POLITECNICO
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Beyond Optimal Cost in Energy Models

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2024-25

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Master of Science – Energy Engineering

Outline

1. Introduction, Motivation & Objectives

2. Literature Review

3. Methodology

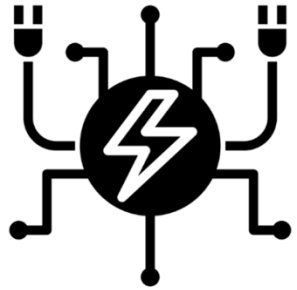
4. Results & Discussion

Energy System Models

Energy models are streamlined manifestation of real-world systems. (Priyanka .L, et al.)

Global Energy Transition

- Environmental dimension
- Economic dimension
- Social Equity
- Governance



More Complex Energy Systems

Examples of Challenges

- High share of Variable sources
- Need of flexibility / storage
- Role of Cross-Sectorial Linkages
- Inter or intra-national connections

Energy System Optimization Models (ESOMs)

Mathematical models used to determine the most cost-effective, efficient, and sustainable way to supply energy while meeting technical and policy constraints. (Pfenninger, S., et al.)

They help policymakers and researchers plan resilient, low-carbon energy systems by evaluating trade-offs between costs, emissions, and technological feasibility.

ESOM Examples:

- TIMES/MESSAGE (Used by IEA and IIASA)
- OSeMOSYS
- Calliope
- **Hypatia** (Developed at Polimi)

Hypatia

Hypatia is an open-source modeling framework written in Python, designed to optimize both the operation and planning of energy systems over short-term and long-term horizons.

Key features:

- Planning & Operation optimization modes
- Sector coupling
- High temporal & spatial resolution
- User-friendly

Hypatia's capacity expansion planning mode has been enhanced and used in this study.

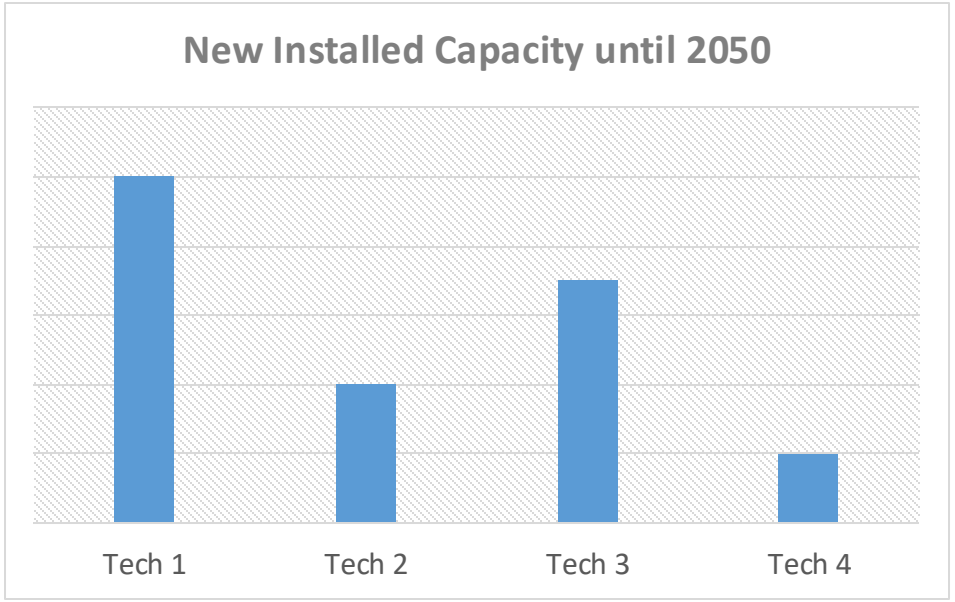
Optimal Solution

Mathematically, the general formulation of an energy system optimization problem can be expressed as follows:

$$\min\ C = \sum_t \sum_i \left(C_i^{\text{cap}} \cdot x_i + C_i^{\text{op}} \cdot y_{i,t}\right)$$

where:

- C is the total system cost,
- C_i^{cap} is the capital cost of technology i,
- x_i is the installed capacity of technology i,
- C_i^{op} is the operational cost per unit of energy produced,
- $y_{i,t}$ is the energy output of technology i at time t.

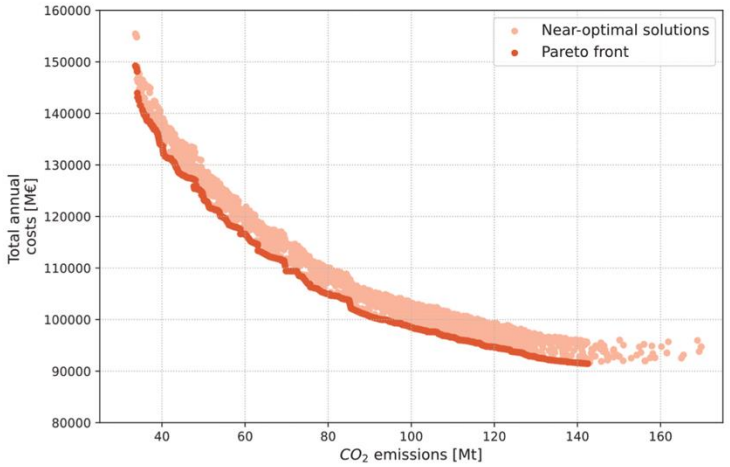


Near-Optimal Solutions

Relaxing the constraint (cost), allowing a range of solutions to flow.

➡ Solutions with different configurations

A solution that achieves an objective value (e.g., cost, emissions) very close to the best possible (optimal) outcome but has different configurations.



Why?

Multi-Criteria

- Feasibility
- Flexibility
- Robustness

Modelling to Generate Alternatives (MGA):

Forcing an optimization model to search the feasible, near-optimal region for alternative solutions that are maximally different in decision space.

Motivation & Objectives

1. Analyze the decision-space for Italian energy sector for 2050

Importance of Model-Based Decision Space Analysis (MGA) in Energy Modelling:
Energy planning involves multiple uncertainties and trade-offs.
Understanding the decision space is crucial for robust policy-making.

➡ **Application to the Italian energy sector**:

- Multi-Criteria Solutions
- Provides alternative pathways to achieve the same goal.
- Offers insights into trade-offs between costs, emissions, and technological choices.

Motivation & Objectives

2. Address the Lack of User-Friendly Automated Alternative Generation Methods in Open-Source Models

- Current open-source energy models, including Hypatia, lack simple, automated methods to generate alternative solutions.
- Existing MGA implementations are often complex, hardly-replicable, and difficult to interpret for non-experts.
- Previous attempts to generate alternatives in Hypatia required manual intervention, limiting the efficiency and scalability of decision-support analysis.

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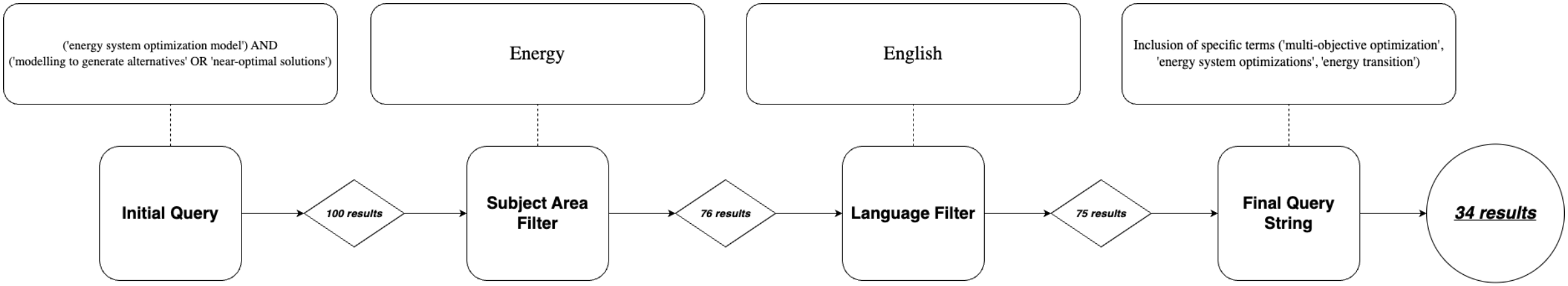
Automation Benefits:

- Enhances both quality and quantity of generated solutions.
- Requires minimal modeller intervention, making the process less biased and more accessible.
- Improves reproducibility and usability for policymakers and researchers.

Literature Review Approach



- **Systematic Review:** 34 peer-reviewed studies selected via Scopus.
- **Key Focus Areas:** Multi-objective optimization, cost-relaxation techniques, resilience.

2. Literature Review

Key Findings:

- Cost-Relaxation Methods (e.g., SPORES by Lombardi et al.) expand the solution space.
- Diversity-Focused MGA (Zhang et al.) ensures robustness against uncertainty.
- Randomized Approach (Trutnevyte) increases diversity in alternatives.

The method to generate near-optimal solutions should have following properties:

1. Dynamic cost relaxation
2. Focus on diversity of the solutions
3. Randomization
4. Broad range of solution, both in term of quality and quantity

Key Approaches to Generating Alternative Solutions

- Hop-Skip-Jump (HSJ) (Brill, 1979)
- Monte Carlo (MC) (Metropolis & Ulam, 1949)
- Linear Programming (LP) Relaxation (Wolsey, 1998)
- Metaheuristic Optimization (Hassan et al., 2005)
- Scenario-Based Optimization (DeCarolis et al., 2012)

- **Heuristic Methods**– Inspired by Natural Evolution

Originating from genetic algorithms (Holland, 1975), heuristic methods mimic biological evolution through mutation, crossover, and selection. They iteratively refine solutions, adapting to problem constraints while maintaining computational efficiency.

Why Use Heuristic Methods in This Study? (Crossover Technique)

1. Enhanced Solution Diversity & Decision Space Quality
Unlike Lombardi et al. (2023), Incorporates randomization, ensuring a broad range of high-quality alternative solutions.

2. More Realistic Representation of the Energy System
Unlike Lombardi et al. (2023), 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.

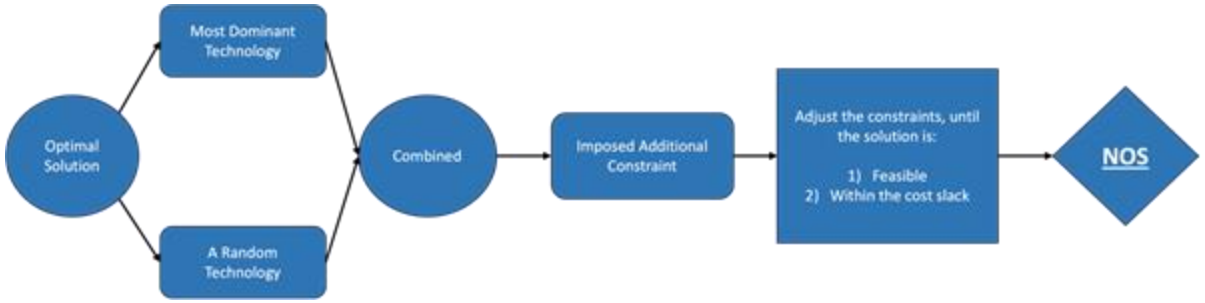
3. Optimal Balance Between Feasibility & Diversity
Avoids the high computational costs of Monte Carlo or extensive scenario-based methods while still capturing diverse outcomes.

4. Adaptability to Italy's Complex Energy System
Effectively models regional constraints and a diverse technology mix.

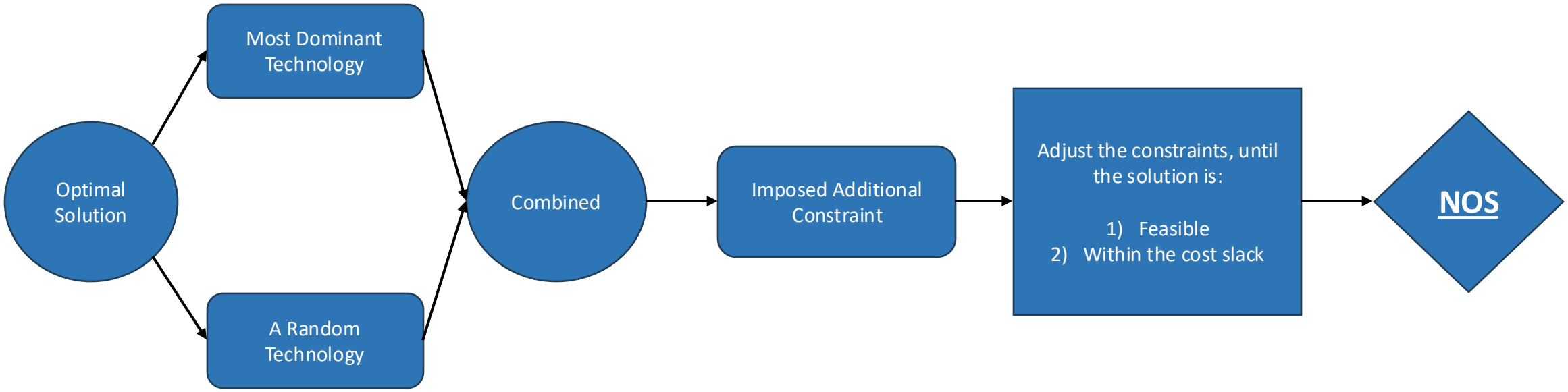
The Heuristic “Combine” Method - Crossover

Concept of the Idea:

- Iteratively impose capacity constraints by blending dominant and random technologies.
- Suppresses dominant technologies in the alternative solutions.
- Encourages underutilized technologies to emerge in alternative solutions to increase the flexibility of the decision space.



3. Methodology



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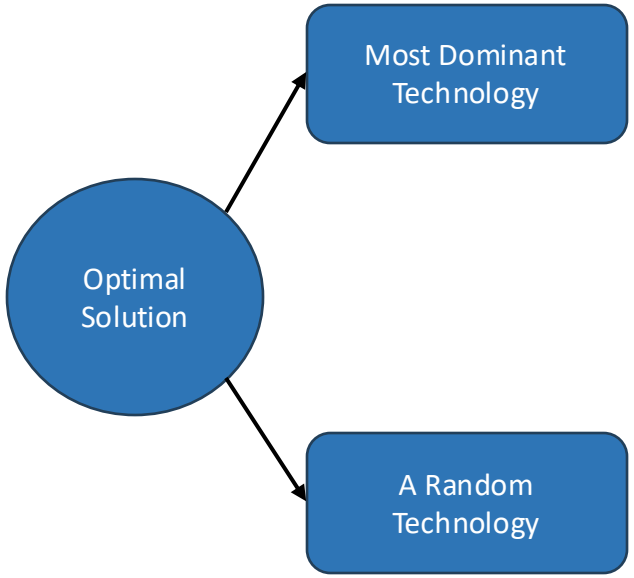

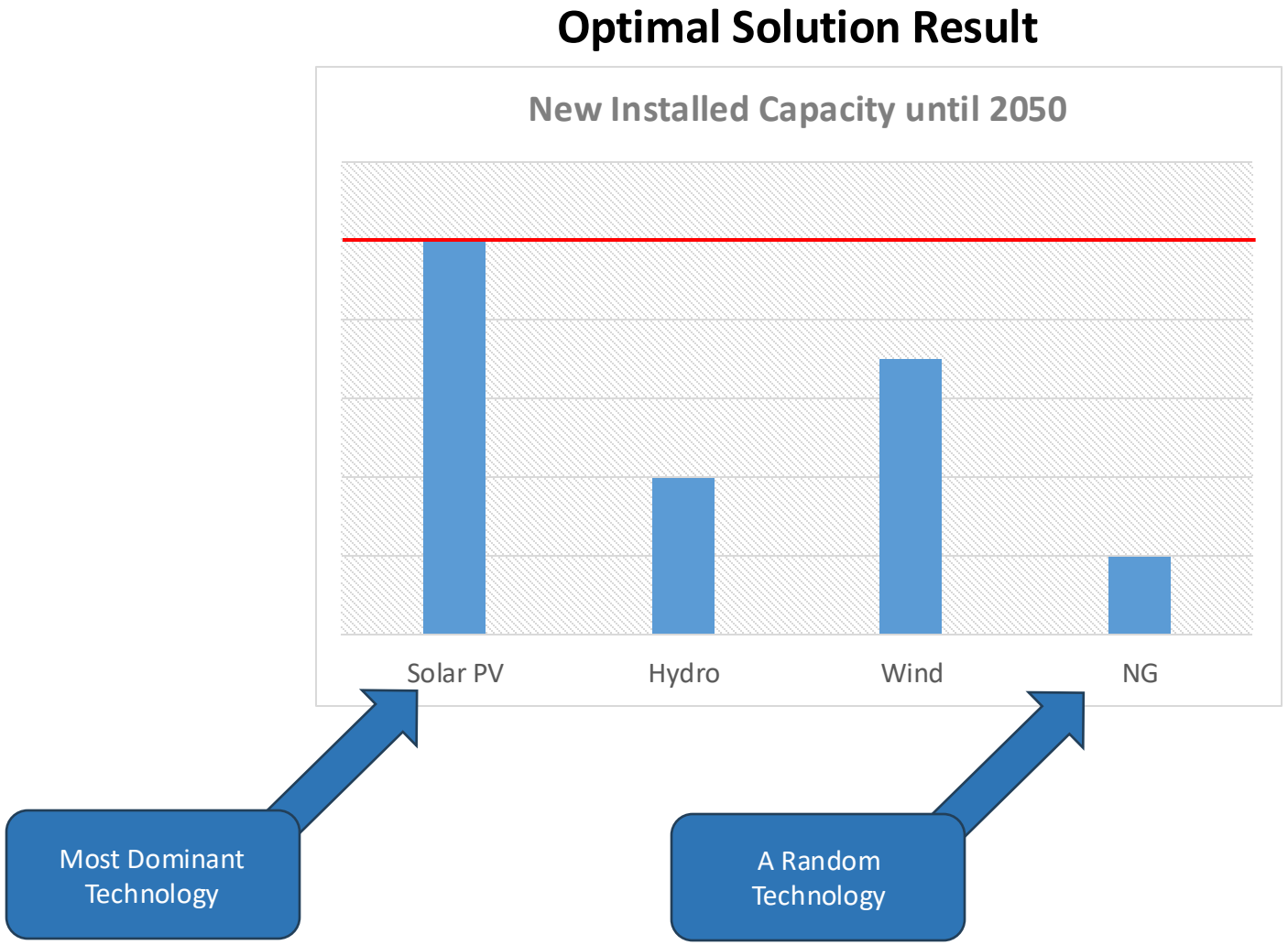

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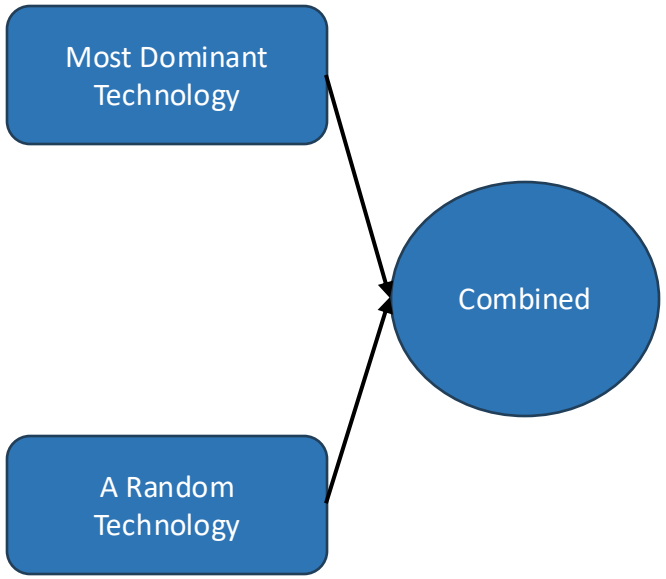
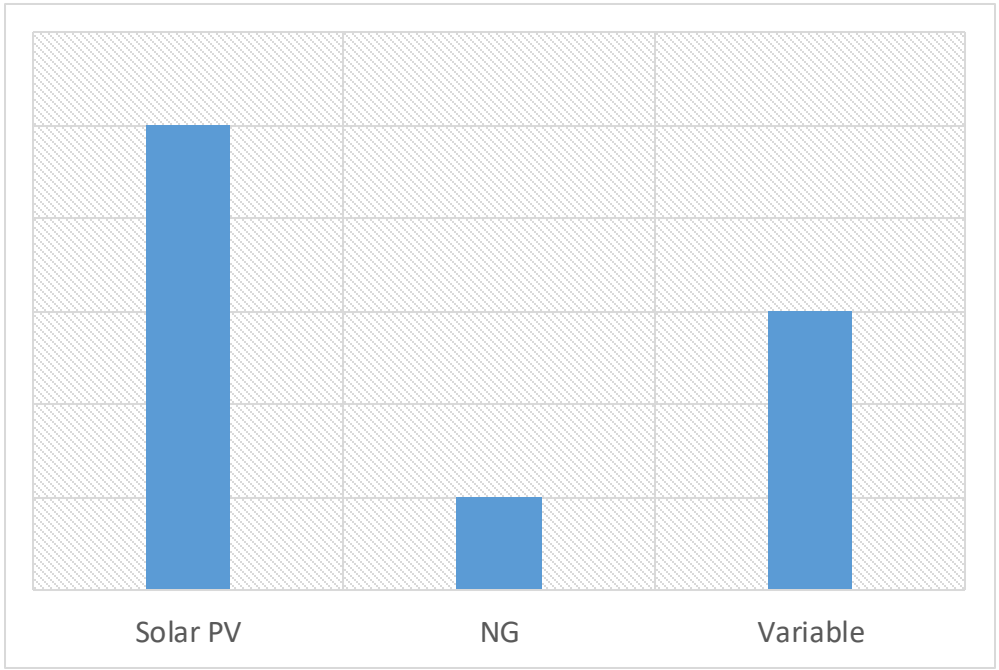
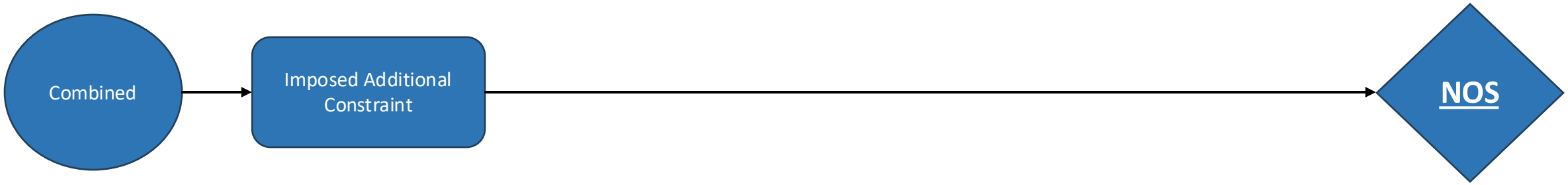
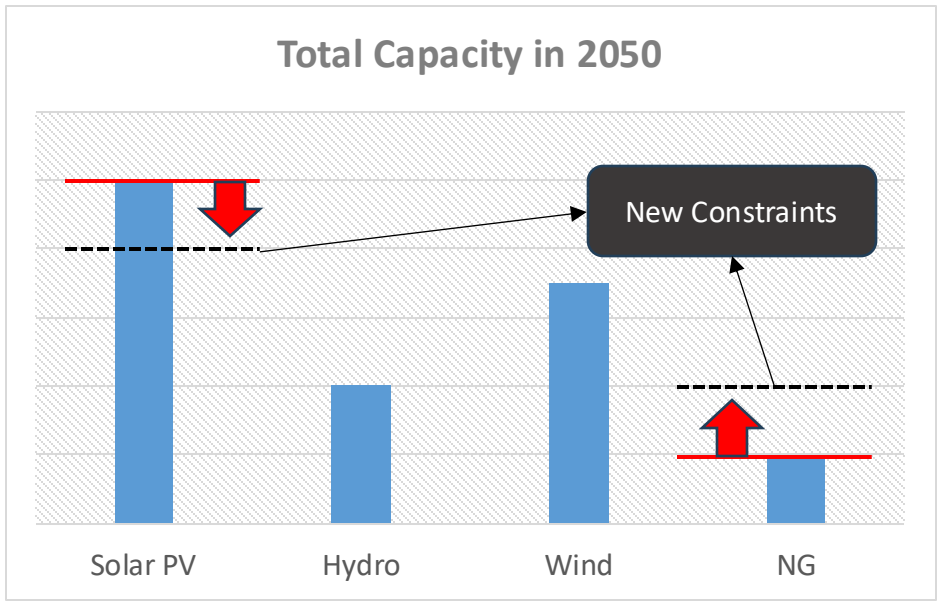




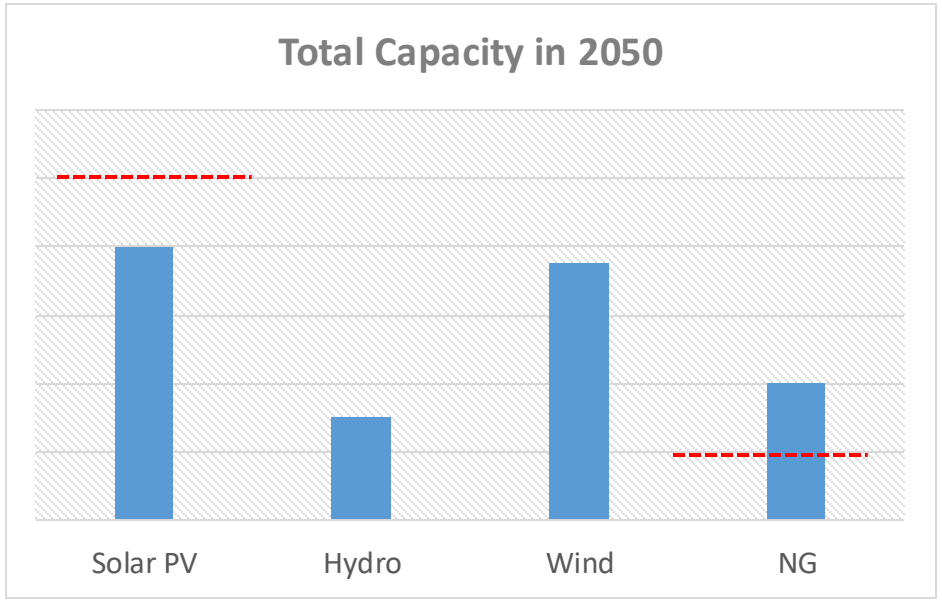
A ***combine variable*** is calculated by averaging the new installed capacities of selected dominant and random technologies. This value serves as the basis for adjusting constraints in subsequent runs.

3. Methodology





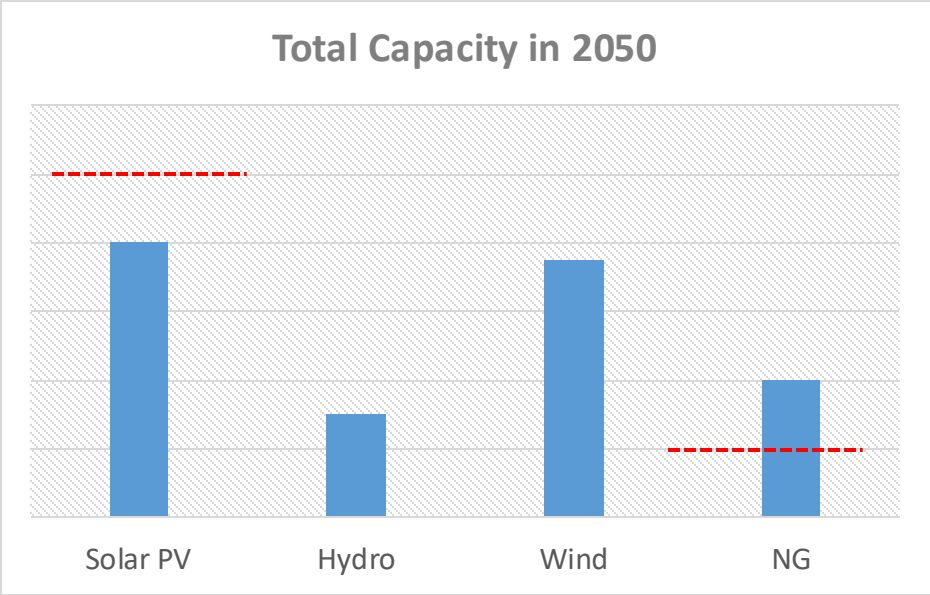
Optimal Solution Result



Near-Optimal Solution Result

3. Methodology

NOS



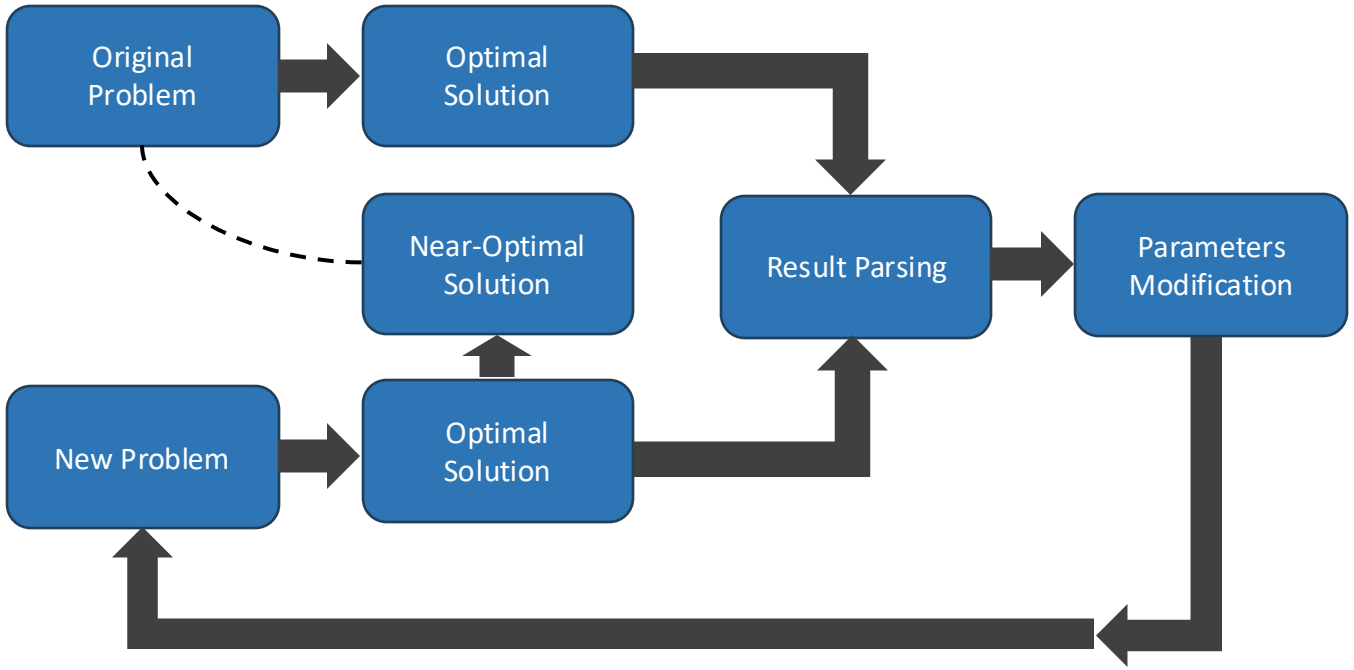
Near-Optimal Solution Result

This new solution is:

- **Feasible**
- **Within the cost relaxation limit**
- **Unique (Randomization)**

3. Methodology

Automated work-flow:

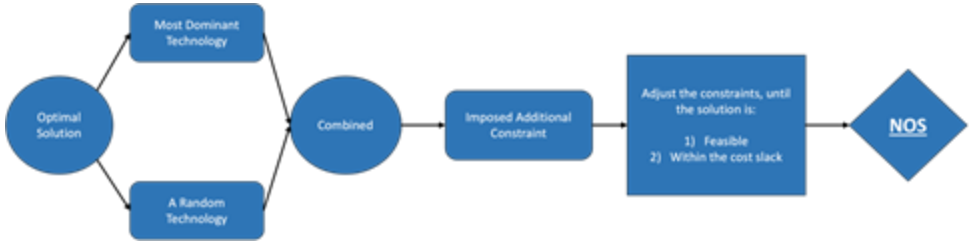


4. Results & Discussion

1) Enhancements made to Hypatia

- ✓ **Extensive Codebase**: Over 1700 lines of Python implementing Machine Learning (ML) and automation.
- ✓ **Fully Automated Pipeline**: Generates multiple near-optimal solutions with zero manual intervention.
- ✓ **Autonomous Execution**: The script reads, analyzes, adjusts, and reruns the model automatically.

1) Enhancements made to Hypatia



Extracted from the function "identify_technology_order"

```
new_capacity_df = pd.read_csv(new_capacity_path)
technologies_order = new_capacity_df['Technology'].unique()
technology_order_mapping = {tech: i + 1 for i, tech in enumerate(technologies_order)}

order_df = pd.DataFrame(list(technology_order_mapping.items()), columns=['Technology', 'Order'])
order_df.to_csv(os.path.join(result_path, 'technology_order_mapping.csv'), index=False)
```

Extracted from the function "find_technologies"

```
top_3 = allowed_technologies.nlargest(3)
max_technologies = top_3.index.tolist()
remaining_technologies = allowed_technologies.drop(labels=max_technologies)

random_technologies = random.sample(remaining_technologies.index.tolist(), min(3, len(remaining_technologies)))
```

Extracted from the function "find_last_year_values"

```
# Retrieve the capacity value for the max_technology in the last year
max_technology_value = last_year_df[last_year_df['Technology'] == max_technology]['Value'].values[0]
# Retrieve the capacity value for the random_technology in the last year
random_technology_value = last_year_df[last_year_df['Technology'] == random_technology]['Value'].values[0]
```

Extracted from the function "run_multiple_solutions"

```
initial_C = (x + u) / 2  # Calculate initial adjustment factor C
```

Extracted from the function "modify_input_parameters"

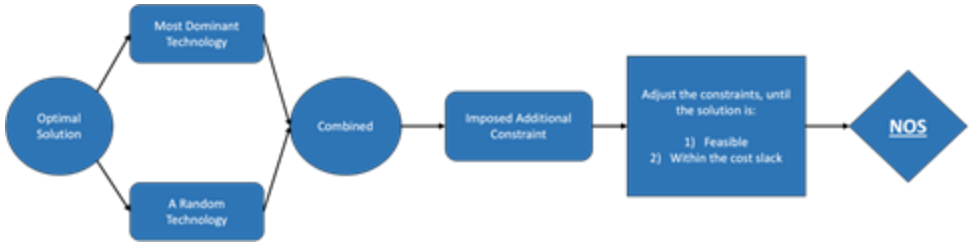
```
min_totalcap_df.iat[i + 3, random_tech_col_index] = T2 + C
max_totalcap_df.iat[i + 3, max_tech_col_index] = T1 - C
```

Extracted from the function "run_with_adjustments"

```
# Adjust the logic until an acceptable result is obtained.
initial_C = (x + u) / 2
C = initial_C
attempt = 0
while self.results is None:
# Adjust C for the next attempt
    attempt += 1
    C = initial_C - (0.05 * initial_C * attempt)
```

4. Results & Discussion

1) Enhancements made to Hypatia



1) Enhancements made to Hypatia

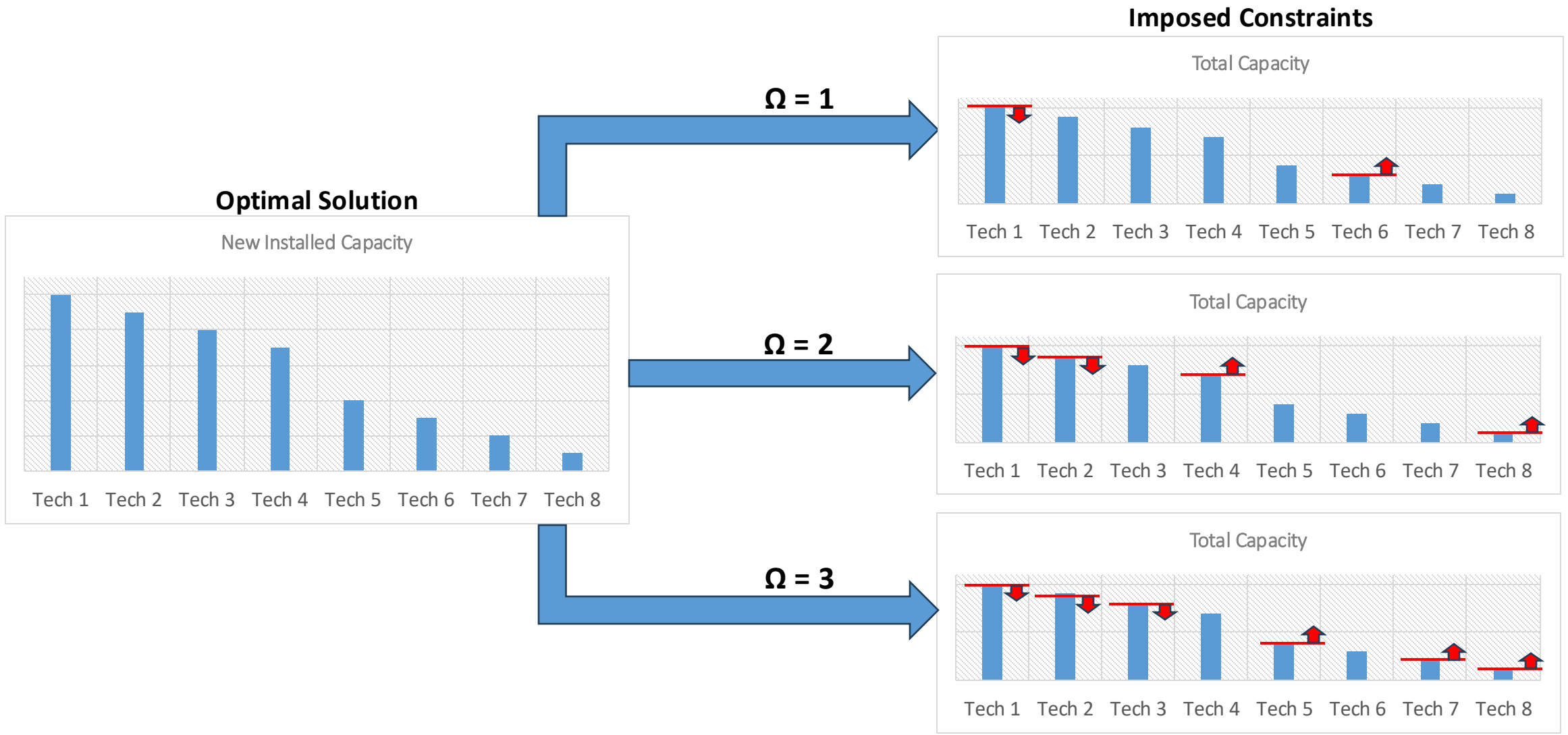
Better solutions = More flexibility & diversity in technology use

Can the <u>same method</u> be expanded to result in <u>better alternative solutions</u>?

Ω:

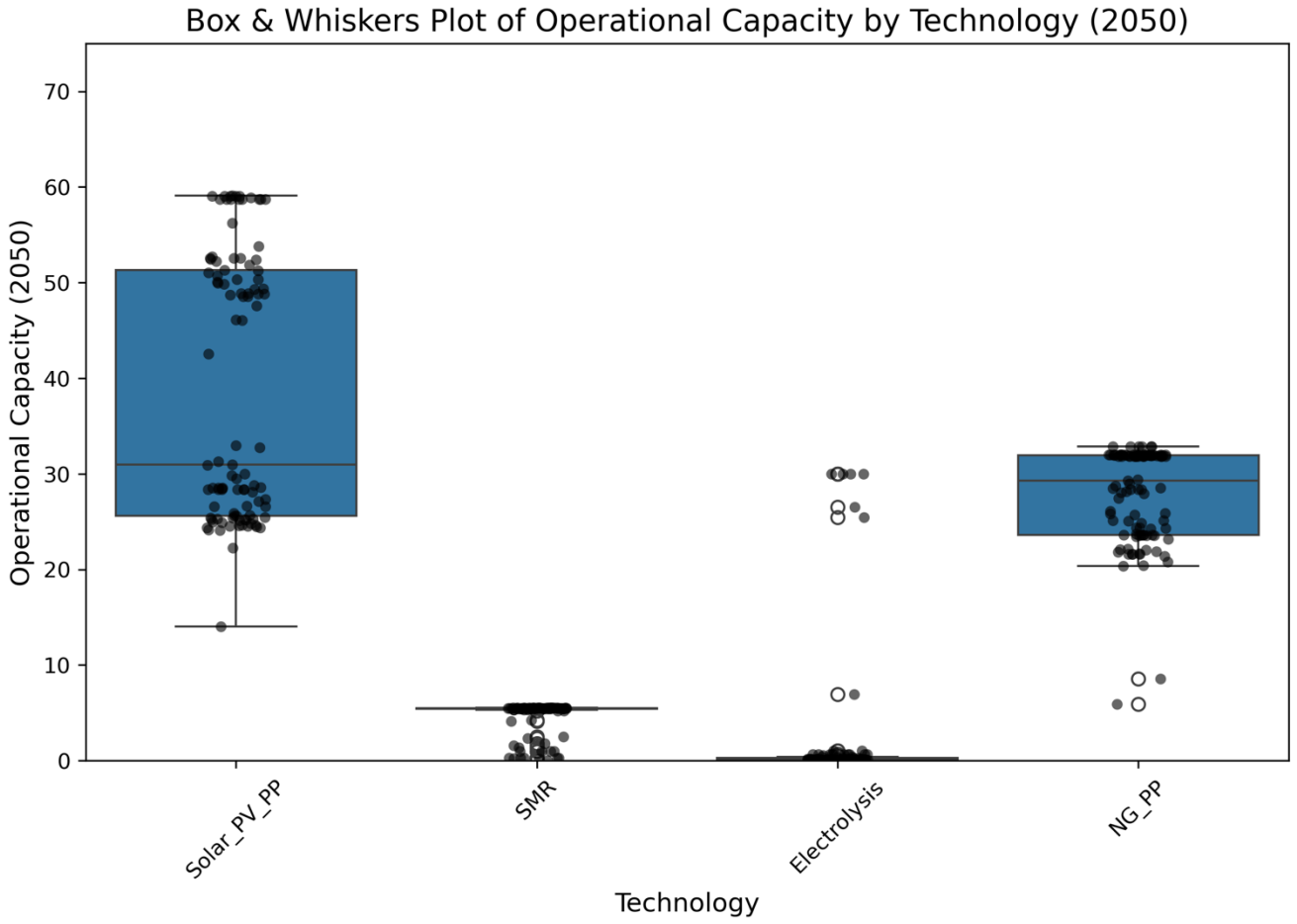
- A user-defined parameter controlling how many technologies are combined in each iteration.
- Enables structured scaling of solution diversity.

4. Results & Discussion



4. Results & Discussion

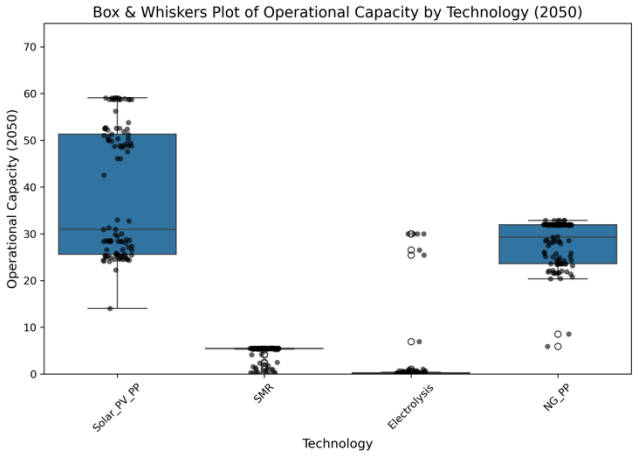
Ω = 1



- Good result
- Very fast!

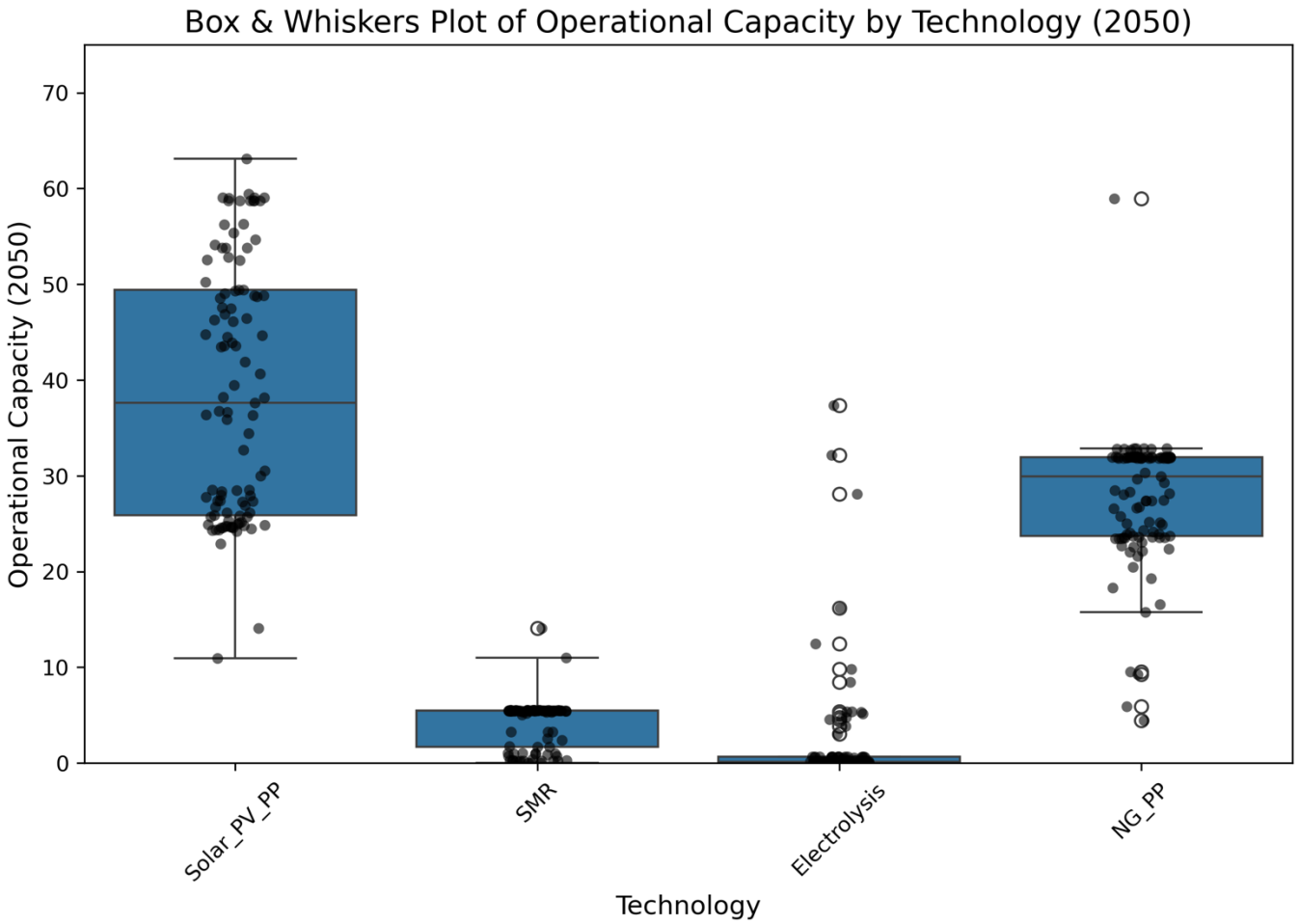
4. Results & Discussion

Ω = 1



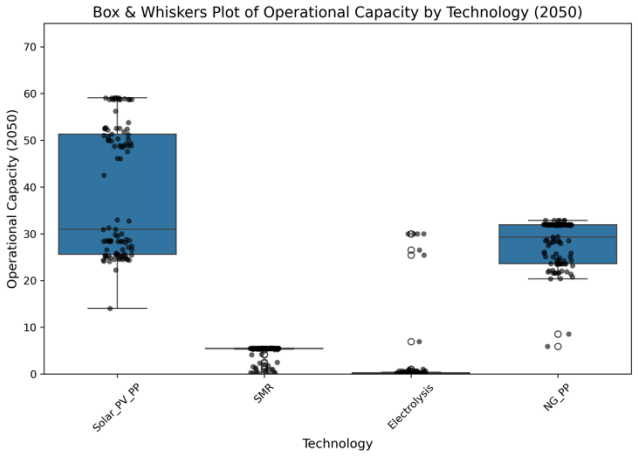
- Better result!
- More time-consuming!

Ω = 2



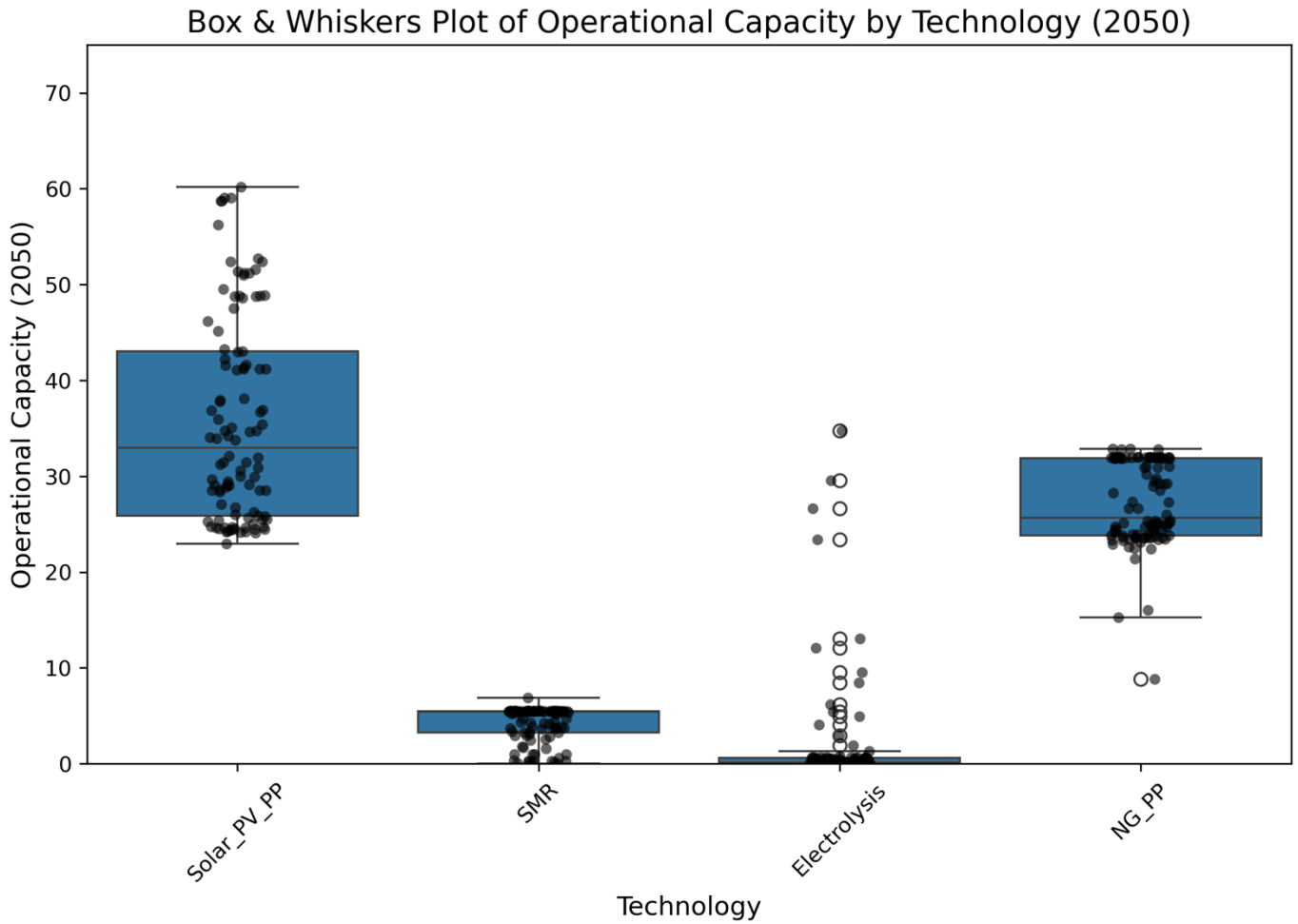
4. Results & Discussion

Ω = 1



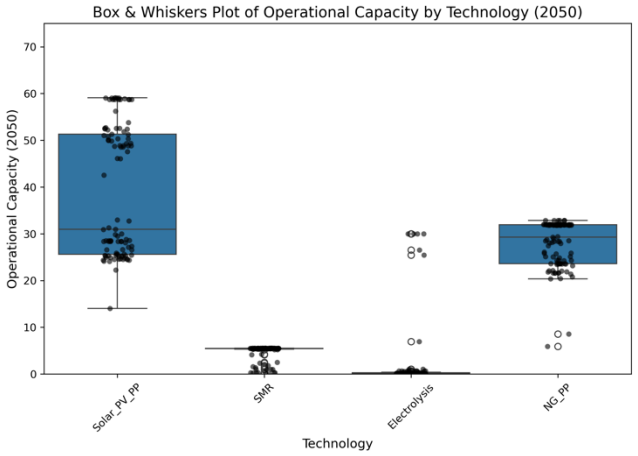
- Not better result!
- Much more time-consuming!

Ω = 3

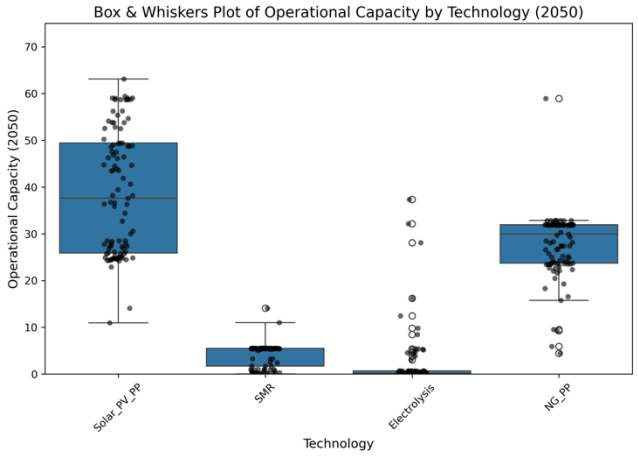


4. Results & Discussion

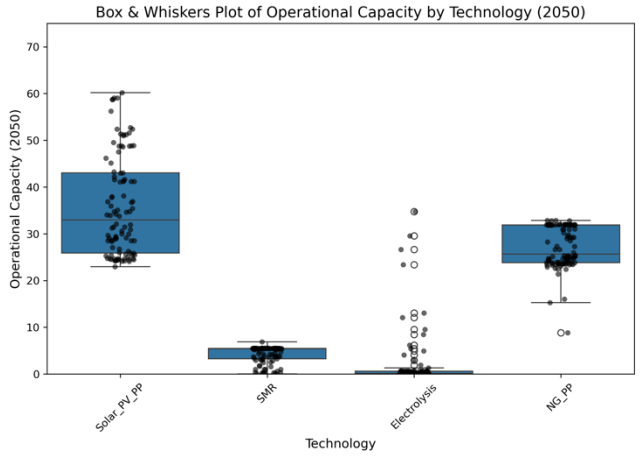
Ω = 1



Ω = 2

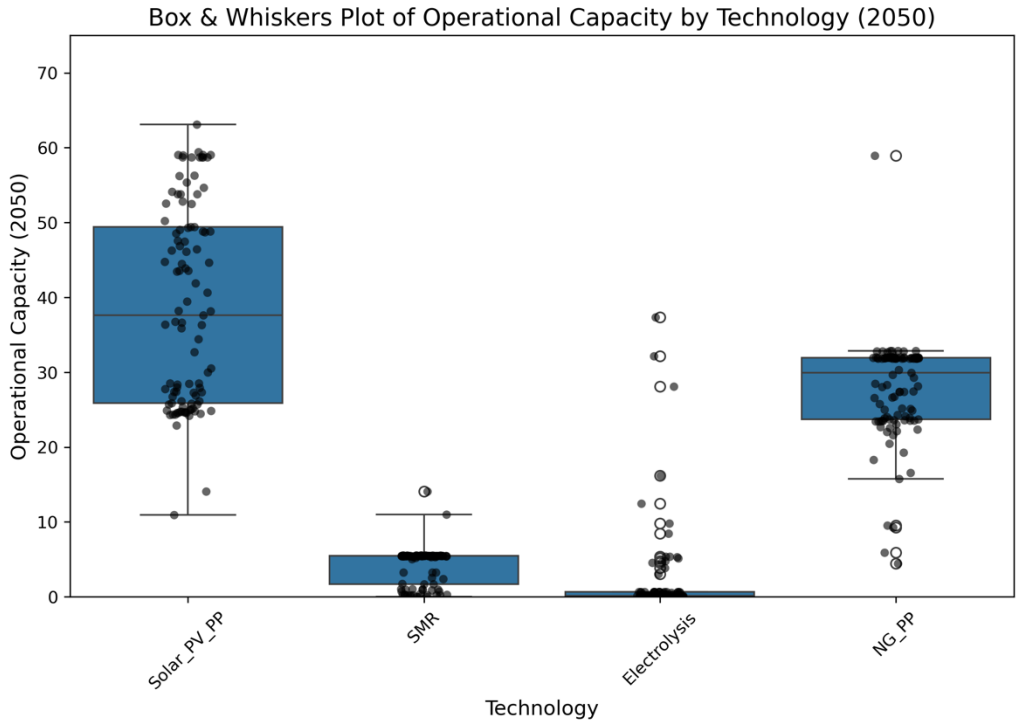


Ω = 3



4. Results & Discussion

Ω = 2



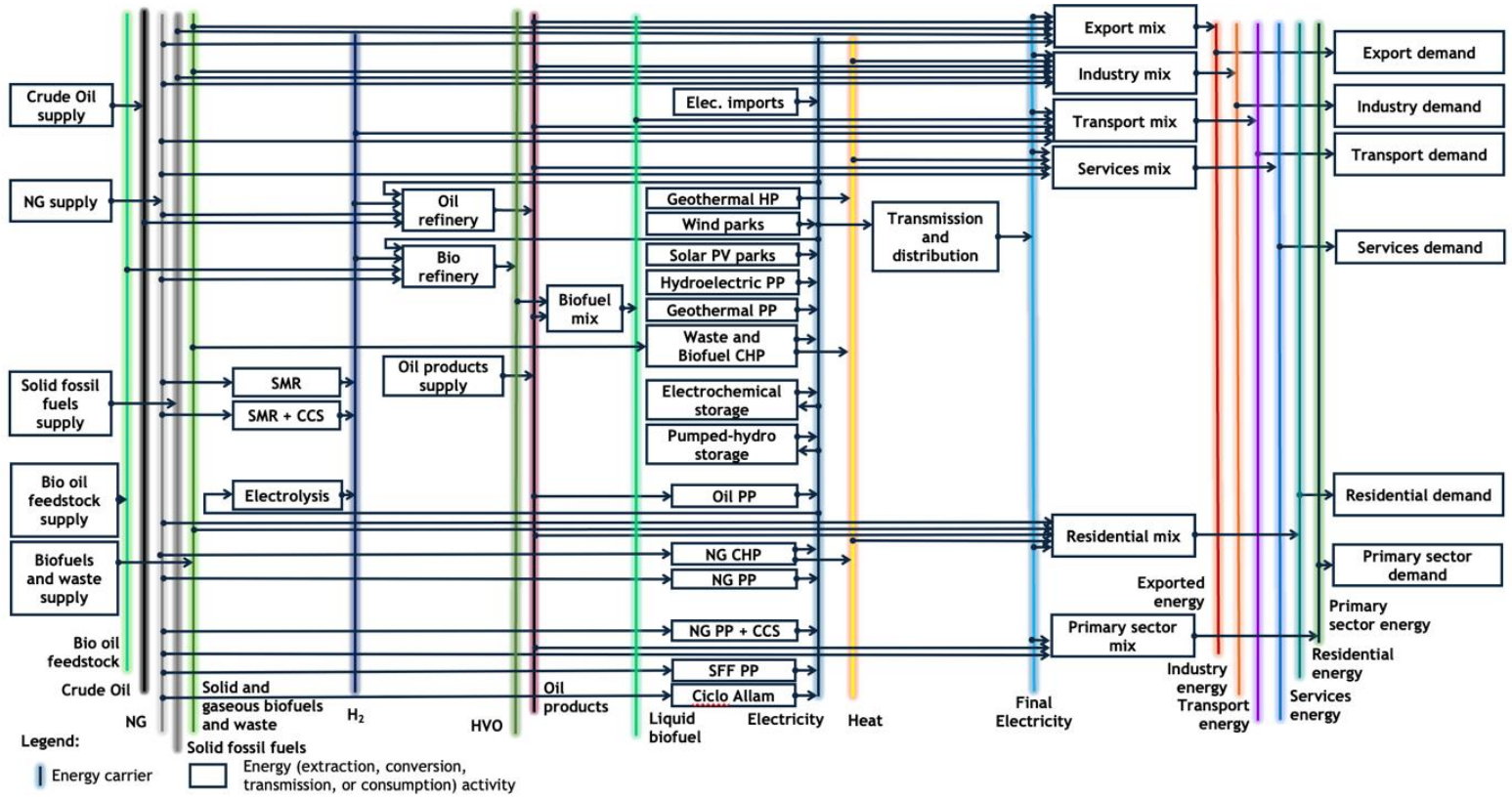
- The output decision-space of method with **Ω = 2**, is better in terms of flexibility and diversity, with a little computational cost.

Key Enhancements

- **Fully Automated Pipeline**: Hypatia now Generates multiple near-optimal solutions with zero manual intervention.
- **Novel Method to Generate Alternatives**: Hypatia uses the crossover technique of the heuristic method to effectively generate the decision space.
- **Quality & Quantity**: Hypatia can generate a high number of solutions in a short time, and with a great diversity.
- **High User Input Compatibility**: Users can define number of results, cost slack, and quality metrics. (Ω)

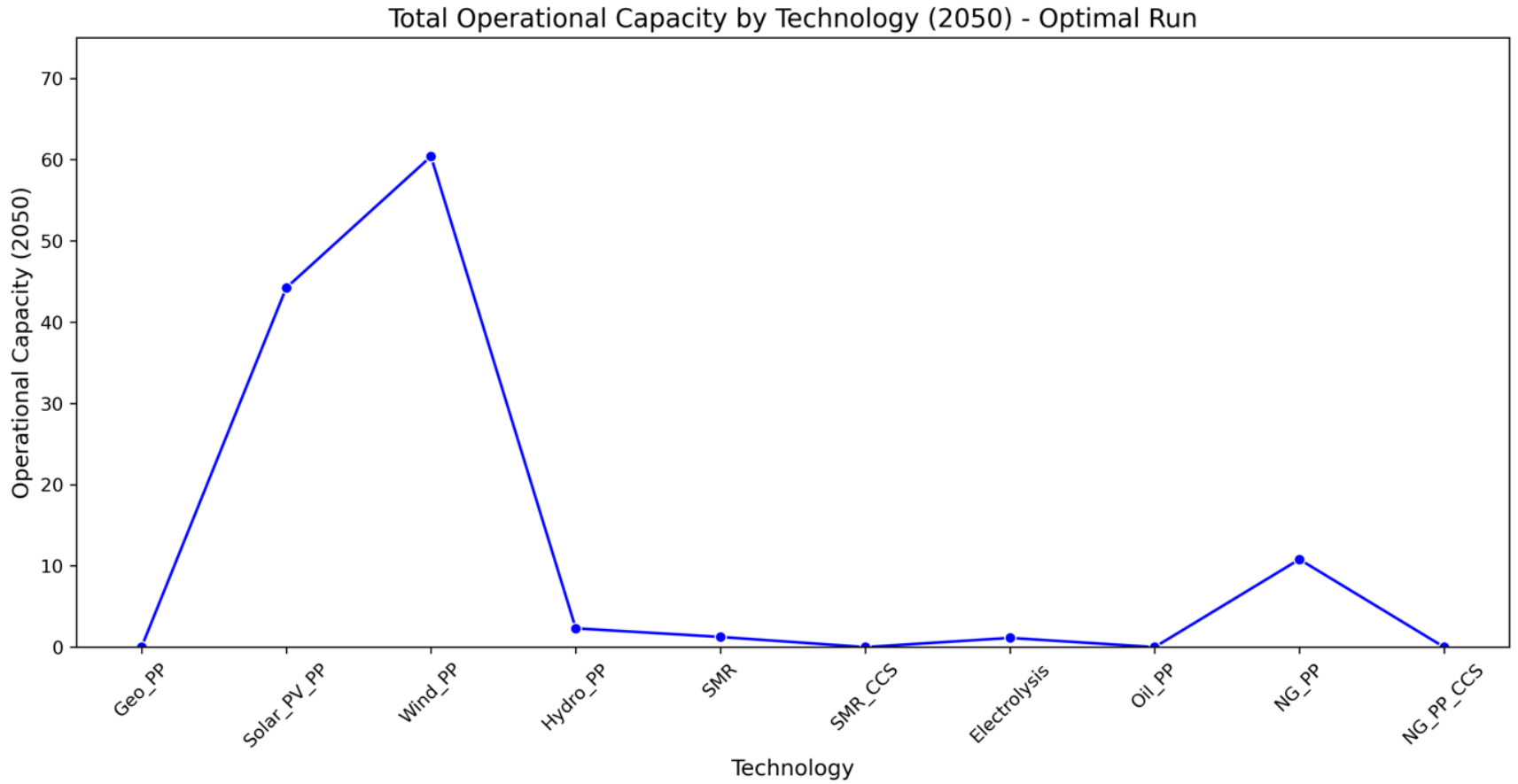
2) Application of the Enhanced Model to the Italian Energy Sector

Reference Energy System (RES)



4. Results & Discussion

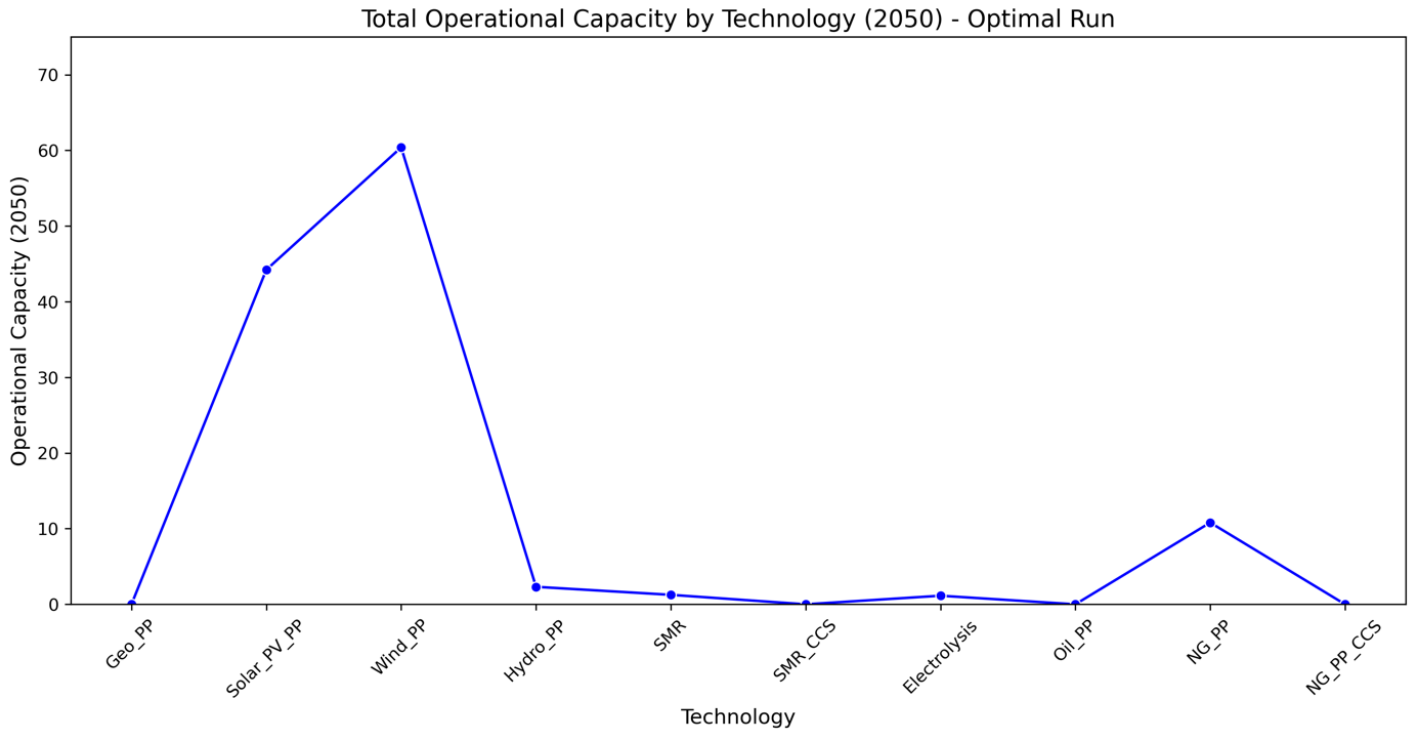
Optimal Solution - Cost Minimization



4. Results & Discussion

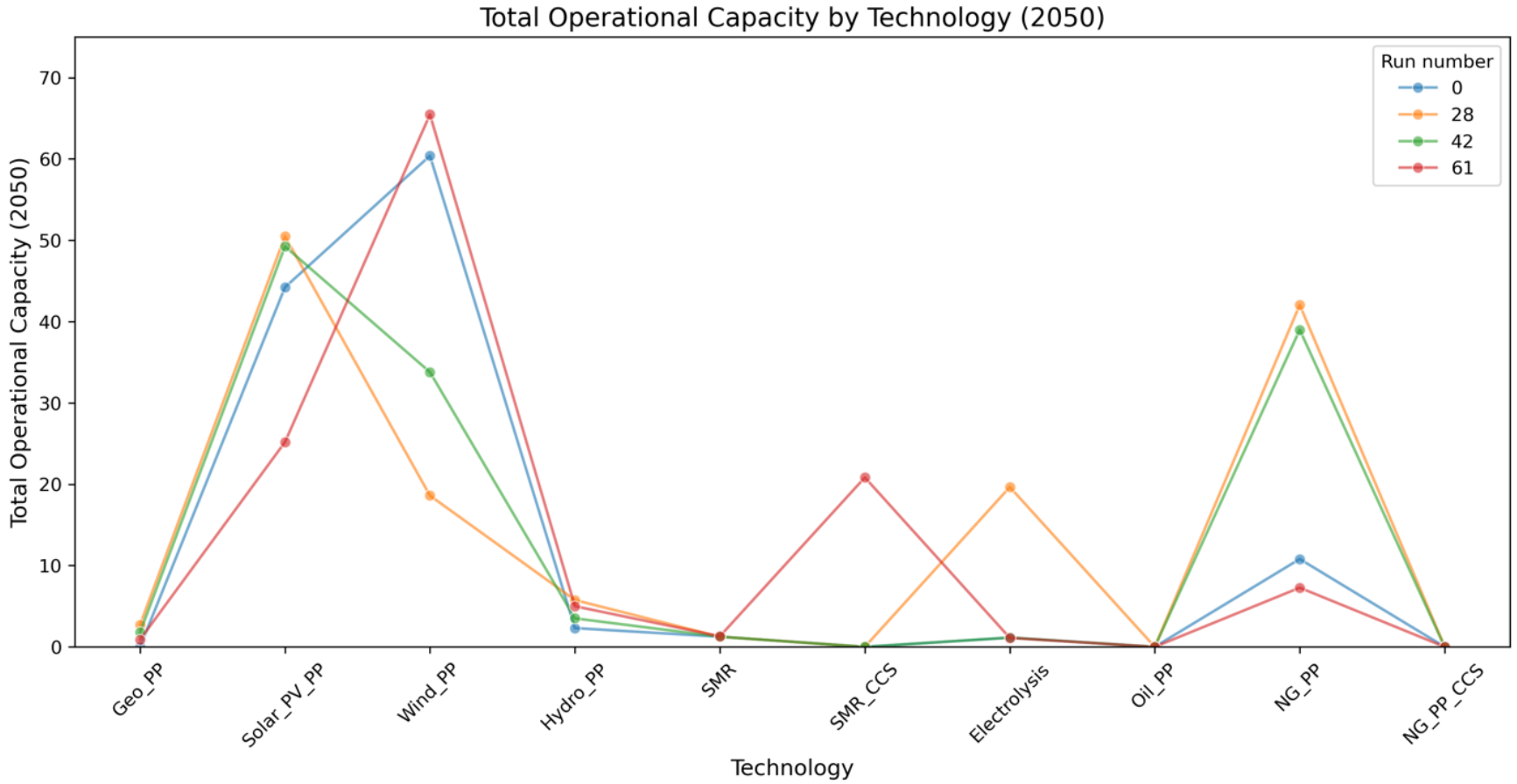
- One single solution (one criterion)
- No flexibility
- Policy-maker preferences do not matter.
- Might not be feasible in real world!

Optimal Solution



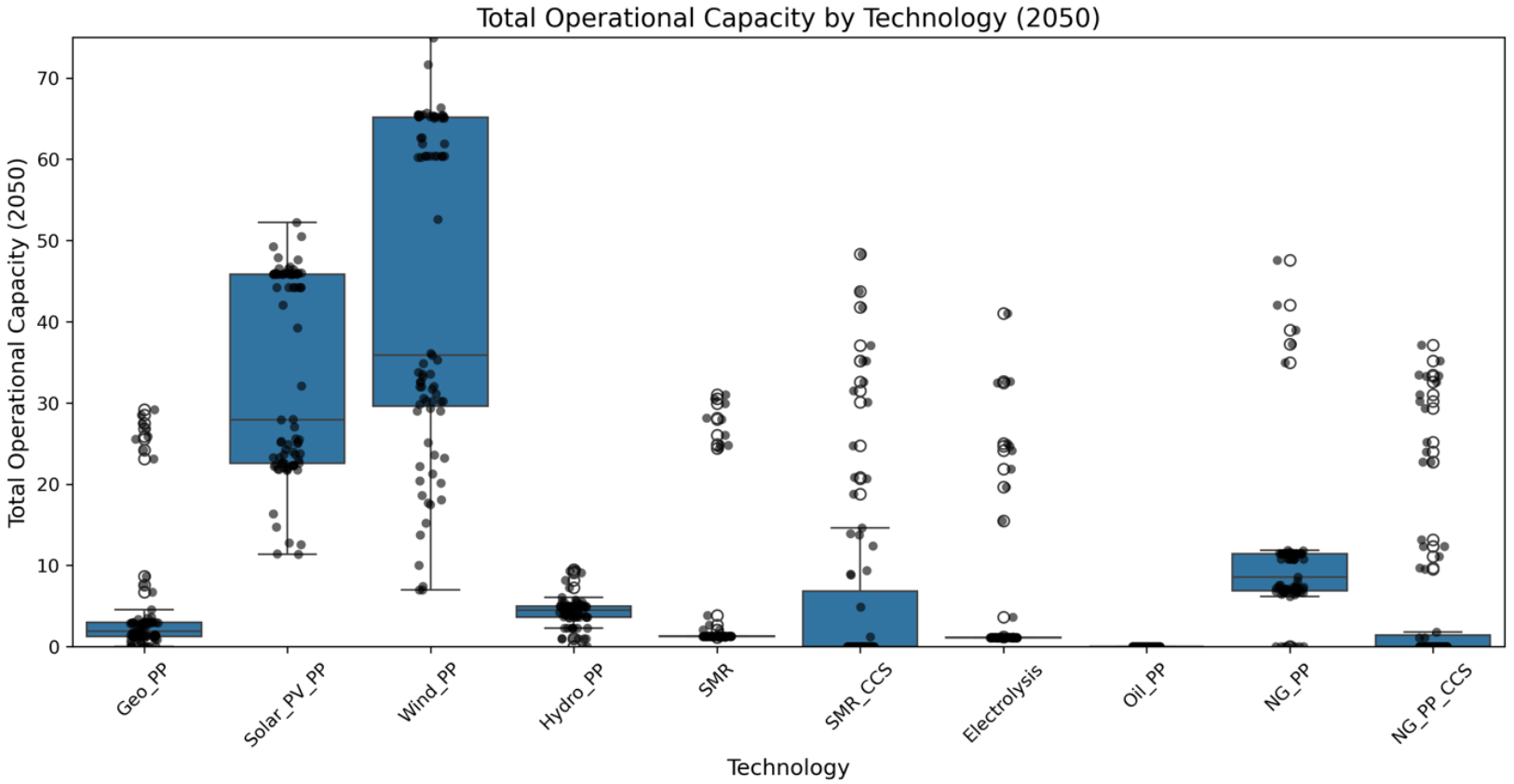
4. Results & Discussion

Optimal Solution with 3 Near-Optimal Solutions



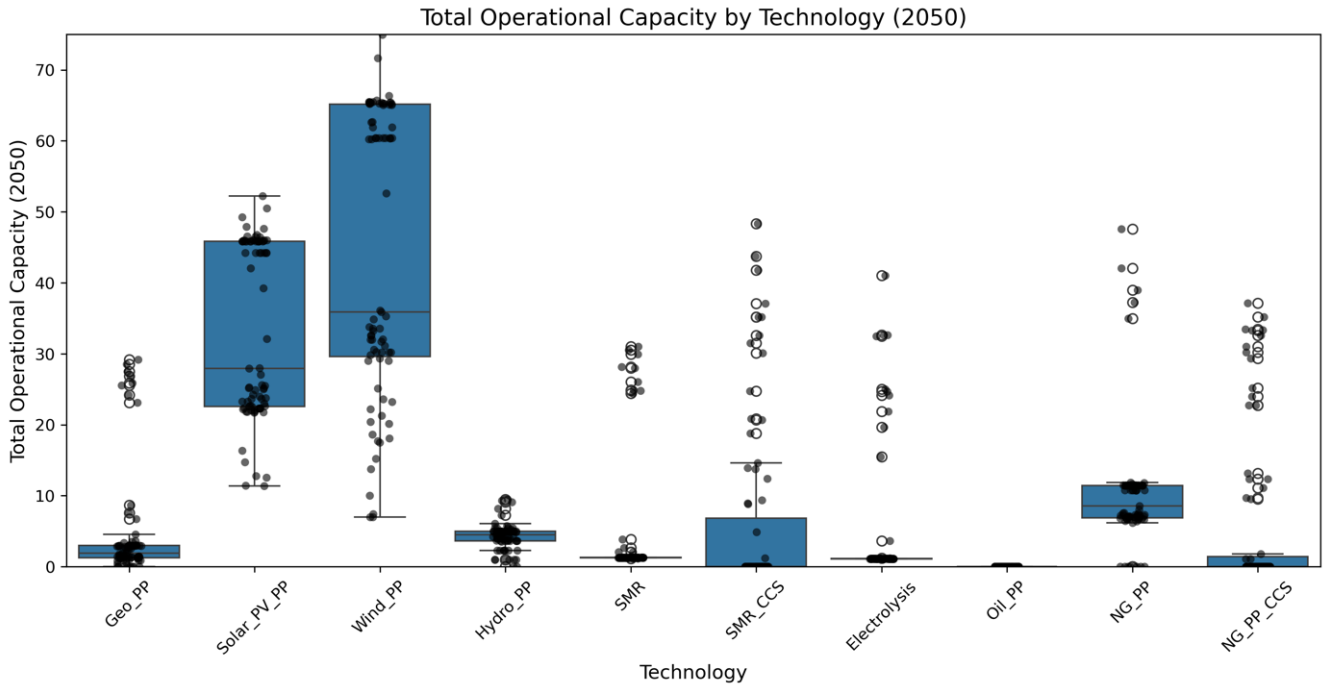
4. Results & Discussion

Decision Space



4. Results & Discussion

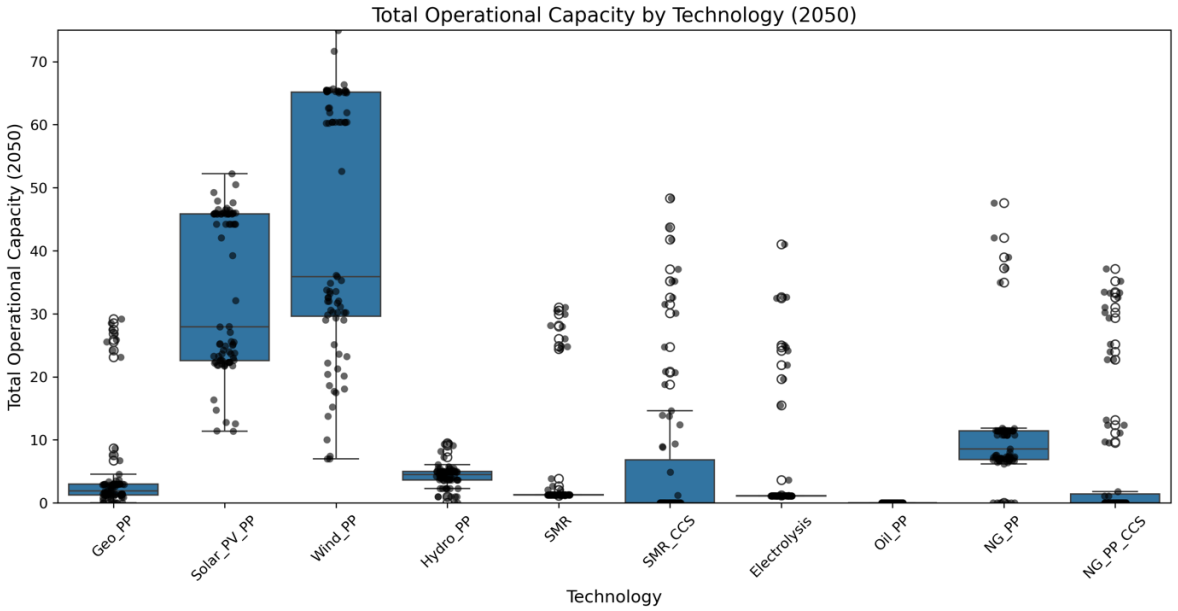
Decision Space



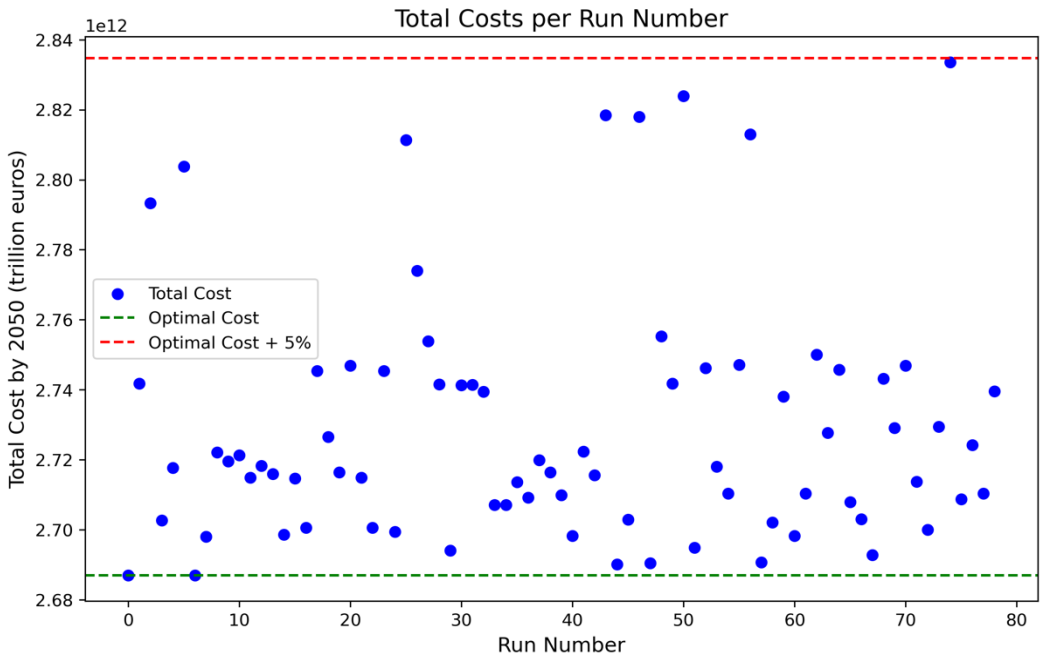
- **Multi-Criteria**
- **Flexibility**
- **Must-have technologies**
- **Policy-maker preference**
- **Real-world feasibility in the range**

4. Results & Discussion

Decision Space

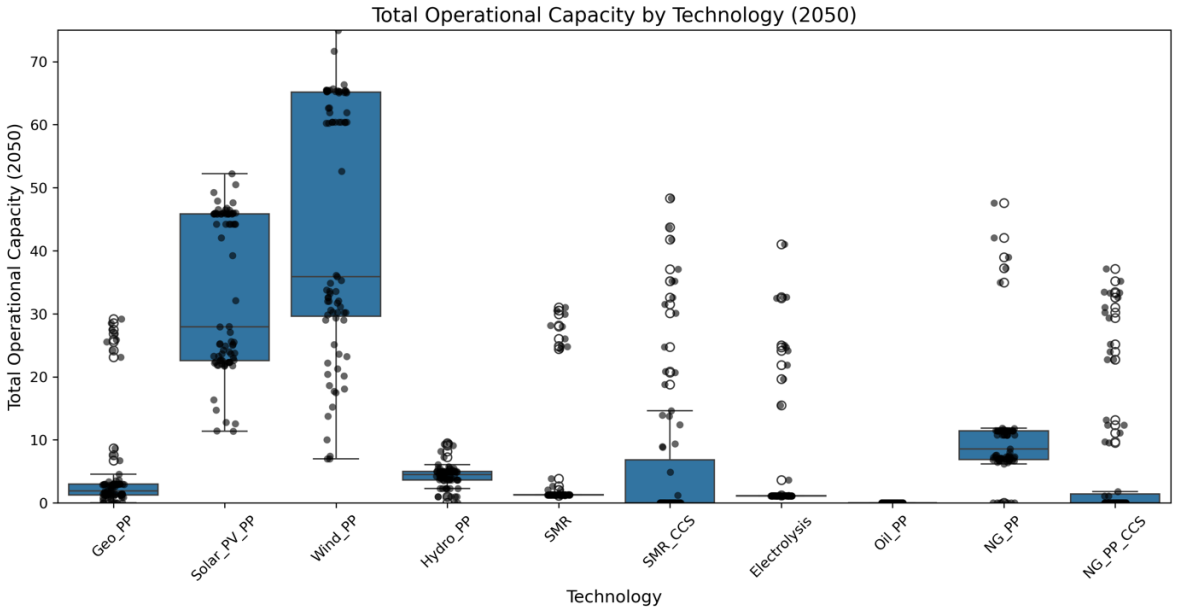


Total Accumulated Cost of Each Run

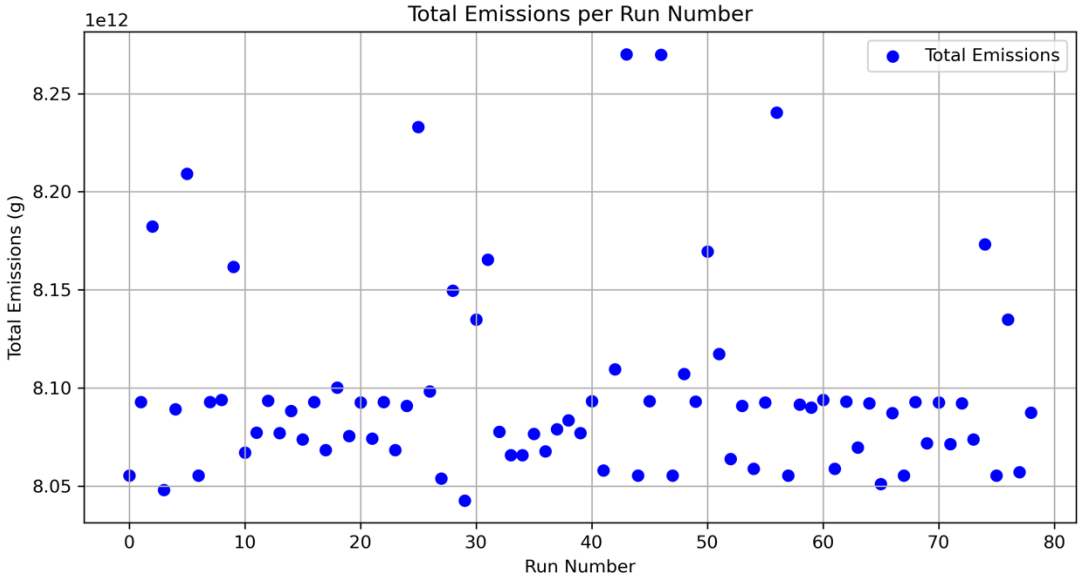


4. Results & Discussion

Decision Space

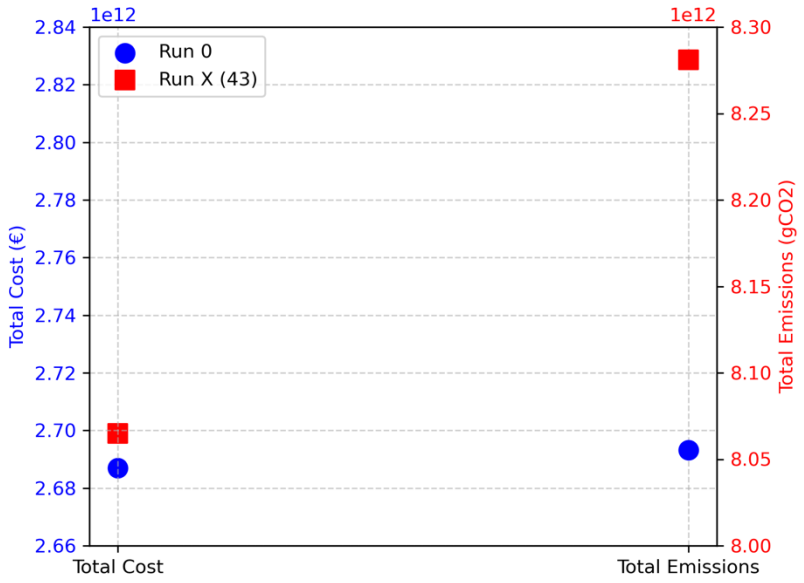


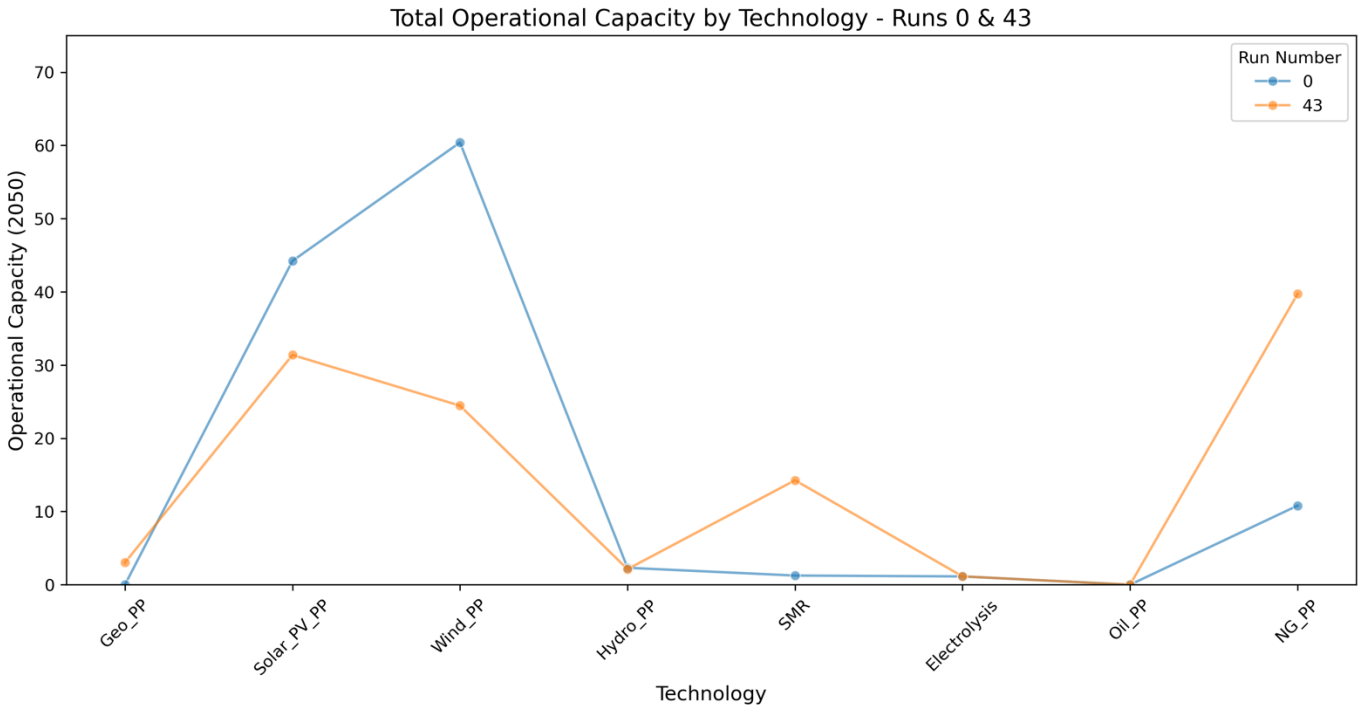
Total Accumulated CO2 Emission of Each Run



4. Results & Discussion

Alternative Pathways: (Run 43)

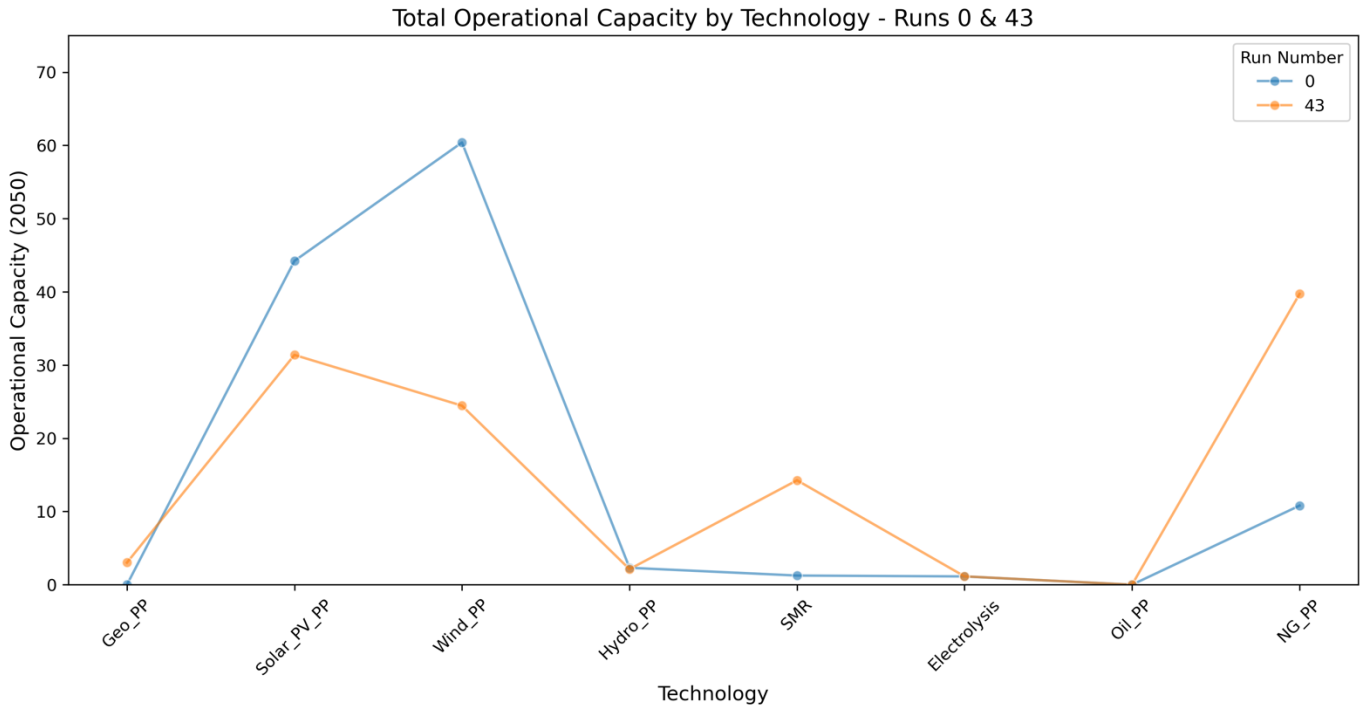




4. Results & Discussion

Alternative Pathways: (Run 43)

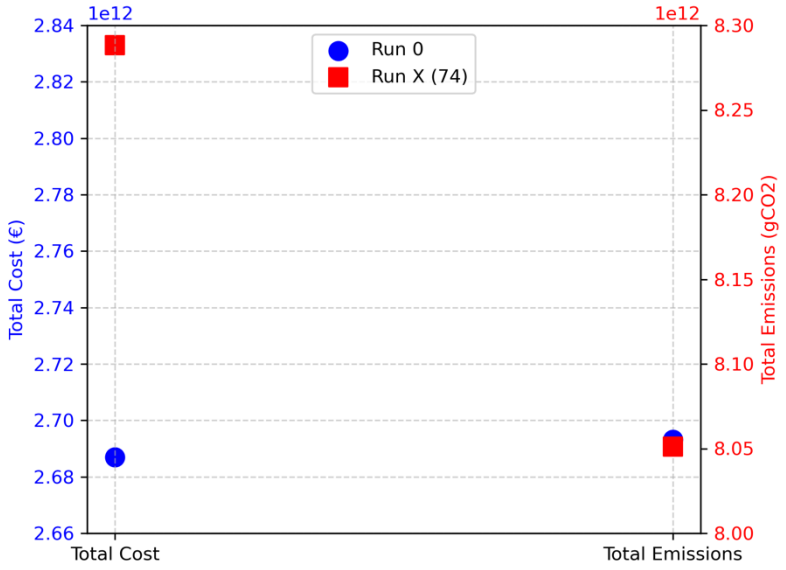
- Preservation of Existing Infrastructure
- Job Security & Local Economic Stability
- Land Use Conflicts
- Community Acceptance (NIMBY Effect)
- Energy Security & Dispatchability
- Political Considerations

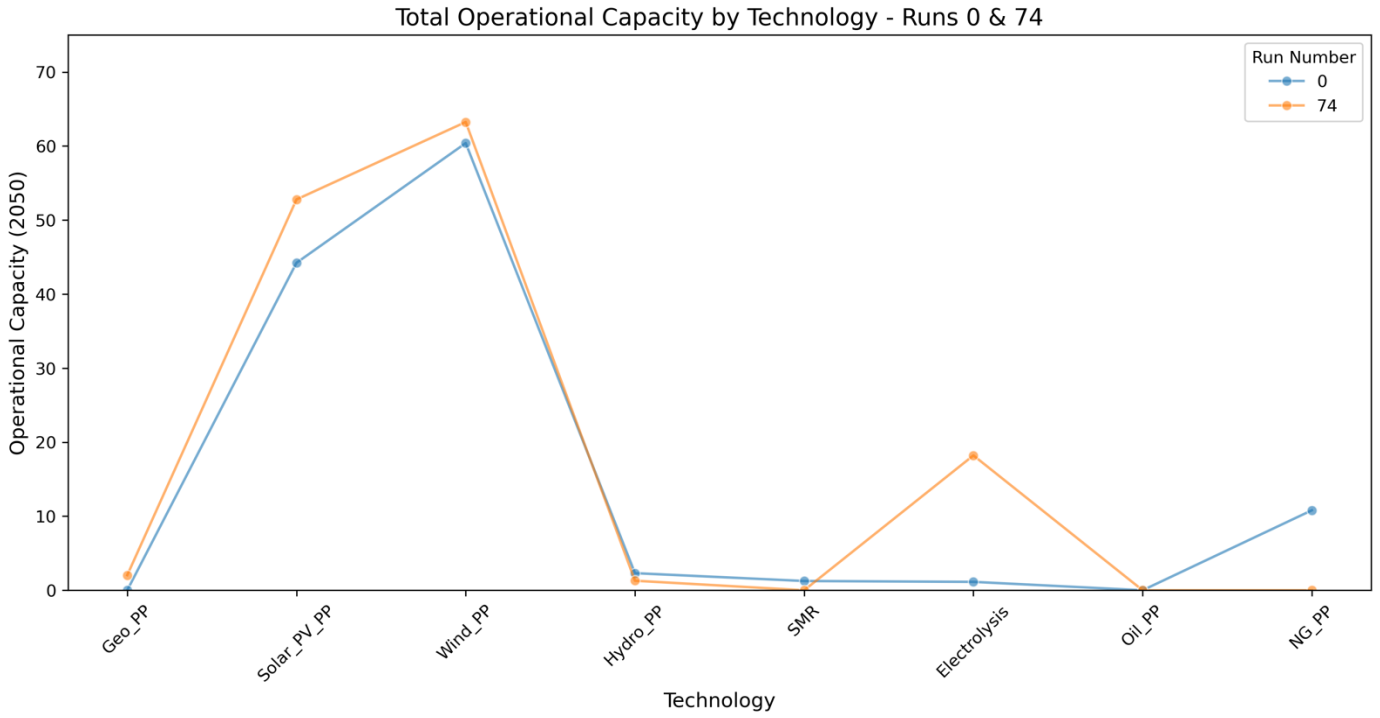


4. Results & Discussion

Alternative Pathways: (Run 74)

- **Zero-Emission by 2050**

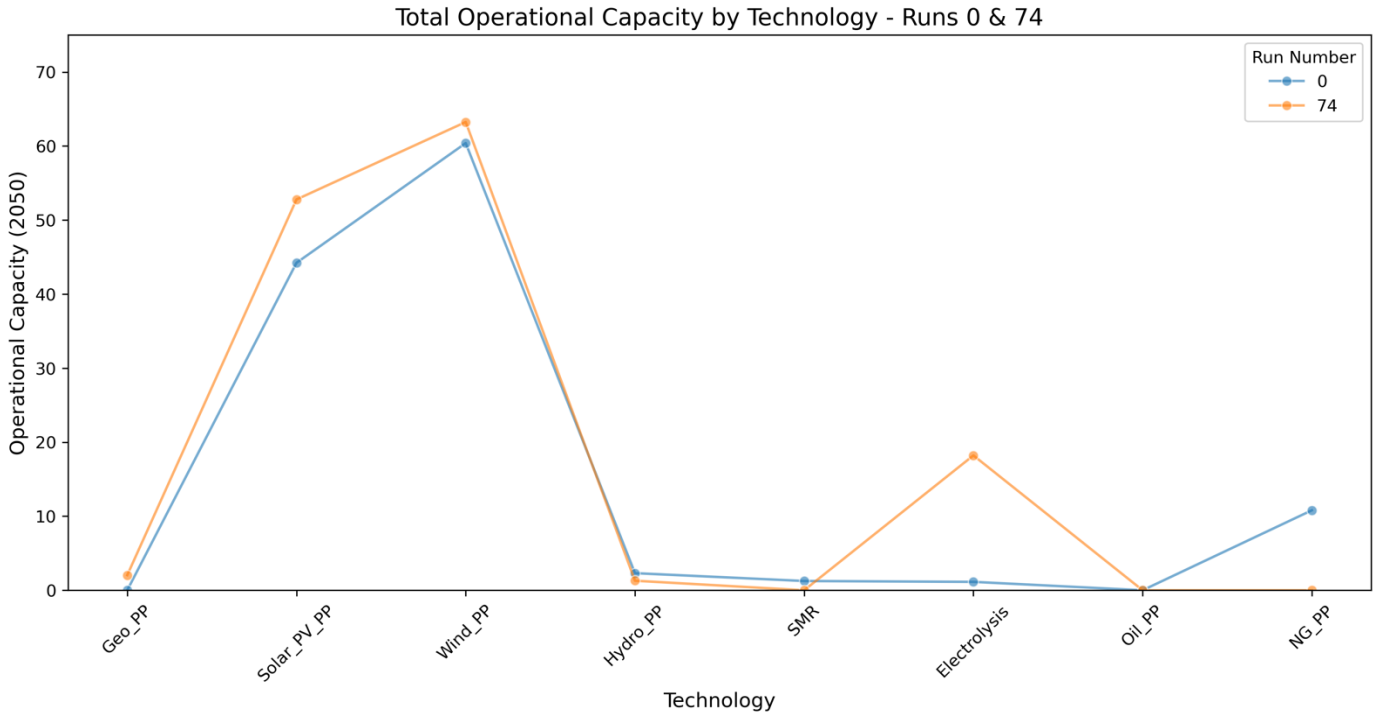




4. Results & Discussion

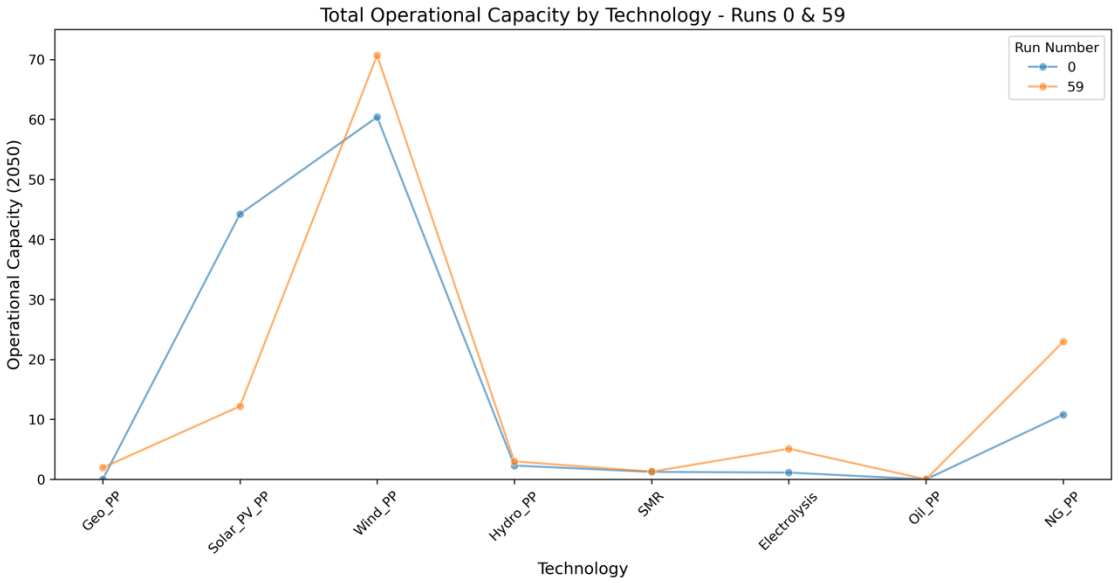
Alternative Pathways: (Run 74)

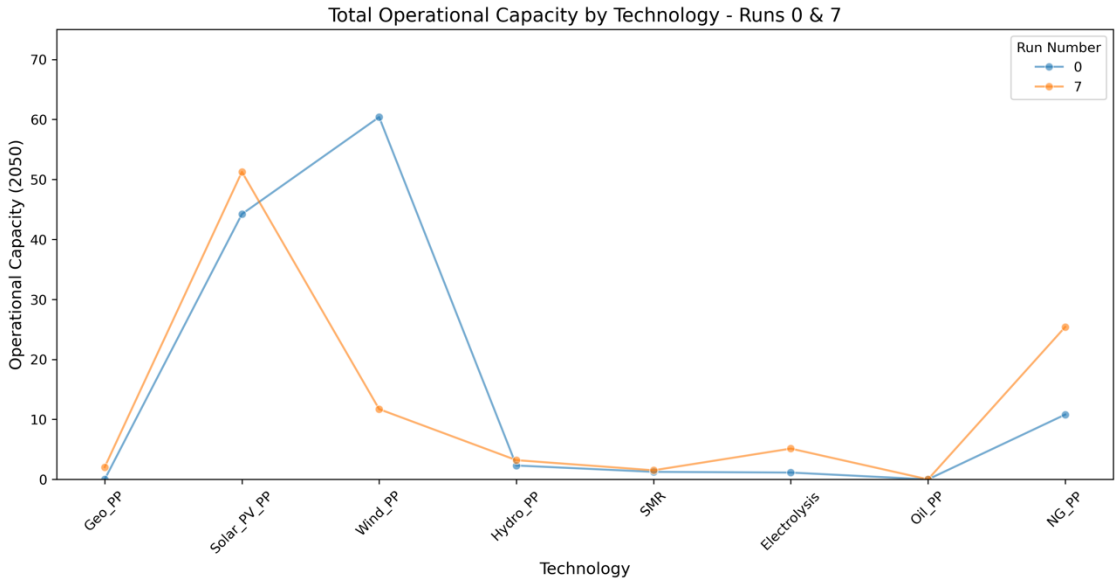
- Climate Change Mitigation
- Policy Commitments
- Energy Independence
- Job Creation in the Green Economy
- Public Health Benefits



4. Results & Discussion

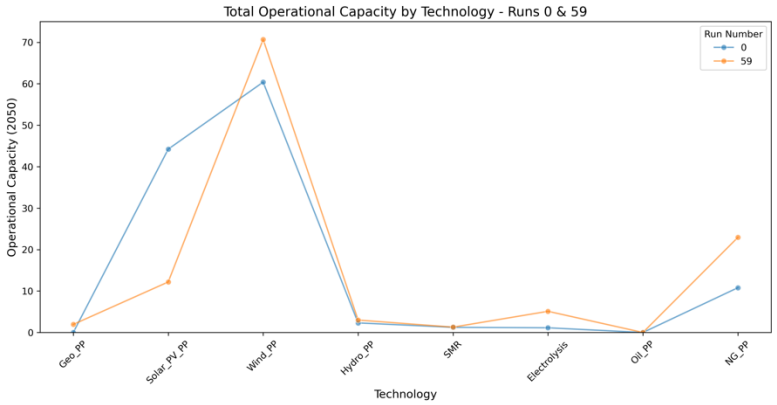
Alternative Pathways: (Runs 59 & 7)

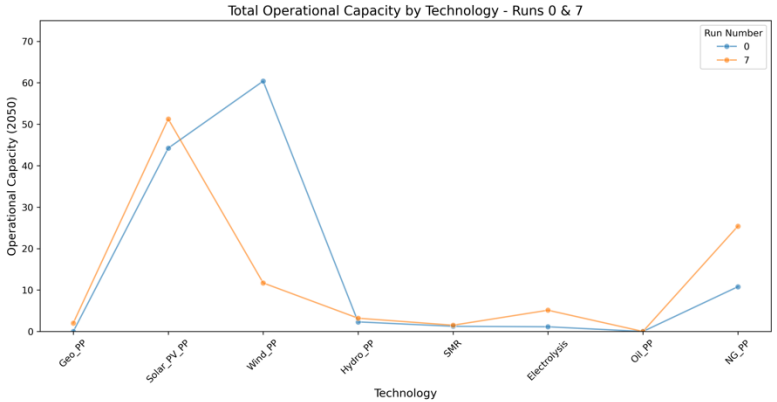




4. Results & Discussion

Alternative Pathways: (Runs 59 & 7)





Even for the same goals, multiple pathways exist!

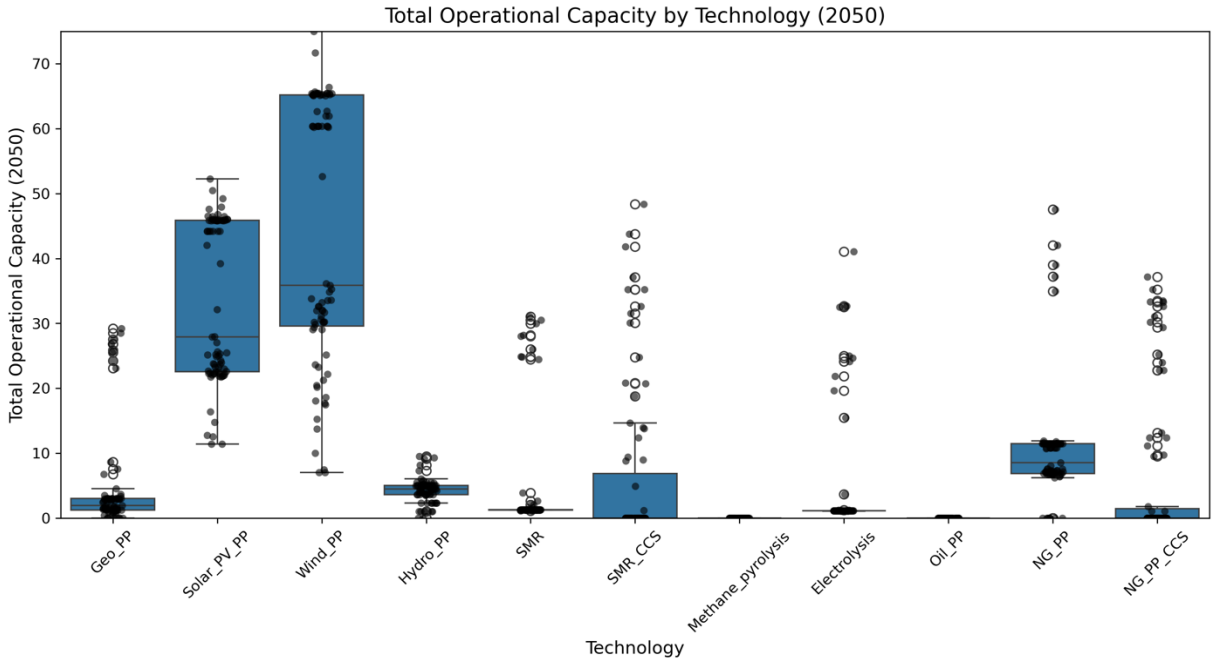
No specific technology is irreplaceable.

Potential challenges associated with wind and solar energy in Italy:

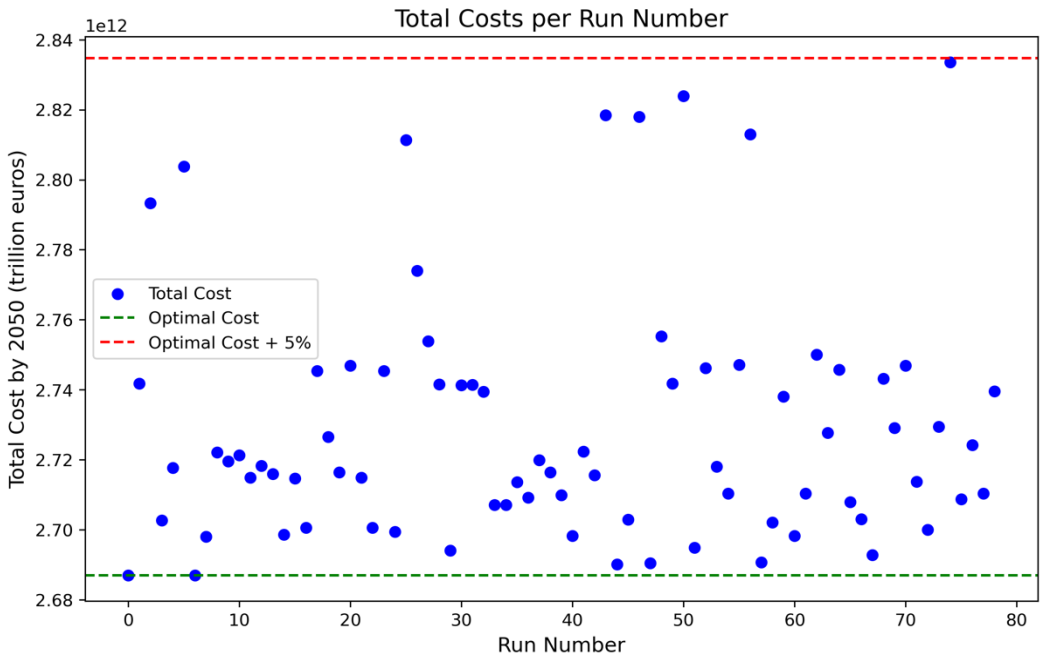
- Geopolitical and Supply Chain Vulnerabilities in Solar PV Deployment
- Land-Use Conflicts and Public Opposition to Wind Energy Expansion

4. Results & Discussion

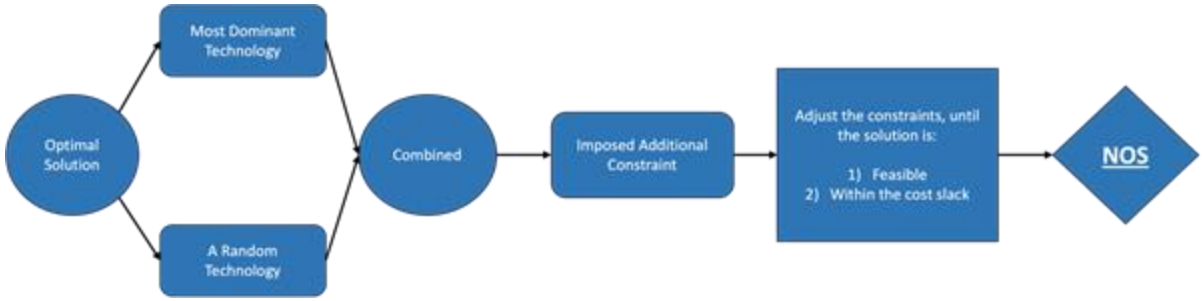
Decision Space

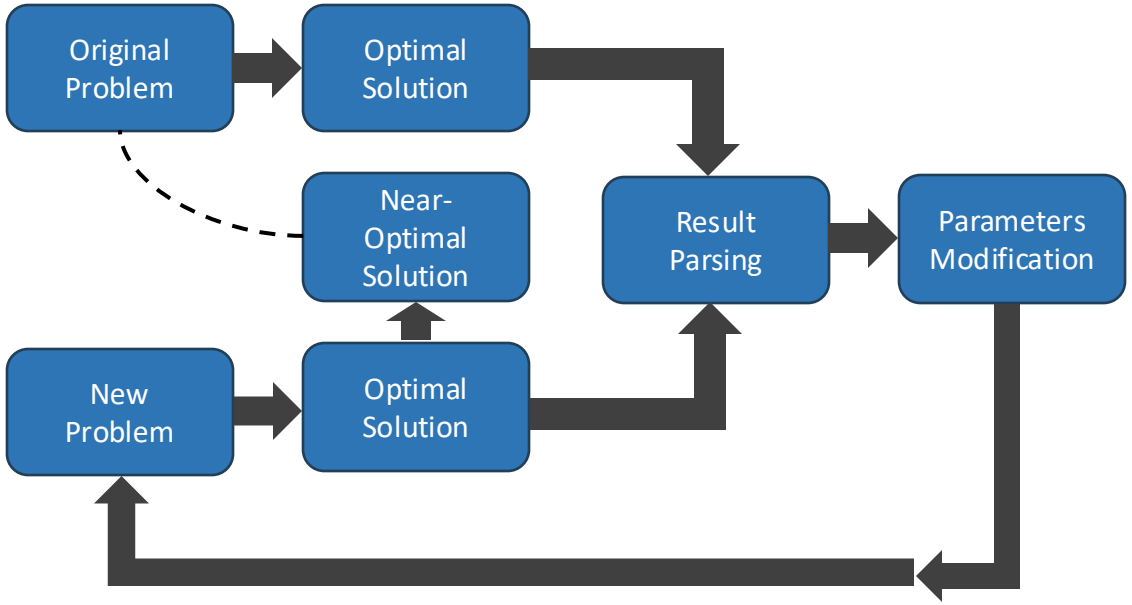


Total Accumulated Cost of Each Run

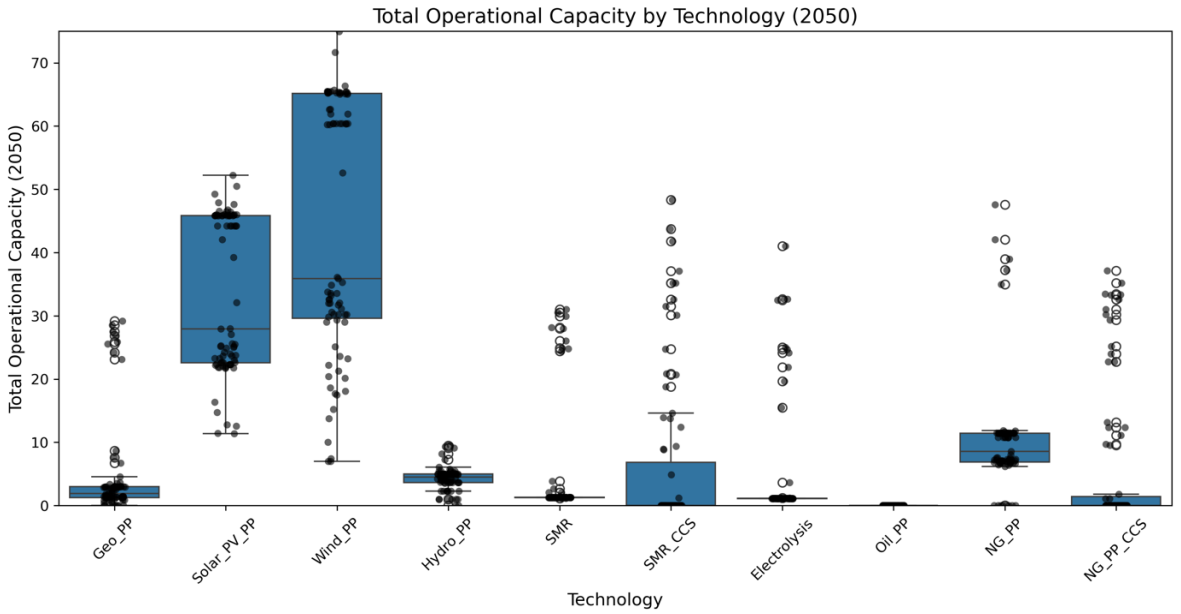


4. Results & Discussion





Decision Space



Thank you for your attention.