

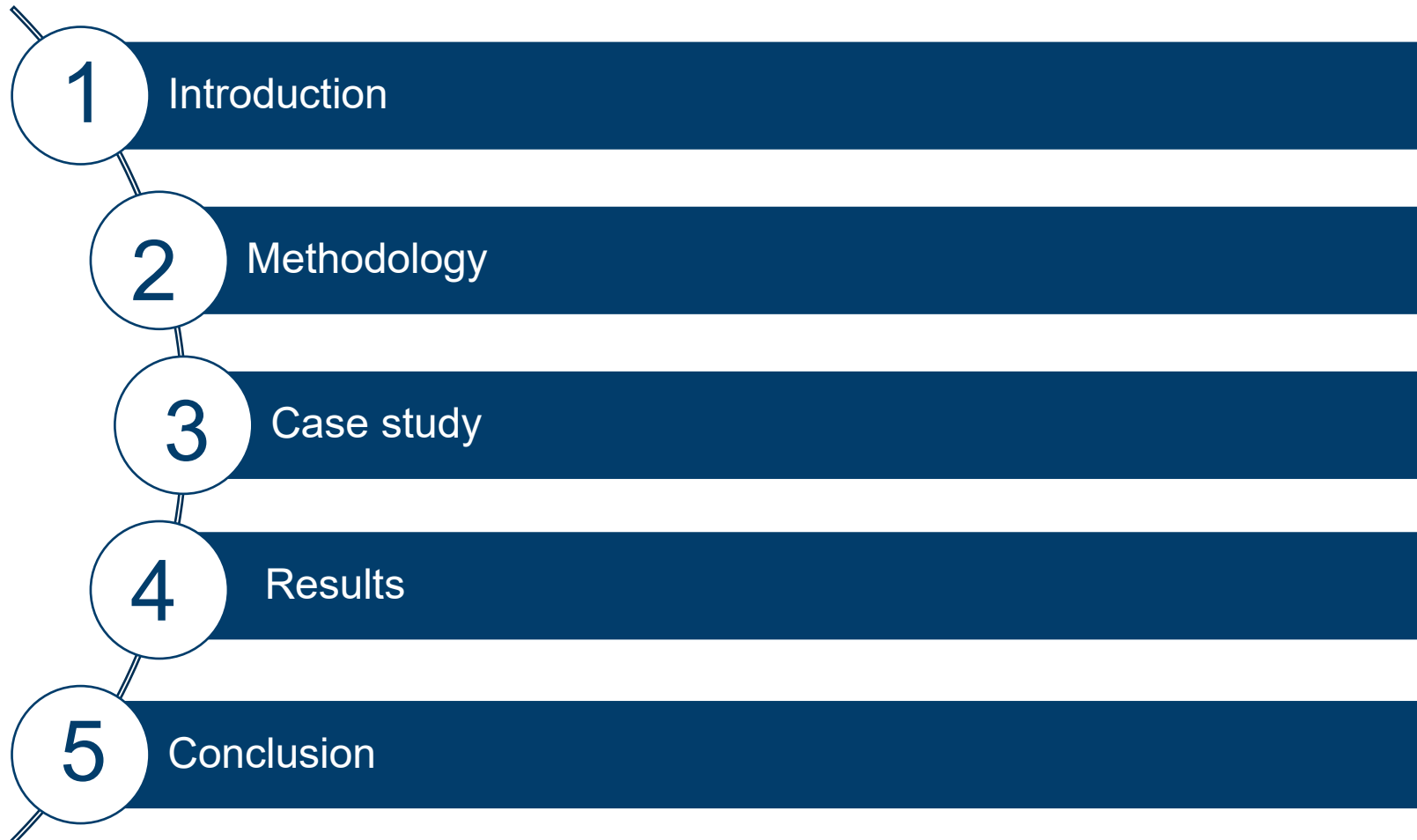
Identifying Flexibility in Autonomous Municipal Energy Systems Using Modeling to Generate Alternatives

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Jülich Systems Analysis

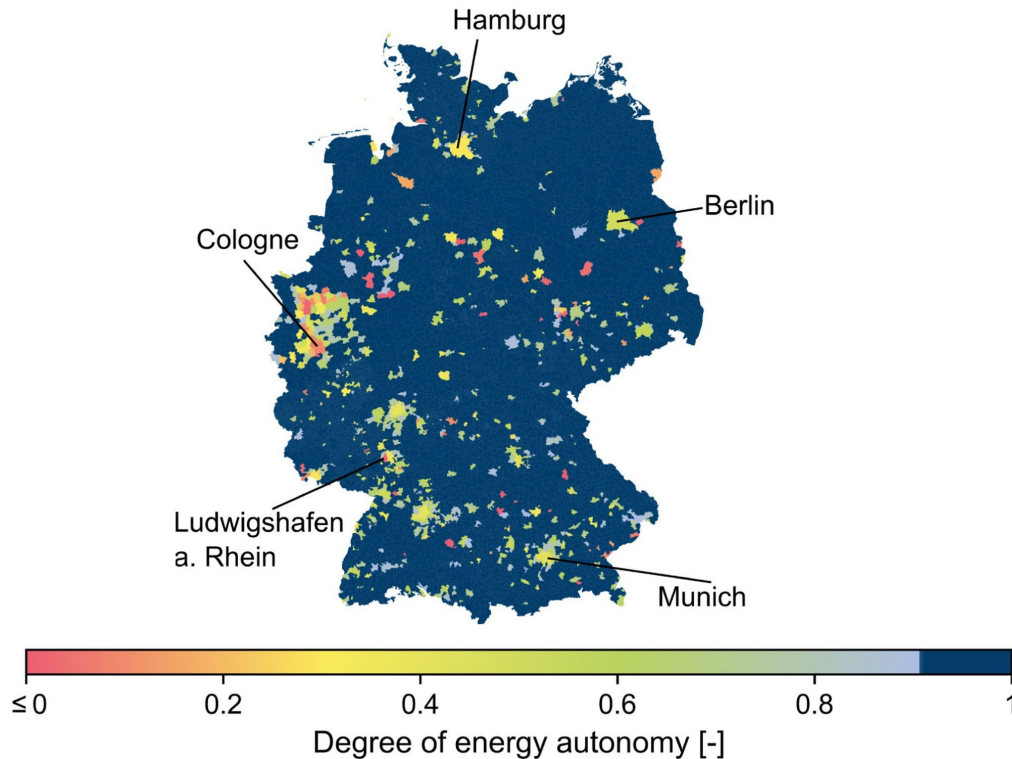
Table of Content

A vertical list of five items, each consisting of a white circle with a dark blue number inside, connected by a thin dark blue line. To the right of each circle is a dark blue horizontal bar containing the corresponding chapter title in white text. The items are: 1 Introduction, 2 Methodology, 3 Case study, 4 Results, and 5 Conclusion.

- 1 Introduction
- 2 Methodology
- 3 Case study
- 4 Results
- 5 Conclusion

Introduction

Autonomous municipal energy systems



Degree of energy autonomy in German municipalities in the year 2045 adapted from [1]

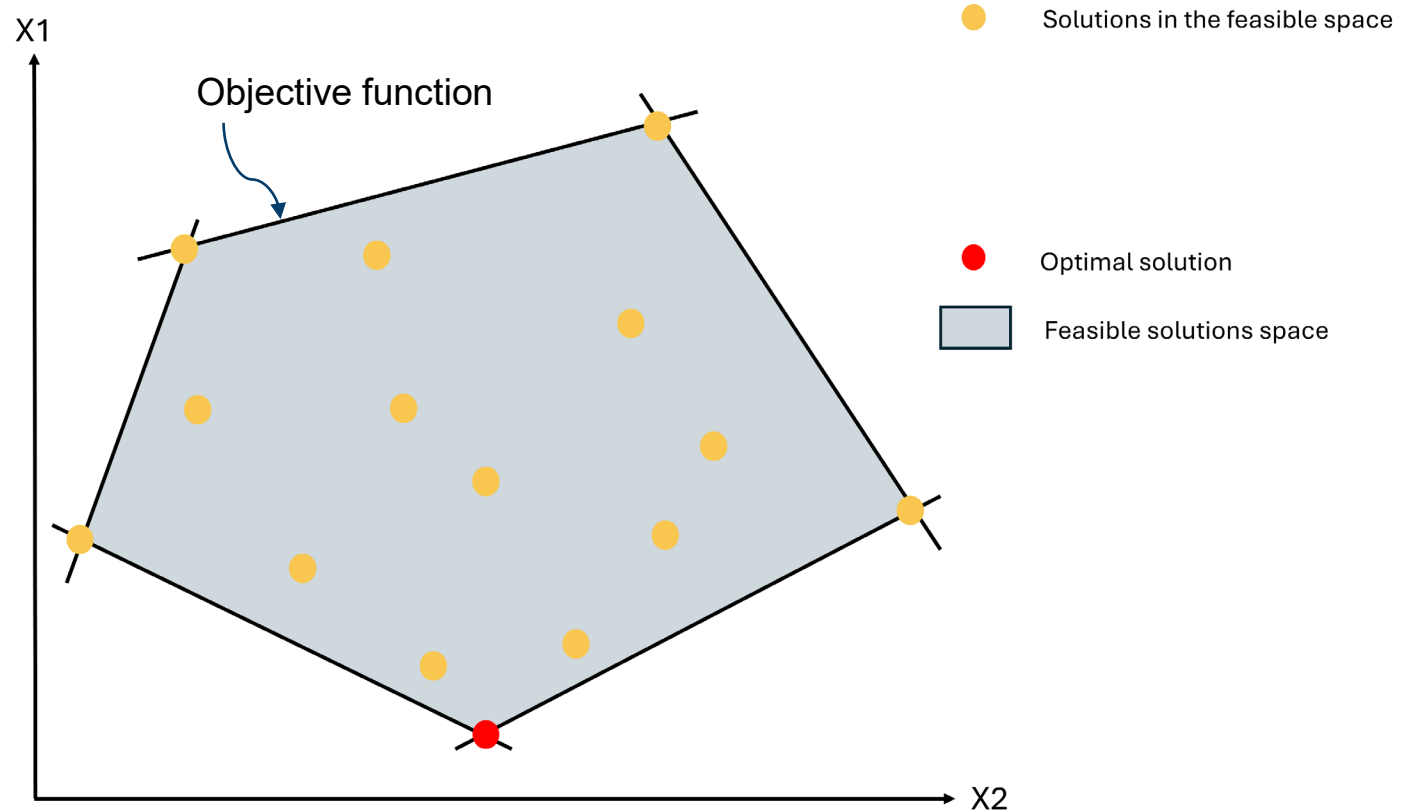
- Germany consists of 11003 municipalities (average area 32.5 km²).
- 93% of the municipalities have the potential to become energy autonomous by 2045 [1].
- These municipalities will be self sufficient without any energy import.
- Cost of autonomy per municipality ranges from 67 €/MWh to 2042 €/MWh [1].
- Results obtained through a least cost-based energy system optimization.
- Can we always rely on the optimal result when there is uncertainty?
- Therefore, alternative solutions, which lie around this optimal solution should be identified.

[1] Risch, Stanley, et al. "Scaling energy system optimizations: Techno-economic assessment of energy autonomy in 11 000 German municipalities." Energy Conversion and Management 309 (2024): 118422.

Introduction

Modeling to generate alternatives

- “*Modeling-to-generate alternatives (MGA) is a technique in which mathematical programming models are applied to complex, incompletely defined problems to produce a small number of different alternatives*” [1]



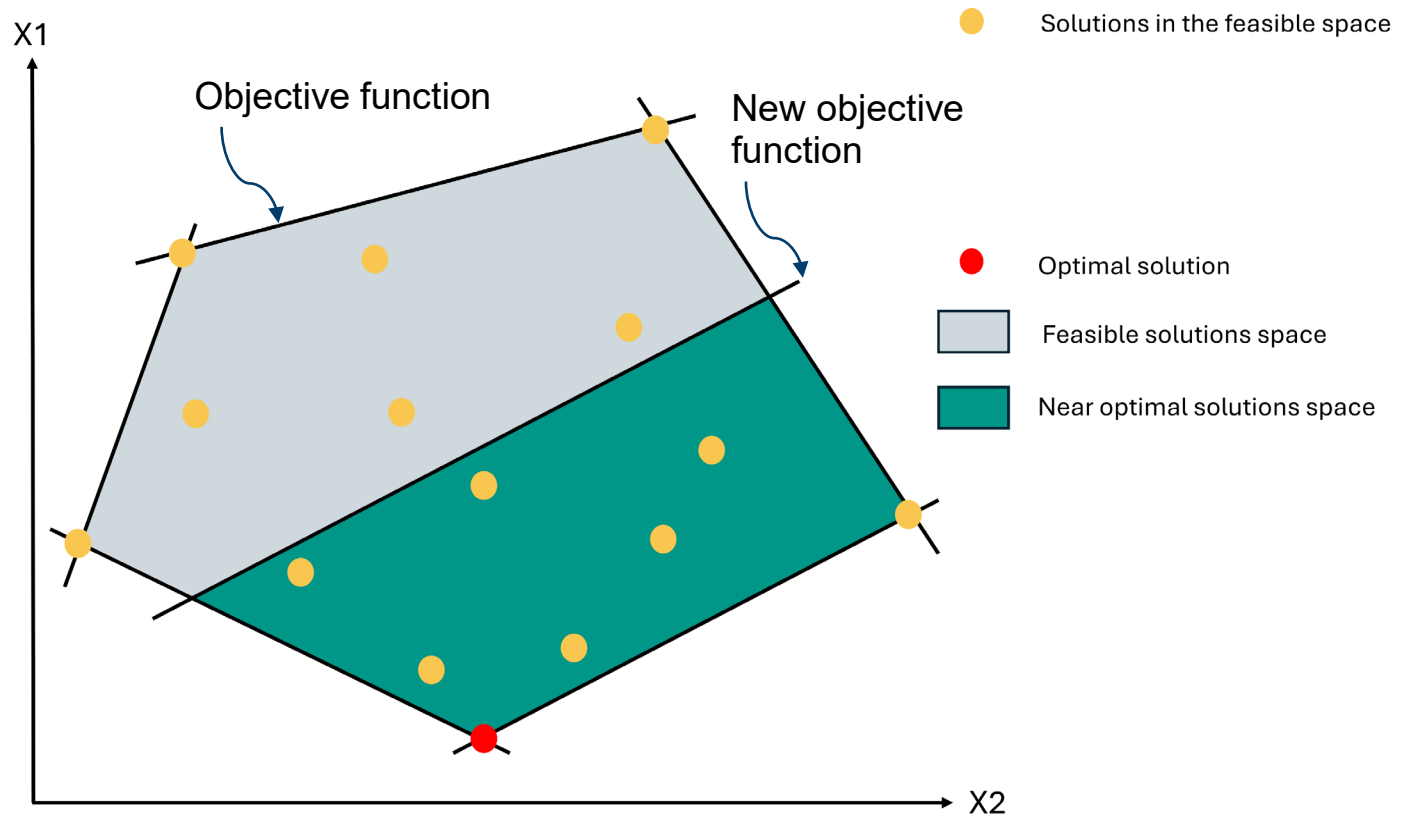
Representation of optimization solutions in the feasible region for a 2-variables problem

[1] Brill et al, J MGA: a decision support system for complex, incompletely defined problems, doi: 10.1109/21.105076.

Introduction

Modeling to generate alternatives

- Introduce a new objective function in the form of $Z = X1.i + X2.j$ where $i, j \in (-1,1)$

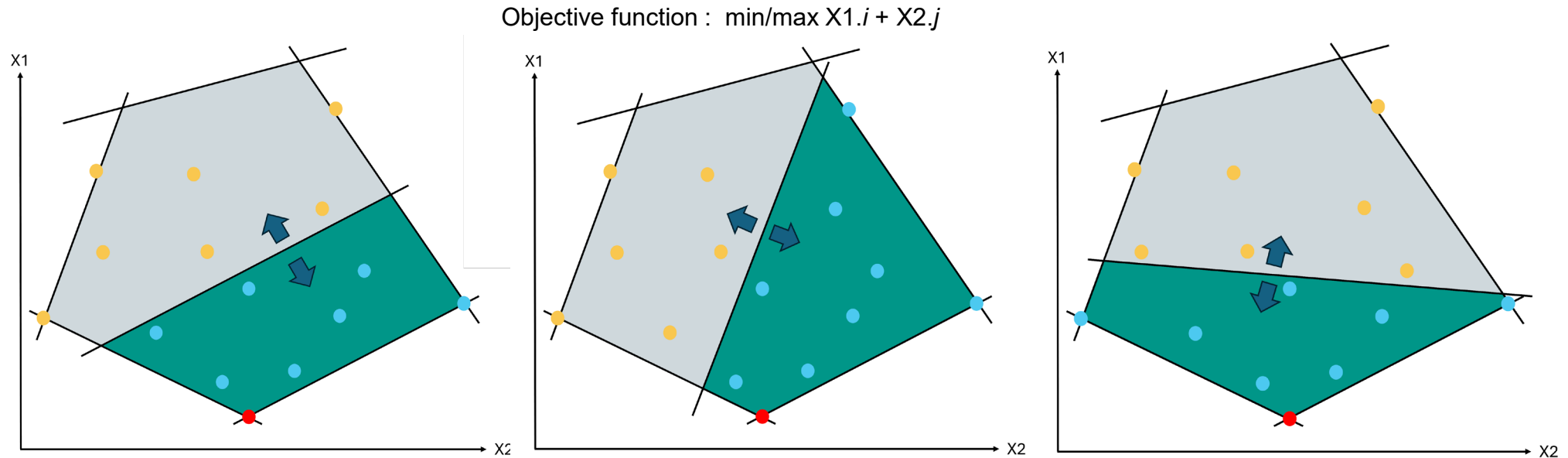


Representation of optimization solutions in the feasible region for a 2-variables problem

Introduction

Modeling to generate alternatives

- When i and j are changing, with alternative objective functions, alternative near optimal solutions spaces and alternative near optimal solutions can be obtained.



Change in the feasible region with the change of the objective function

- MGA represents a fundamental departure from other forms of uncertainty analysis
- MGA uses the optimal model solution as an anchor point to explore the surrounding feasible region [1]

[1] DeCarolis, J. F. (2011). Using modeling to generate alternatives (MGA) to expand our thinking on energy futures. Energy Economics, 33(2), 145-152.

Methodology

Implementing MGA in ETHOS.FINE

- The optimization objective function of ETHOS.FINE is to minimize the annualized system cost.
- Costs of the components such as source, storage, transmission etc. and inputs or outputs of these components contribute to the objective function and energy balances, respectively [1]

NPV_{cap} - Net present value of capacity variables over the useful lifetime

NPV_{op} - Net present value of operation variables over the useful lifetime

$c \in M$ - Components

$t \in T$ - Time steps

A - Coefficient matrix of constraints

B - Right-hand side vectors of constraints

C^* - Optimal cost value of original problem

The objective function:

$$\min \sum_c \left(NPV_{cap}^c + \sum_t NPV_{op}^{c,t} \right)$$

s.t. $Ax = B$ (to represent all the constraints)

Solution:

Take the optimal solution as C^*

[1] Welder, Lara, et al. "Spatio-temporal optimization of a future energy system for power-to-hydrogen applications in Germany." Energy 158 (2018): 1130-1149.

Methodology

Implementing MGA in ETHOS.FINE

- NPV_{cap} - Net present value of capacity variables over the useful lifetime
- NPV_{op} - Net present value of operation variables over the useful lifetime
- $c \in M$ - Components
- $t \in T$ - Time steps
- A - Coefficient matrix of constraints
- B - Right-hand side vectors of constraints
- C^* - Optimal cost value of original problem
- x_{cap} - Installed capacity variable
- x_{or} - Operation-rate variable
- β - Random coefficient between -1 and 1
- K - Total number of MGA iterations
- δ - Slack

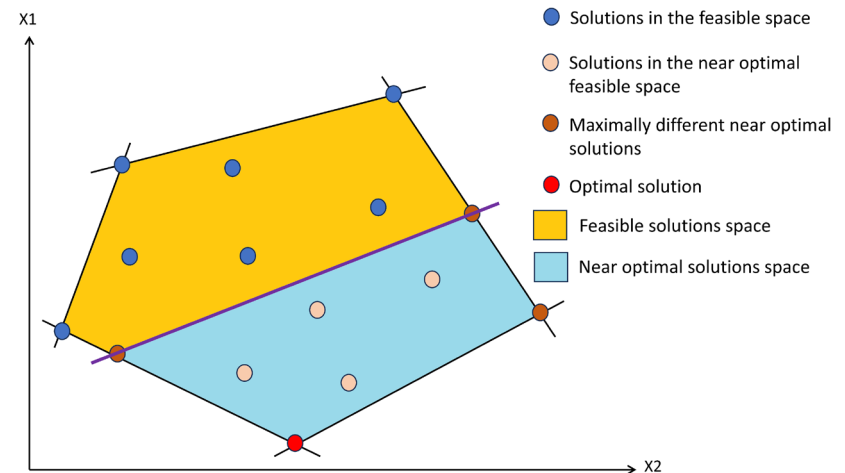
The MGA objective function:

$$\min/\max \sum_c \left(x_{cap}^c + \sum_t x_{or}^{c,t} \right) \cdot \beta^{c,k} \quad \forall k = 1, 2, \dots, \mathbb{K}$$

s.t.

$$Ax = B$$

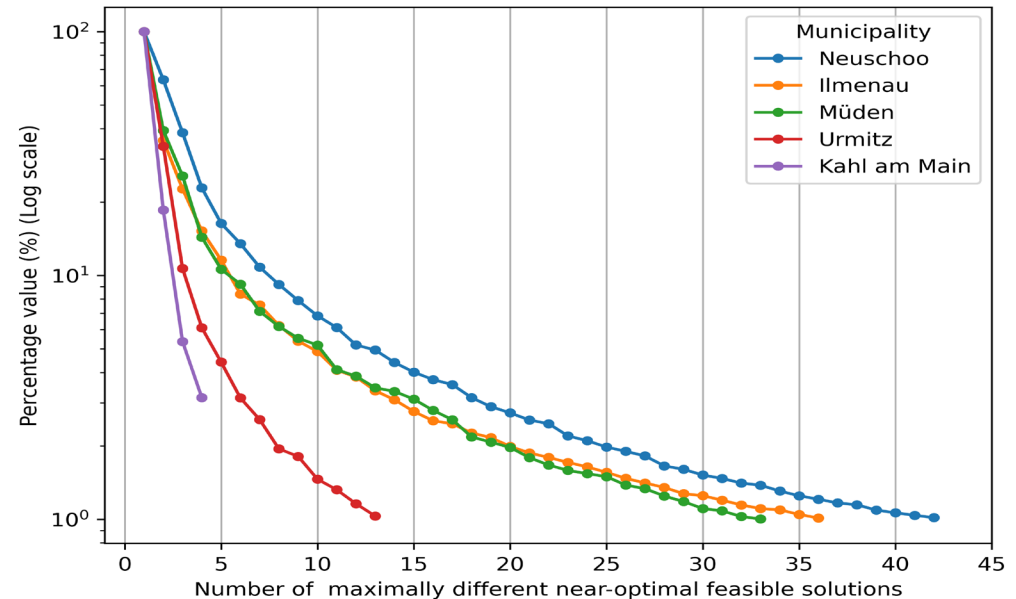
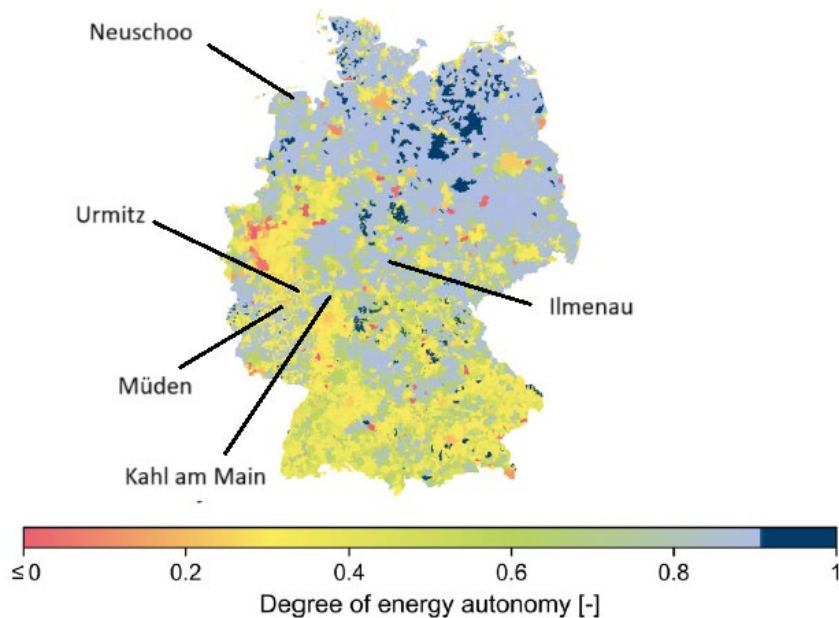
$$\sum_c \left(NPV_{cap}^c + \sum_t NPV_{op}^{c,t} \right) \leq C^* (1 + \delta)$$



Case study

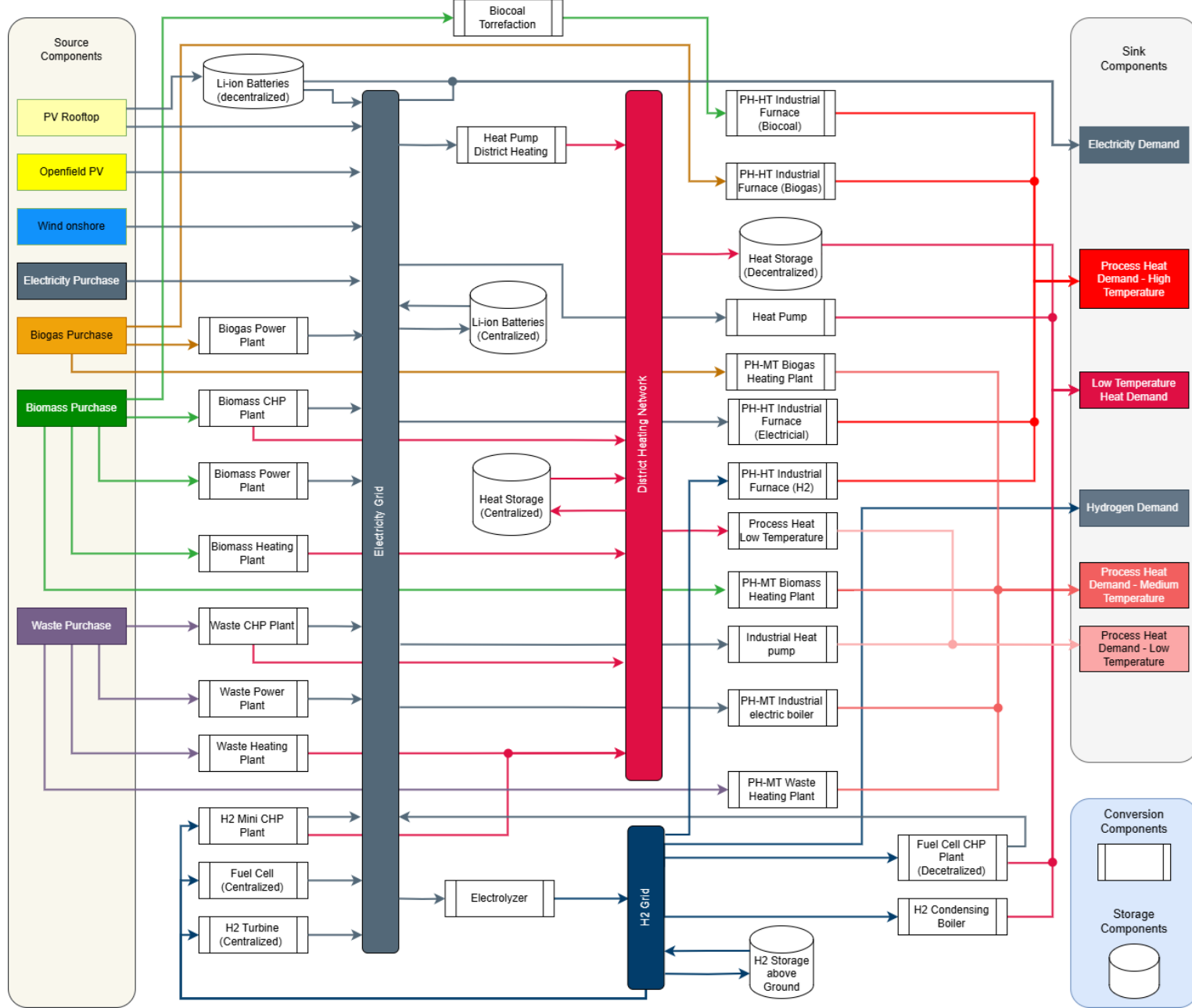
Identifying autonomous municipalities for flexibility exploration

Autonomy cost level	Municipality	State	Population	Area (km ²)	Annual electricity equivalent energy demand (GWh)	Specific system cost (€/MWh)
Low cost	Neuschoo	Niedersachsen	1171	14.47	25.79	65
	Ilmenau	Thüringen	38891	198.69	414.33	92
Medium cost	Müden (Mosel)	Rheinland-Pfalz	642	7.49	3.27	120
High cost	Urmitz	Rheinland-Pfalz	3435	3.77	33.14	988
	Kahl am Main	Bavaria	8033	10.64	75.49	2064



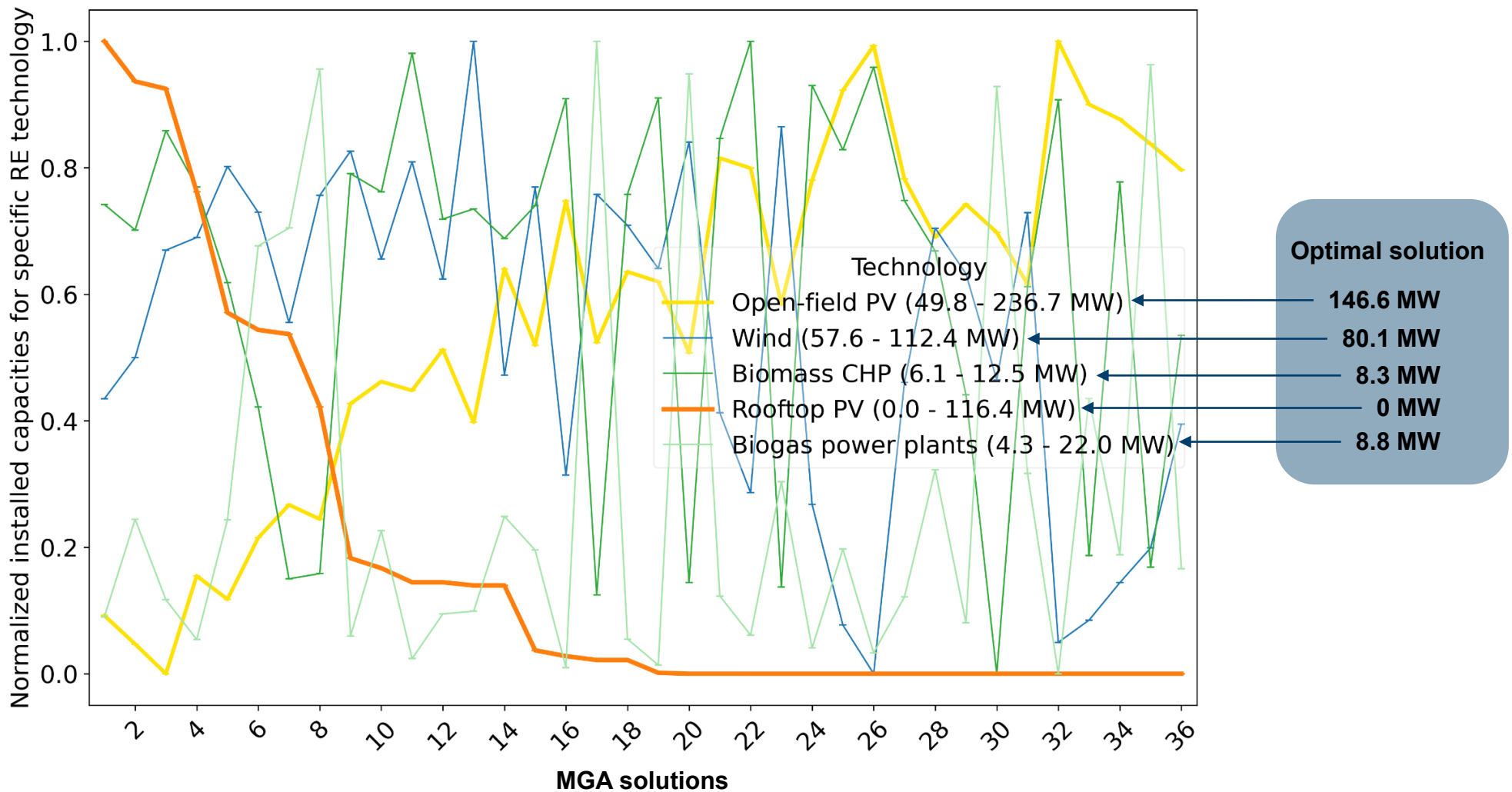
Case study

- Only renewables supply energy.
- Electricity purchase is the last available option.
- In each time step, demand must be fulfilled.
- Conversion and storage component capacities are decided in the optimization process.



Results

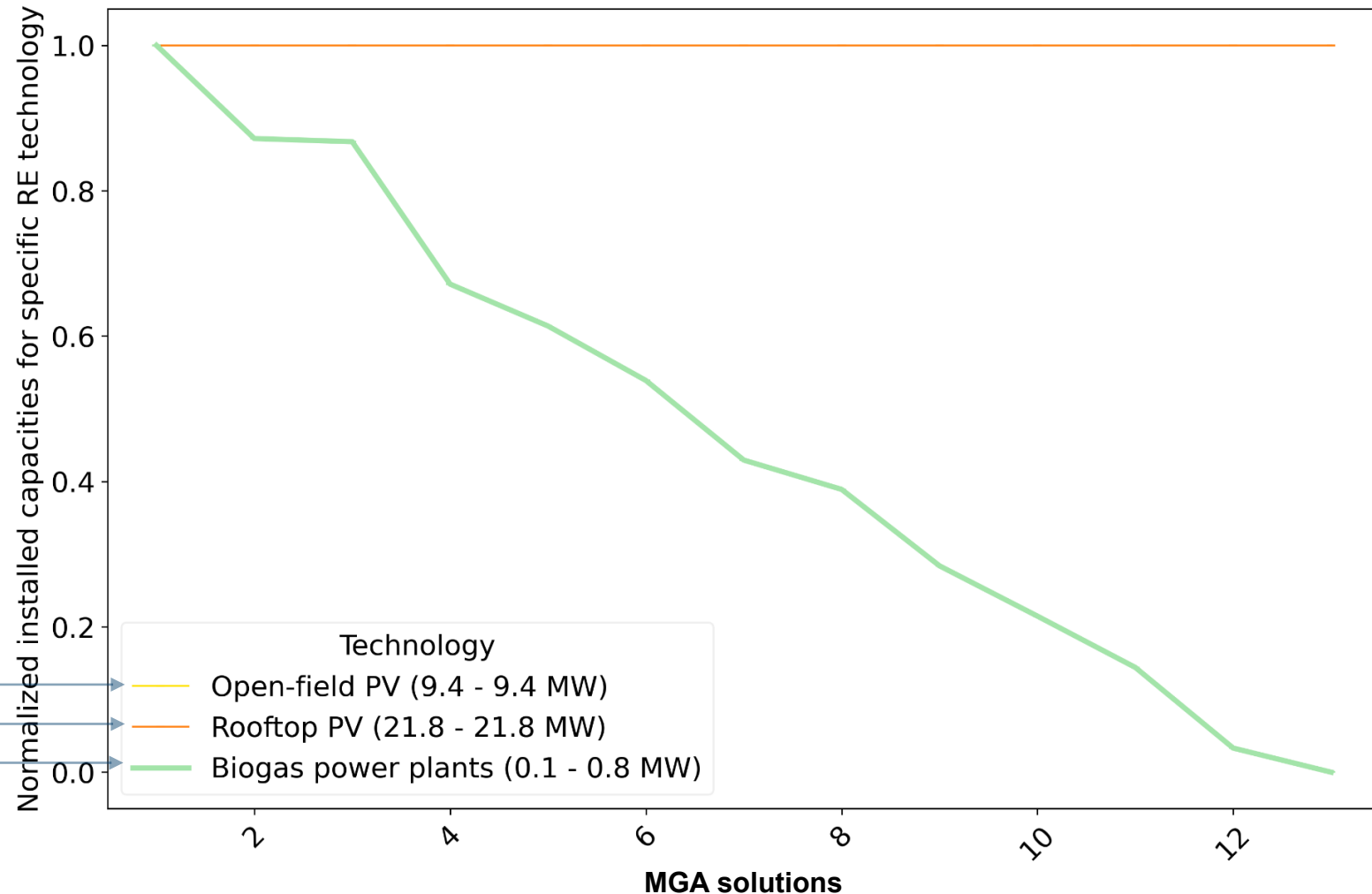
Flexibility in the source components in Ilmenau (low-cost municipality)



- Rooftop PV capacities of the MGA solutions are arranged in descending order. Capacities of the MGA solutions in other technologies are appeared accordingly.

Results

Flexibility in the source components in Urmitz (high-cost municipality)



Optimal solution

9.4 MW

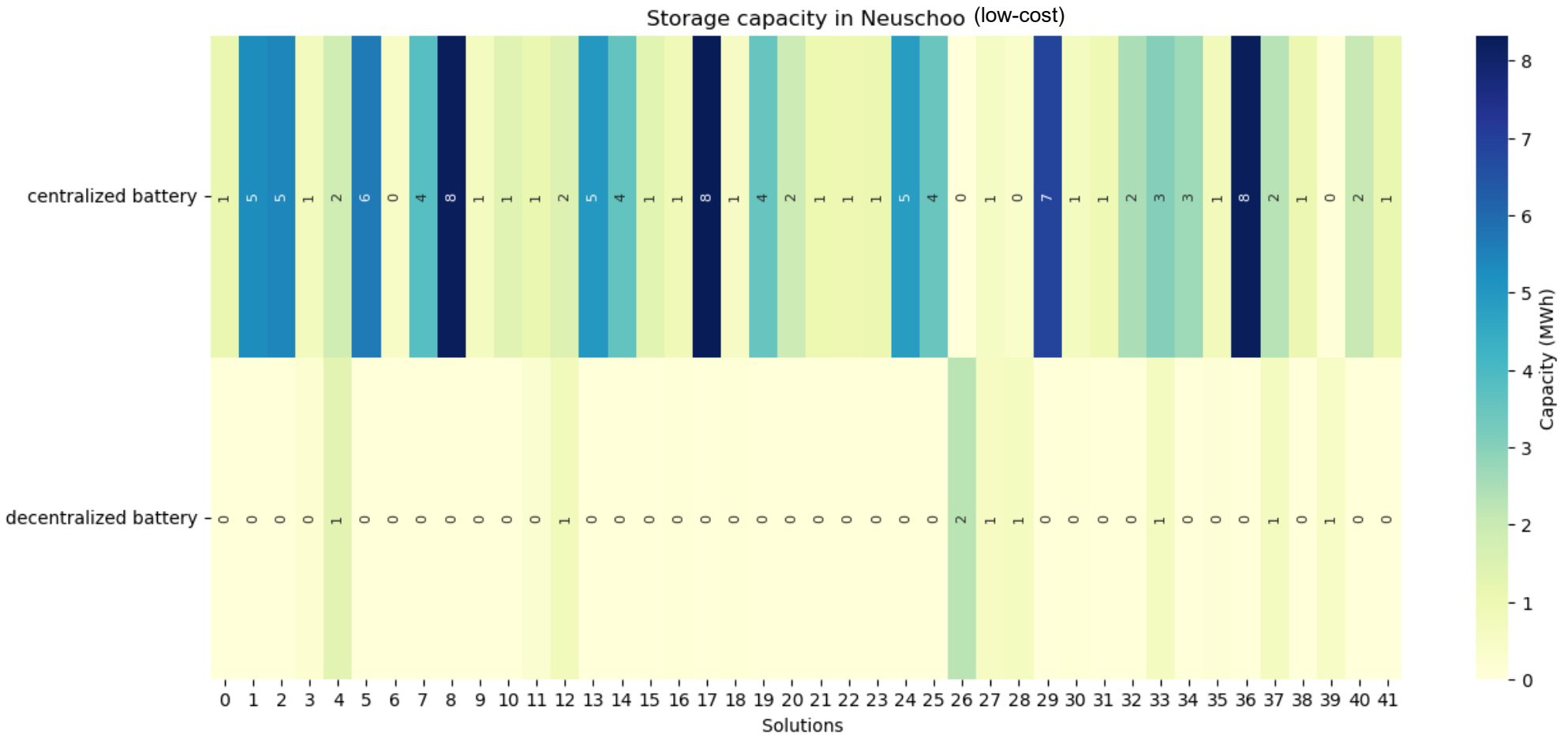
21.8 MW

0.06 MW

- Biogas power plant capacities of the MGA solutions are arranged in descending order. Capacities of the MGA solutions in other technologies are appeared accordingly.

Results

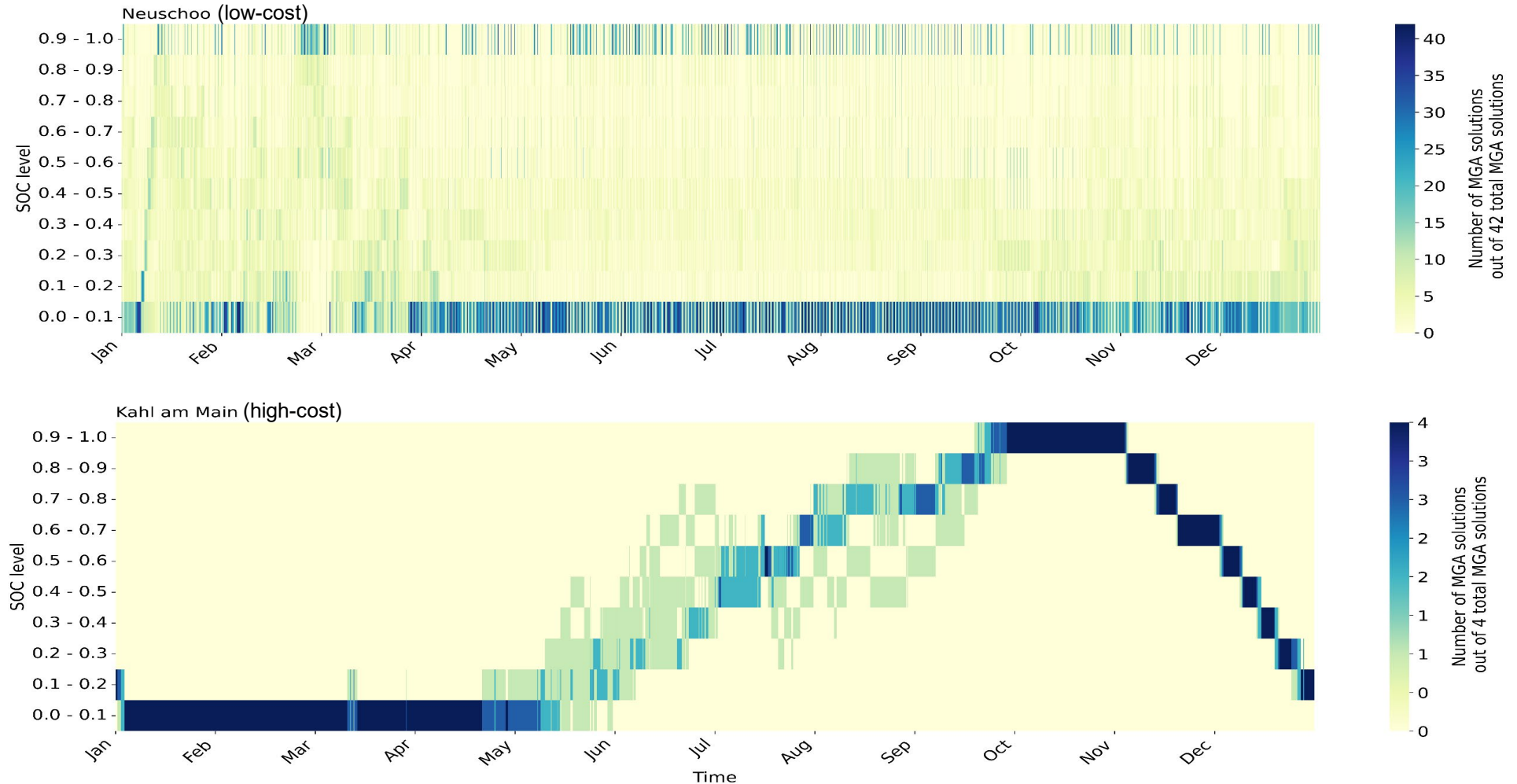
Flexibility in the storage components



- Neuschoo shows that it can operate without any centralized batteries, with a 10% cost relaxation

Results

Flexibility in the storage components

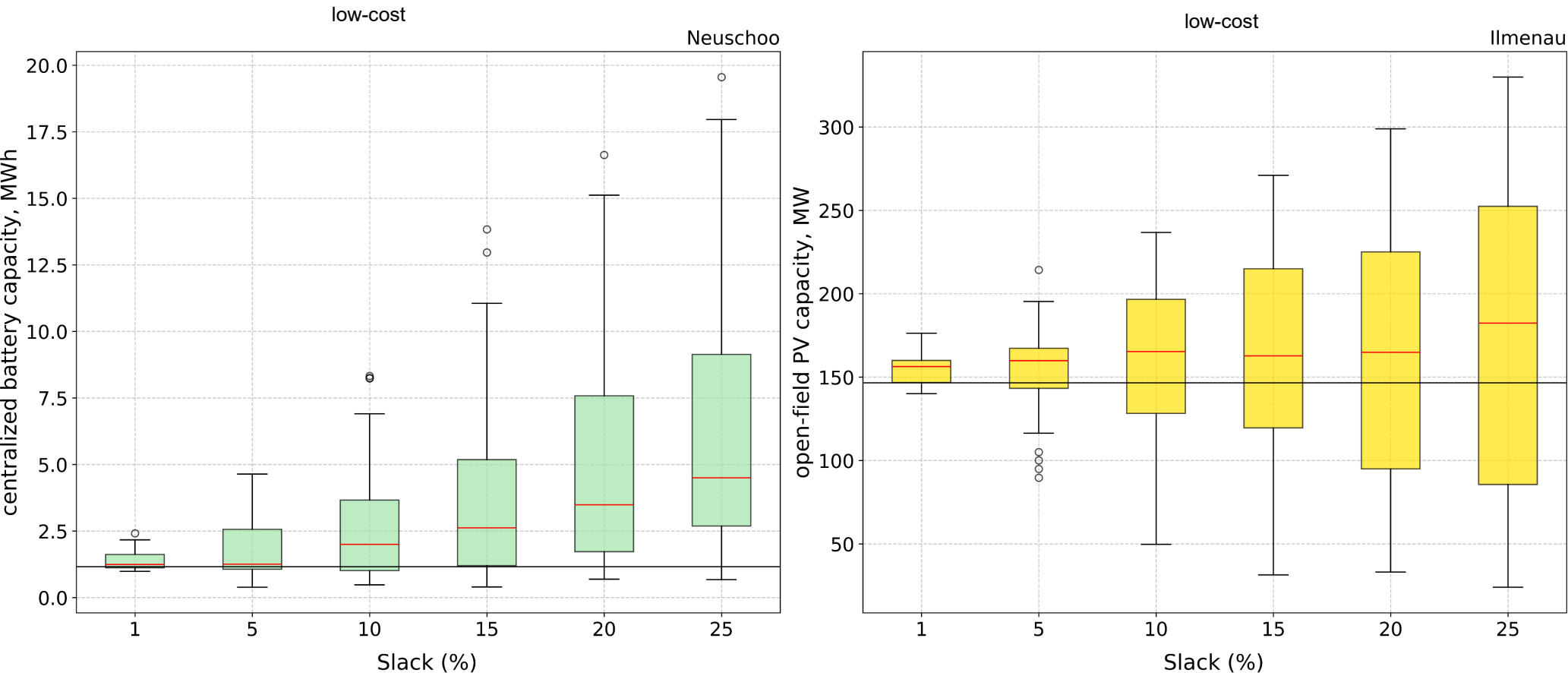


- Decentralized batteries are directly connected with rooftop PV, hence with more decentralized battery capacities, electricity demand in high-cost municipalities can met easily compared to centralized batteries.

Results

Sensitivity of the slack value

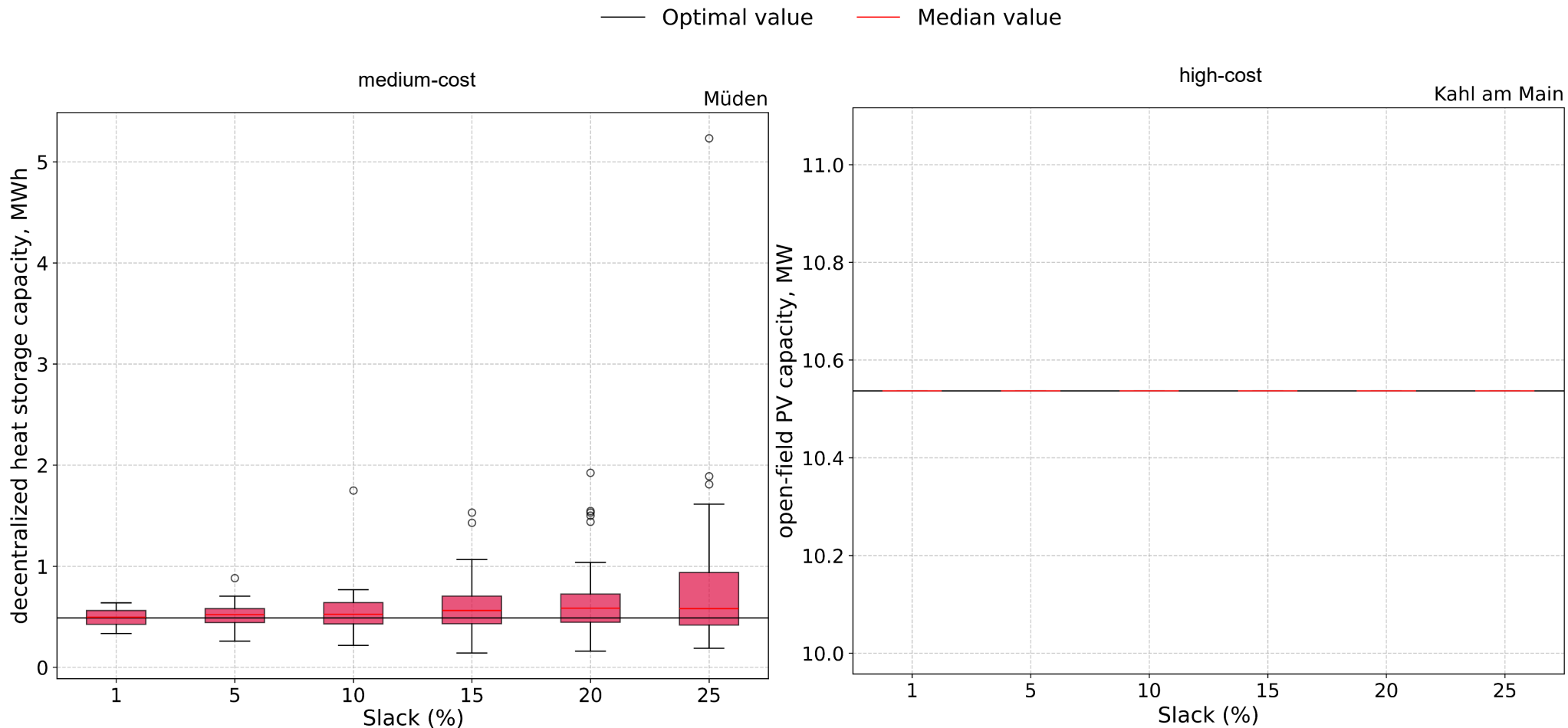
— Optimal value — Median value



- In Neuschoo, when the slack increases by more than 1%, the range of feasible solutions expands considerably
- Ilmenau's open-field PV capacity shows a systematic shift, both upward and downward

Results

Sensitivity of the slack value



- An increasing but limited scalability of capacity with the increasing slack value is seen in decentralized heat storage in Müden.
- In Kahl am Main, no changes with increasing slack value

Results

Summary

- MGA revealed substantial flexibility for low-cost municipalities.
- Medium-cost municipalities had more limited substitution possibilities.
- In high-cost municipalities, the limited range of solutions highlighted the vulnerability of autonomous energy provision.
- The study also pointed to several limitations, including the restricted number of municipalities that were analyzed and the dependency of results on the chosen slack and β values.
- This study did not consider transmission components. Not considering transmission components strengthens the focus on autonomy but reduces applicability to real-world conditions where inter-municipal or regional transmission could significantly lower costs and further increase the flexibility.

Thank you for your attention!



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Project Resur

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