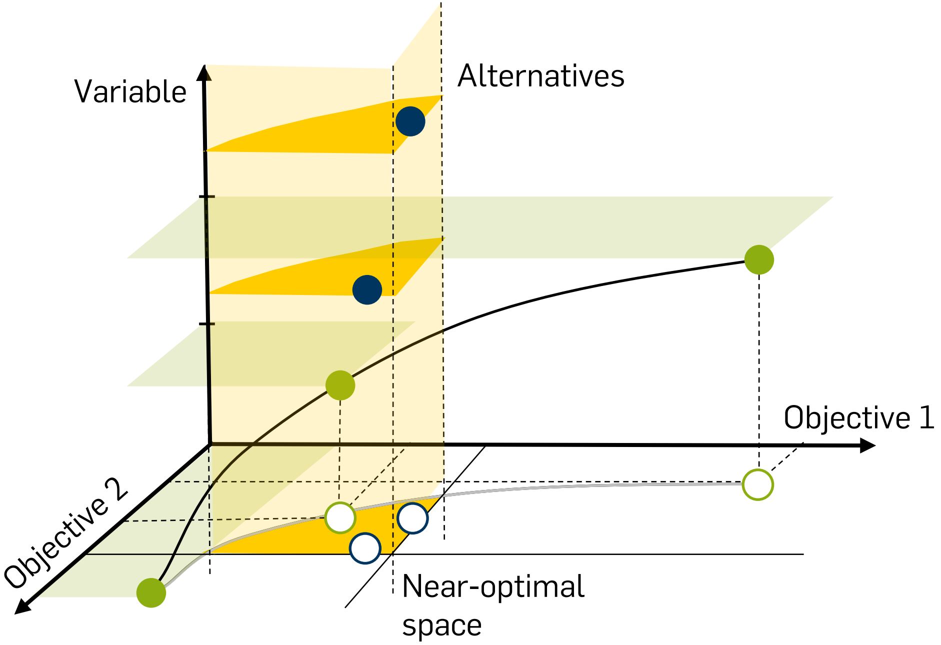

RUHR-UNIVERSITÄT BOCHUM

COMBINING PARETO FRONT-GENERATING AND DIVERSIFYING OPTIMISATION METHODS FOR MUNICIPAL ENERGY SYSTEMS PLANNING

Chair of Energy Systems & Energy Economics

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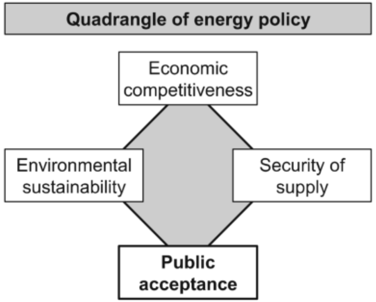
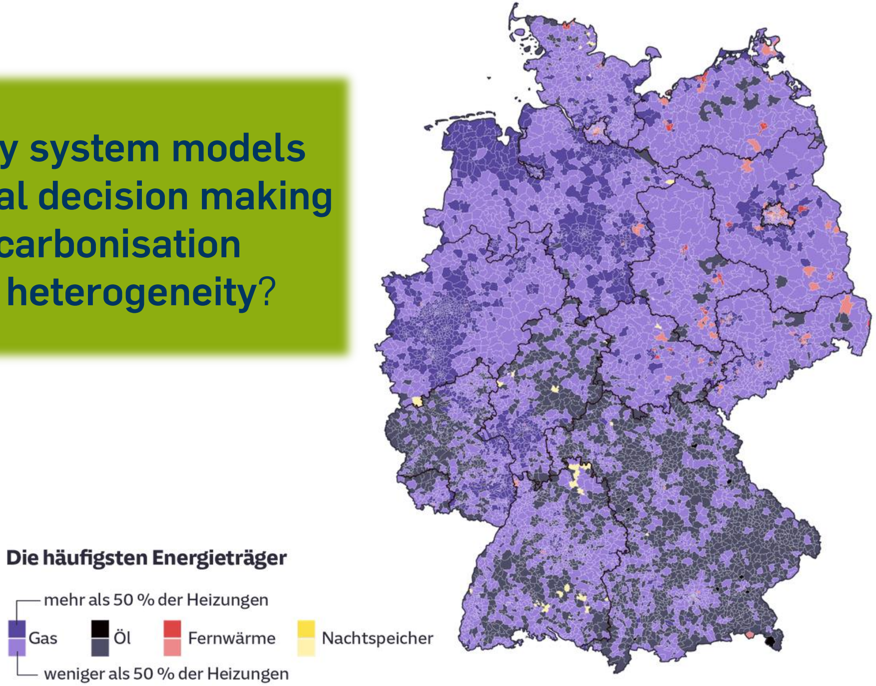
Motivation

Decarbonising municipalities: One doesn't fit all

How can **energy system models** support **municipal decision making** towards **decarbonisation** in light of this **heterogeneity**?

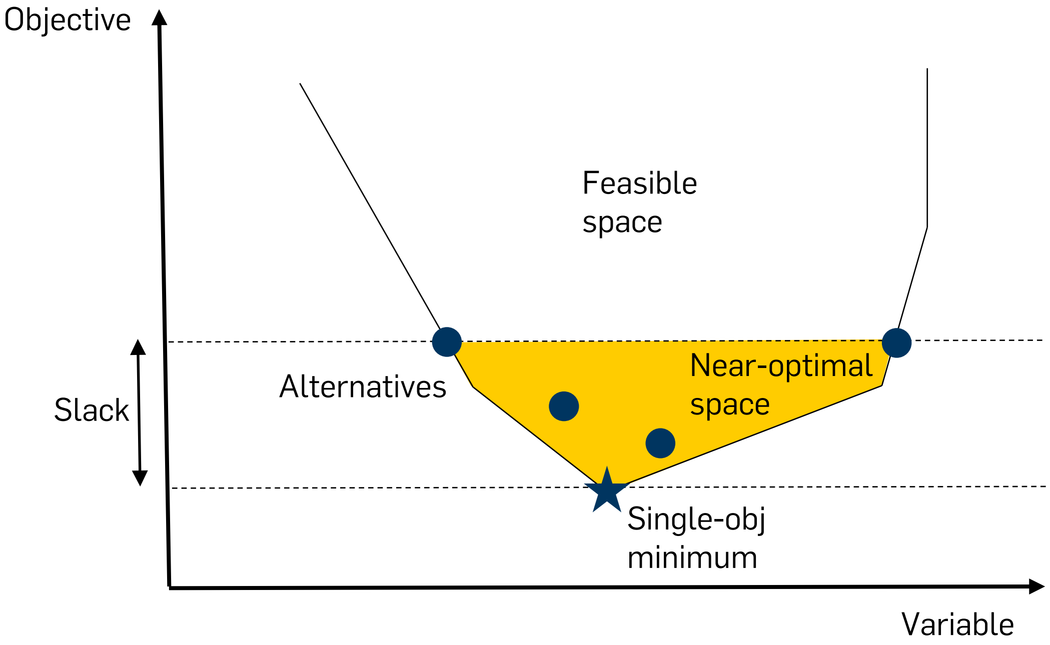




Right hand side: Figure from Markus Hametner et al., *So heizt Deutschland*, Süddeutsche Zeitung 09.06.2023, https://www.sueddeutsche.de/projekte/artikel/wirtschaft/heizungsgesetz-2024-deutschland-e683258/ retrieved 04.07.2023, 16:30 and quote translated from Laurenz Gehrke et al., *Koalition will Heizungen bundesweit erfassen*, Süddeutsche Zeitung 24.05.2023, https://www.sueddeutsche.de/politik/heizungen-ampel-koalition-waermewende-gesetz-daten-1.5878656 retrieved 04.07.2023, 16:40
Left hand side: Quote translated from UBA, *Energieverbrauch privater Haushalte*, https://www.umweltbundesamt.de/daten/private-haushalte-konsum/wohnen/energieverbrauch-privater-haushalte#endenergieverbrauch-der-privaten-haushalte retrieved 04.07.2023 17:16 and data for figure taken from UBA, *Energieverbrauch nach Energieträgern und Sektoren*, https://www.umweltbundesamt.de/daten/energie/energieverbrauch-nach-energietraegern-sektoren retrieved 04.07.2023, 17:20

Methods

Method 1: Modelling to Generate Alternatives (MGA)



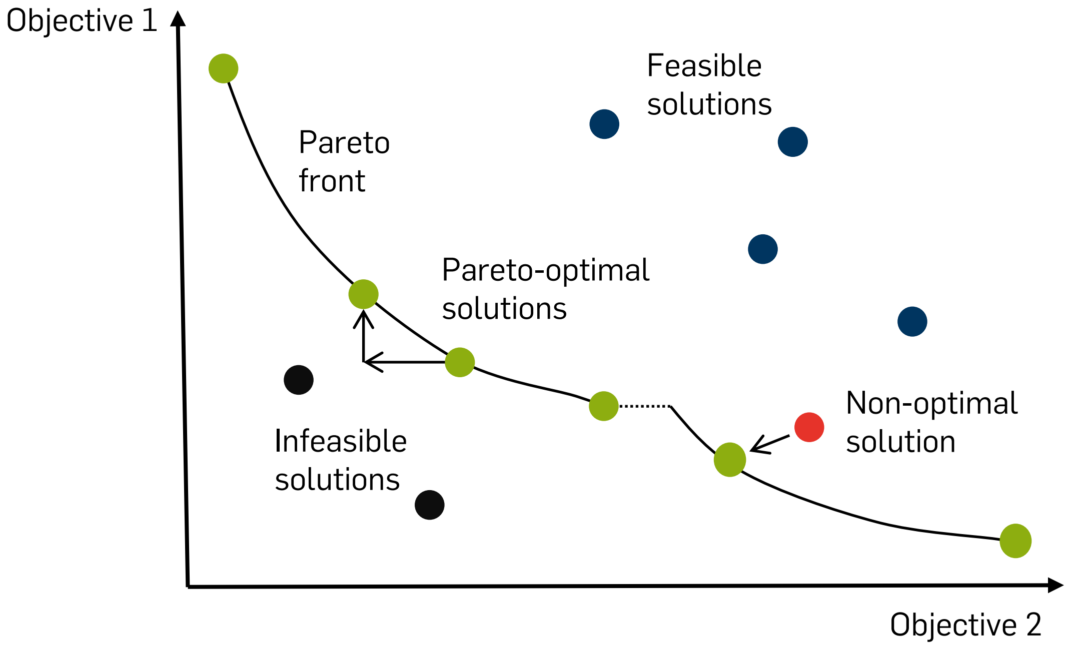
- Reduces **uncertainty**, considers **unmodelled interests** and generates more **feasible solutions**
- But only applied to **costs** as **single objective**[1], **requiring a priori assumptions**

DeCarolis, *Using modeling to generate alternatives (MGA) to expand our thinking on energy futures*, Energy Economics 2011. https://doi.org/10.1016/j.eneco.2010.05.002

[1] For a review of existing MGA studies, see e.g. Neumann and Brown, *The near-optimal feasible space of a renewable power system model*, Electric Power Systems Research 2021. https://doi.org/10.1016/j.epsr.2020.106690

[2] Concerning advantages of multi-objective optimisation approaches, see the following slides and e.g. Finke and Bertsch, *Implementing a highly adaptable method for the multi-objective optimisation of energy systems*, Applied Energy 2023. https://doi.org/10.1016/j.apenergy.2022.120521

Method 2: Generate a Pareto front with AUGMECON

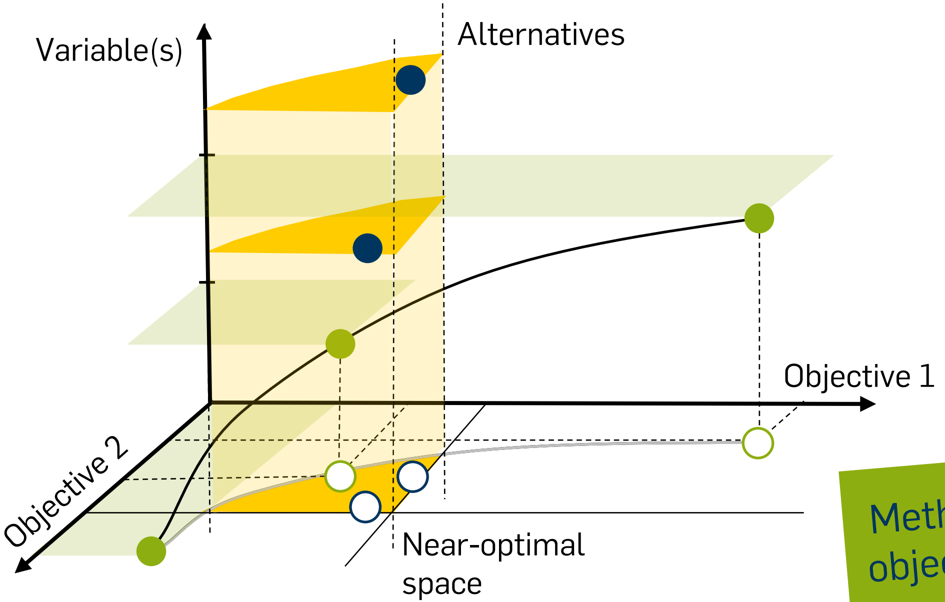


- Reveals **feasible ranges**, **trade-offs** and general **trends**
- But **neglects diversity** in near-Pareto-optimal space[1]

Mavrotas, *Effective implementation of the epsilon-constraint method in Multi-Objective Mathematical Programming problems*, Applied Mathematics and Computation 2009. https://doi.org/10.1016/j.amc.2009.03.037
Finke and Bertsch, *Implementing a highly adaptable method for the multi-objective optimisation of energy systems*, Applied Energy 2023. https://doi.org/10.1016/j.apenergy.2022.120521

[1] There is one very recent study that includes the near-Pareto-optimal solution space, but does not use MGA to diversify in this space, not focus on heterogeneity and not on municipal systems. See Prina et al., *Evaluating near-optimal scenarios with EnergyPLAN to support policy makers*, Smart Energy 2023. https://doi.org/10.1016/j.segy.2023.100100

New method: Combine Pareto front and diversification



Small scalar | Slack variables

$$\min \sum_i w_i v_i - c\left(\frac{s_1}{O(f_1)} + \frac{s_2}{O(f_2)}\right)$$

Weights | Variables | Orders of magnitude

$$\text{s.t.} \quad f_1 + s_1 = \epsilon_1$$

$$f_2 + s_2 = \epsilon_2$$

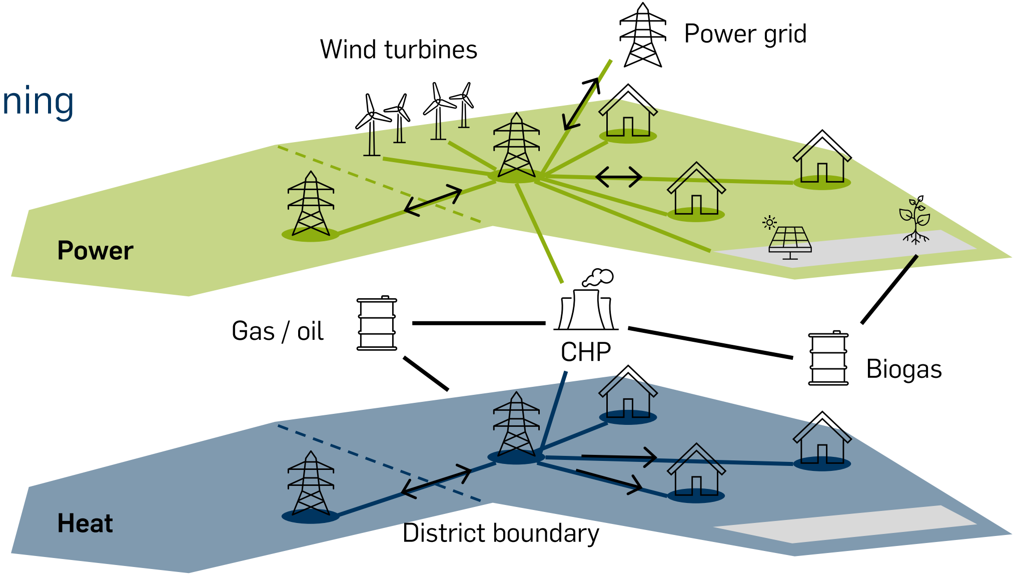
Objectives | Upper bounds

Method **agnostic** of objectives, variables and context

Case studies

General setting

- Energy system optimisation framework Backbone
- One municipality with multiple districts
- Each with multiple aggregated buildings
- One year investment and operational planning



Investment options at district level

- Wind, CHP, battery, ground-mounted PV
- CHP (+ district heating)
- Biogas
- Land use conflict biogas vs PV

Helistö et al., *Backbone – An Adaptable Energy Systems Modelling Framework*, Energies 2019. See also https://gitlab.vtt.fi/backbone/backbone.
Building stock and renewable potentials are mainly from the RE3ASON model, see Mainzer, *Analyse und Optimierung urbaner Energiesysteme - Entwickung und Anwendung eines übertragbaren Modellierungswerkzeugs zur nachhaltigen Systemgestaltung*. Dissertation. Karlsruher Institut für Technologie, 2018.
Cost data is mostly based on IEA, *Annex 73 Technologies Database*, 2021. https://annex73.iea-ebc.org/Data/publications/Annex73-Technologies-Database.xlsx and Danish Energy Agency (DEA), *Technology data for generation of electricity and district heating*, 2016. https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-generation-electricity-and

General setting at aggregated building level

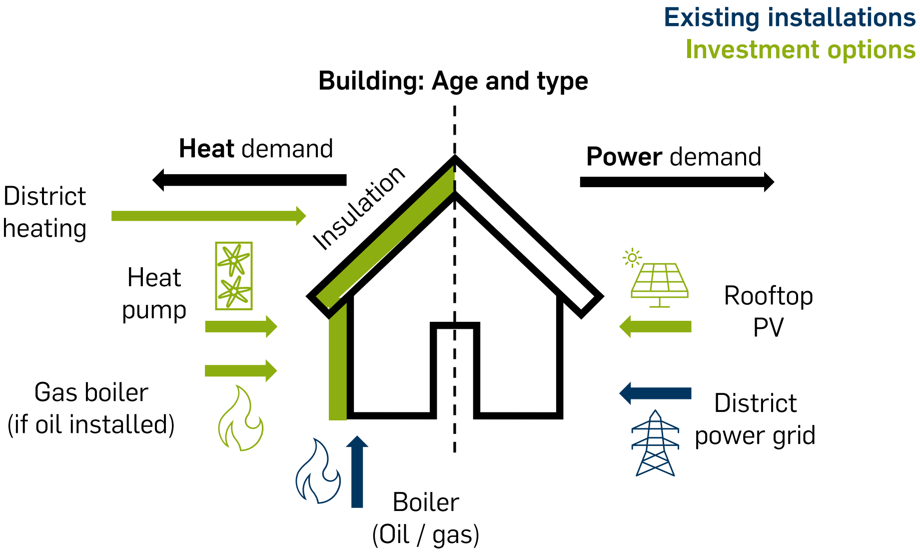
- Distinction between age and existing boiler

Existing installations

- Oil / gas boiler
- Power and gas / oil supply

Investment options

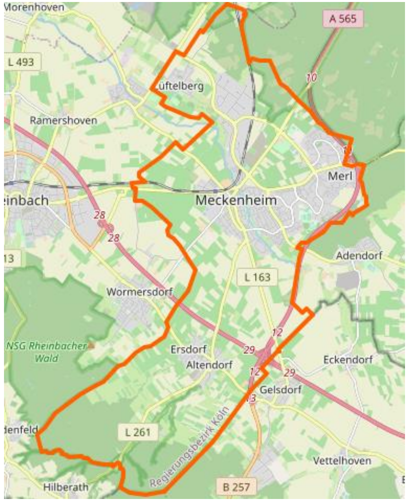
- Rooftop PV
- Heat pump
- Insulation
- Gas boiler (if oil installed)



Demand profiles are generated with nPro - District Energy Planning Tool, https://www.npro.energy
Time series for demand and renewables' capacity factors are aggregated with TSAM, see Kotzur et al., *Impact of different time series aggregation methods on optimal energy system design*, Renewable Energy, 2018. https://doi.org/10.1016/j.renene.2017.10.017
Loga et al., *Deutsche Wohngebäudetypologie Beispielhafte Maßnahmen zur Verbesserung der Energieeffizienz von typischen Wohngebäuden*, Institut Wohnen und Umwelt, 2015. https://www.iwu.de/fileadmin/publikationen/gebaeudebestand/episcope/2015_IWU_LogaEtAl_Deutsche-Wohngeb%C3%A4udetypologie.pdf

Municipality selection

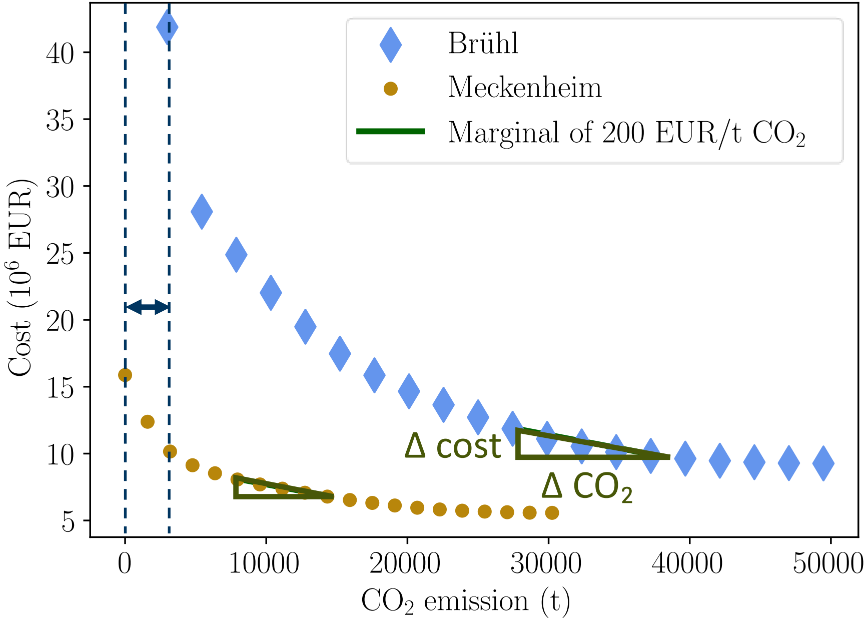
	Cluster[1] 2		Cluster[1] 5
Stands for …	"All major German cities with particularly low potential for renewables"		"'Average'" cluster containing the majority of municipalities"
Example municipality	**Brühl**		**Meckenheim**
Population	44768	>>	24357
Household density (1/km²)	560	>>	289
Old[2] residential buildings (%)	~ 95	>>	~ 45
Renewable potential			
- Wind (kW / capita)	0	<<	1.6
- Area for PV or biomass (m² / capita)	90	<<	200
- Rooftop PV (kW / capita)	2.5	<<	3.7



[1] Based on Weinand et al., *Developing a municipality typology for modelling decentralised energy systems*, Utilities Policy 2019. https://doi.org/10.1016/j.jup.2019.02.003
[2] "Old" refers to buildings from 1979 and before.

Preliminary results

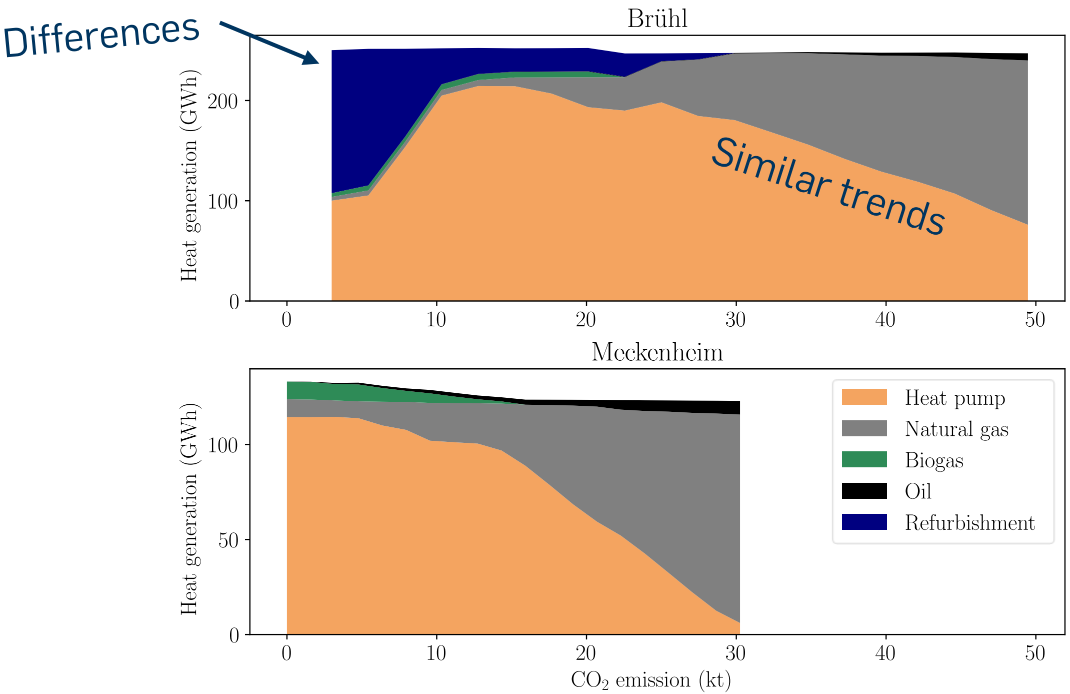
Pareto fronts for Brühl and Meckenheim



- Absolute **decarbonisation potential** differs
- Relative emission reduction at **abatement cost** of **200 €/t**
  - Brühl ~35 % (670 kg/capita/a)
  - Meckenheim ~65 % (375 kg/capita/a)
- Decarbonisation potential and its marginal costs **unknown** and **heterogeneous**

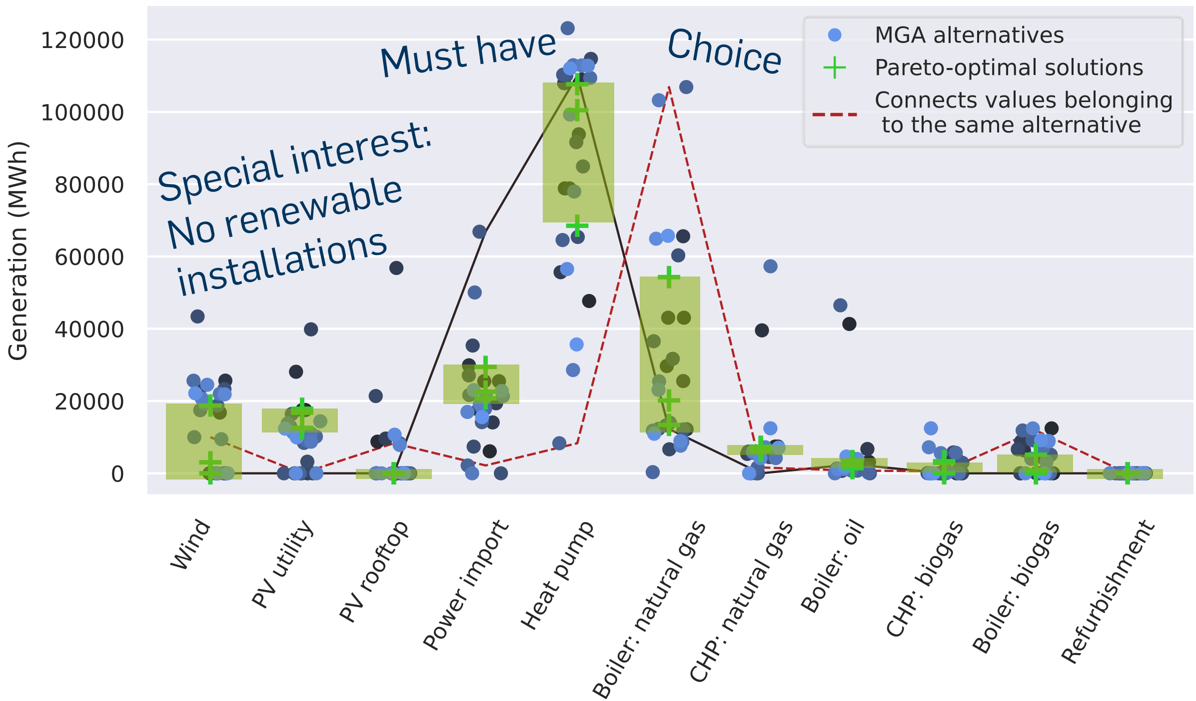
  → **Pareto front** supports decision making (MGA would need a priori assumptions)

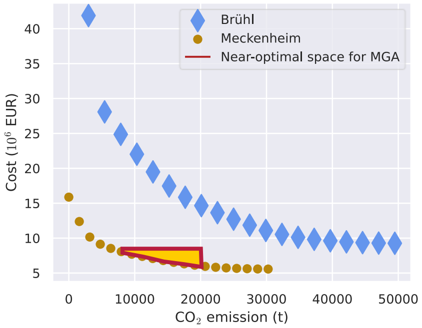
Heat generation along Pareto front



- Technology mix changes **continuously** along Pareto front, **low diversity** in small region
- Pareto front neglects diversity in **near-Pareto-optimal space**

Meckenheim: Diversification with MGA





Range of choices with MGA bigger than in Pareto front only

→ **Diversification** supports decision making for technology choices

Conclusion & outlook

Conclusion and outlook

- **New method** combines AUGMECON and MGA

- In light of **heterogeneity** of **municipal energy systems**…
  - Pareto front supports decision making for **decarbonisation targets**
  - Diversification supports decision making for **technology choices**

  → Both is needed!

Outlook

- Use method & results for real **decision making** process with **stakeholder interaction**

Thank you for your attention!

Questions?

Suggestions?