity limit to the most dominant technology, and a new minimum capacity limit to the random technology. The value of these limits is based on the variable we just calculated. These new constraints form the new optimization problem and are adjusted until we have an optimal solution (to this new problem, which is equal to a near-optimal solution to the original problem) that is both feasible, and within a cost slack.

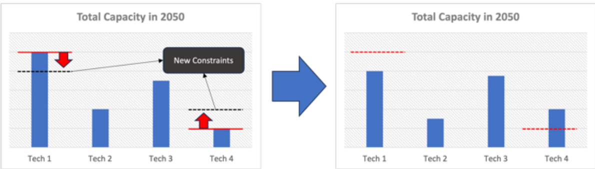

Figure 2 - How the New Imposed Constraints Force The Near-Optimal Solution

This new solution is feasible, within the cost relaxation limit and unique. Each time this process is done, as a result of the new dominant technologies and a randomly selected technologies, we end up with a near-optimal solution that is unique.

3.3 Automated Workflow

Having an automated workflow to generate the alternative solutions is a crucial objective. An automated workflow can ideally perform all the required steps to generate the decision space, with minimal modeller's intervention. It also improves the efficiency and scalability of the decision space. Last but not least, an automated workflow to generate alternative solutions makes it easier for everybody to have access to all the insight of the decision space.

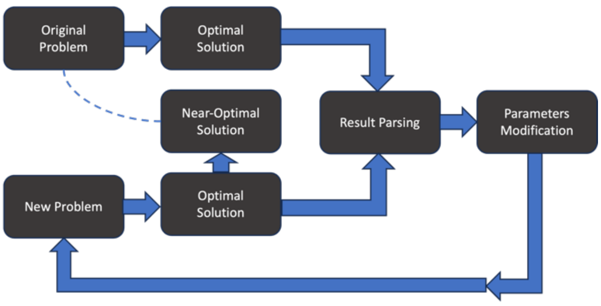

Figure 3 - Automated Workflow Process Chart

Automation enhances quality and quantity of generated solutions, requires minimal modeller intervention, and improves reproducibility and usability for policymakers and researchers.

3.4 Italy as the Case Study

A Reference Energy System (RES) serves as the structural representation of an energy system within an optimization model. The goal in constructing it is to closely reflect the real-world energy system of the case study.
For this case study, was defined a RES for each Italian bidding-zone defined by Terna [5].

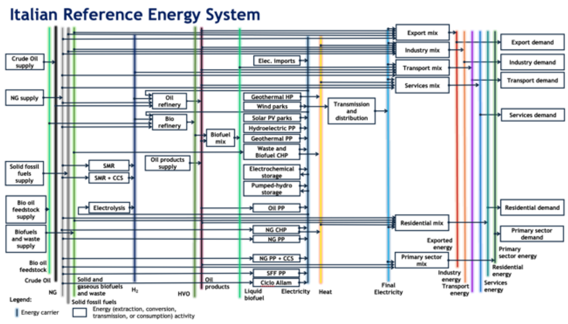

Figure 4 - Reference Energy System of Italian Energy Sector

4. Results and Discussion

4.1 Enhancements of Hypatia

The main objective of this study has been the presentation of a tool applied to an open-source energy modelling platform to address the lack of automation and simplicity in the alternative solution generation. To address this objective, the Hypatia core model has been enhanced with a new python script (enhancements.py) with over 1700 lines of code and more than 15 new functions. This enhancement is integrated seamlessly with the original code of Hypatia, and with minimal interface change of the code, allowing Hypatia to have a fully automated pipeline that generates multiple near-optimal solutions with zero manual intervention.
The main focus in this whole workflow and method to generate alternative solutions has been diversity of the technology use. The mentioned method to generate alternatives used two technologies (the most dominant technology and a random technology) to generate the alternative solutions. But can the same method be expanded to result in better decision space?
To analyse this idea, a user-defined parameter has been implemented in Hypatia. It is called Ω. It is a parameter that controls how many technologies are combined in each iteration, and enables structured scalling of solution diversity. Clearly, the higher the Ω, the higher the complexity of the

problem. It takes more time to generate the decision space, as the problem will be over-constrained and it has higher computational cost. On the other hand, with higher Ω we expect a more diverse decision space in the end, as more dominant technologies are suppressed and more underutilized technologies are encouraged in the alternative solutions.
After assessment, we see that there is a trade-off in this method. Working with higher number of technologies to generate the alternative solutions (higher Ω) result in the higher quality of the decision space until a certain point. After that, increase the number of involved players complicates the problem with no sensible outcome of quality. Of course, all of the inputs result in a decision space in the end. The difference is the time and the diversity of the solutions. For the analysis of the Italian energy sector, Ω of 2 has been selected as the best compromise of quality and speed.

4.2 Application to the Italian Energy Sector

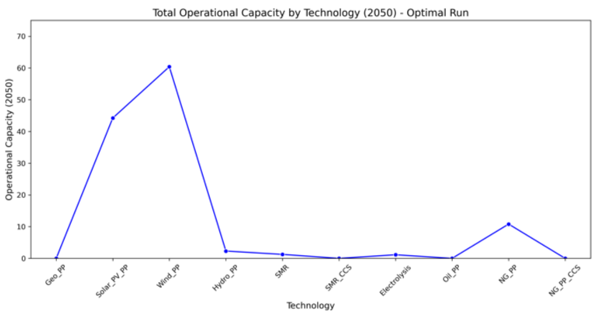

Figure 5 - The Total Operational Capacity of the Optimal Solution (GW)

This is the technology mix suggested by the cost-minimization result of the Hypatia. As we can see, there is only one single solution. It offers no flexibility, and the policymaker preferences does not matter. It takes into account only the cost, and other criteria important to the policymaker are not considered. It might not even be feasible in the real world.
With only 3 near-optimal solutions, we can see the flexibility in the planning. Not only we can see the most-important technologies, but we can also see that for all technology there is a range of outcomes.

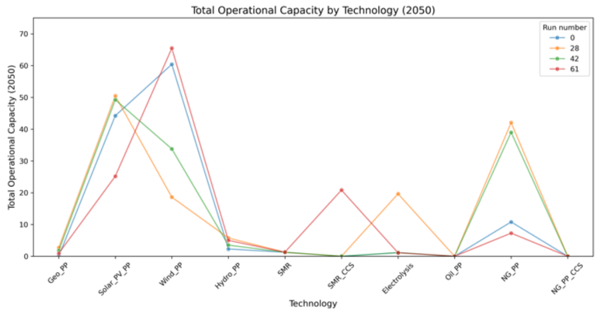

Figure 6 - The Total Operational Capacity of 4 Different Solutions (GW)

If we increase the number of solutions to 100:

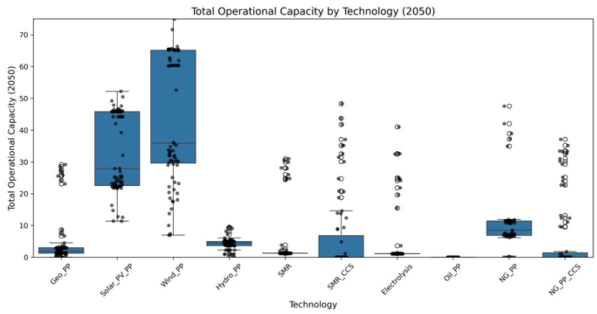

Figure 7 - The Decision Space of the Italian Energy Sector with 5% Cost Relaxation

Compared to the single optimal solution, this decision space offers flexibility. We can see that Solar PV and Wind power plants are the most important ones for the future. However, we can also see that there are feasible solutions where Solar and Wind are not required that much. The Policymaker now can make a decision, based on the preferences, and considering other metrics than cost. The decision space is not solely for the electricity generation technology. As we can see, even among the technologies producing hydrogen, we can have different pathways to achieve the same goal. (meeting the demand) It is also much more possible to have a real-world feasible solution in this decision space, than in the single optimal solution. The decision space includes different solutions that can be very different from each other. As a matter of fact, this has been the criteria to assess a decision space: A good decision space should have diverse solutions, meaning solutions that are maximally different from each other.
Following, we can see one of the solutions of the decision space, compared to the optimal solution:

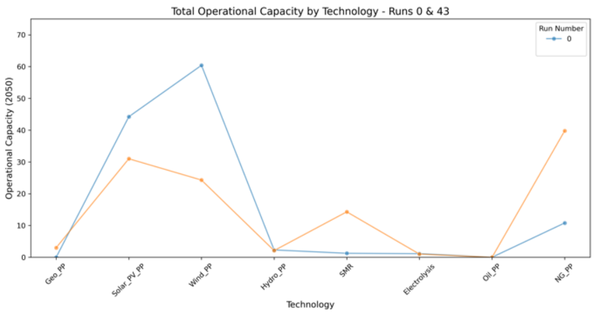

Figure 8 - Total Operational Capacities for Run 0 (Optimal Run) & Run 74 (GW)

This run represents a lower-renewable, fossil fuel-based scenario, where natural gas power plants replace much of the renewable capacity, and hydrogen is primarily produced via steam methane reforming instead of electrolysis. While this solution emits more CO2 and is costlier than the optimal model, it aligns with other policymaker priorities such as:

- Preserving existing infrastructure and avoiding stranded assets, reducing financial losses from early decommissioning.
- Ensuring job security, particularly in regions historically reliant on conventional energy industries.
- Minimizing land-use conflicts, which have hindered renewable energy expansion in Italy due to concerns over agriculture, tourism, and local aesthetics.
- Providing dispatchable and reliable energy, ensuring grid stability without dependence on weather conditions.

Next, we can see another solution of the near-optimal solutions (Run 74), compared to the optimal solution:

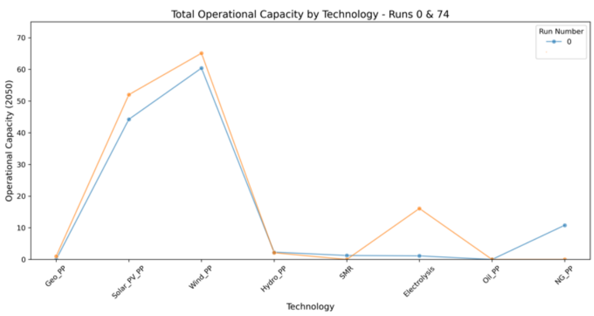

Figure 9 - Total Operational Capacities for Run 0 (Optimal Run) & Run 74 (GW)

this solution envisions a high-renewable, zero-emission scenario, eliminating fossil fuels by 2050 and meeting hydrogen demand solely through electrolysis. While it offers lower cumulative CO2 emissions, aligning with Italy's environmental targets, it comes with notable trade-offs:

- High infrastructure costs for grid upgrades, battery storage, and hydrogen production.
- Land footprint issues, as large-scale wind and solar projects face opposition from local communities.
- Intermittency challenges, requiring significant investments in storage and flexibility solutions.
- Enhanced energy security and independence, reducing reliance on imported fossil fuels and insulating the economy from geopolitical price volatility.
- Public health benefits, cutting pollution-related healthcare costs.

The number of solutions and the quality of them is a user input, and also is the reference energy system. The RES can include different regions, higher precisions in the site location of the renewable power plants, different sectors to be interconnected, and different kinds of energy carriers to consider. The decision space can offer flexibility in all of these scenarios. With the application of the mentioned reference energy system of Italy, and among 100 near-optimal solutions, we witness a high degree of flexibility in technology use. We note which technologies are the most important ones, while understanding that almost no technology is irreplaceable. Each solution has some pros and some cons, and there is no right and wrong among solutions. In the end, it is just what the policymaker desires in the decision space.

5. Conclusions

This study explores the role of near-optimal solutions in energy system planning, moving beyond strict cost and CO2 minimization to incorporate broader policymaker priorities. Unlike traditional optimization models that yield a single "optimal" solution, near-optimal approaches provide a range of viable pathways, allowing for greater flexibility and resilience in decision-making. By considering factors such as economic stability, energy security, and public acceptance, this method offers a more realistic and adaptive framework for long-term energy transitions.

The study introduces enhancements to Hypatia, integrating an automated pipeline with over 1,700 lines of Python code to generate and analyze 100 near-optimal solutions within a +5% cost constraint. A key innovation is the Ω parameter, which controls the diversity of solutions by adjusting the number of technologies in each iteration. The results demonstrate that this method effectively expands the decision space, offering policymakers multiple viable alternatives without requiring extensive manual adjustments.

Two contrasting scenarios illustrate the trade-offs inherent in energy planning. Run 43 represents a fossil fuel-based pathway, where natural gas and steam methane reforming dominate. While this scenario emits more CO2 and costs more than the optimal model, it aligns with policies focused on job security, infrastructure preservation, and grid stability, while reducing land-use conflicts that often hinder renewable energy expansion. Conversely, Run 74 envisions a zero-emission energy system by 2050, relying entirely on renewables and electrolysis for hydrogen production. While environmentally superior, it presents higher infrastructure costs, land footprint issues, and intermittency challenges, though it enhances energy independence and public health.

What this study ultimately highlights is that there is no single "correct" energy pathway—only trade-offs that must be weighed based on societal priorities. A model may define an "optimal" solution mathematically, but in reality, policymakers operate in a world of competing interests, economic pressures, and political constraints. Some may prioritize affordability over emissions reductions, while others focus on long-term sustainability despite higher upfront costs. By embracing near-optimal solutions, we move away from rigid decision-making and instead offer a spectrum of choices, making energy planning more democratic, inclusive, and adaptable.

Moreover, this research underscores the growing importance of open-source and automated modeling tools in shaping the energy transition. Energy planning is no longer limited to a select group of experts—accessible, flexible models like Hypatia empower a wider range of stakeholders, from policymakers to researchers and local communities, to engage with energy transition scenarios. By refining decision-making processes and enhancing transparency, this approach ensures that future energy systems are not just technically feasible, but also socially and economically sustainable.

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6. Acknowledgements

I would like to express my deepest gratitude to my supervisor, Professor Emanuela Colombo, for her guidance and support throughout this research. Her insights and expertise have been invaluable in shaping this work.

A special and heartfelt thank you to my co-supervisor, Francesco Cruz Torres, whose patience, continuous feedback, and unwavering support over the past 14 months have been crucial in bringing this thesis to completion.

I am also deeply grateful to my family and friends for their constant encouragement and belief in me, even during the most challenging moments of this journey.