DTU

46770 Integrated energy grids

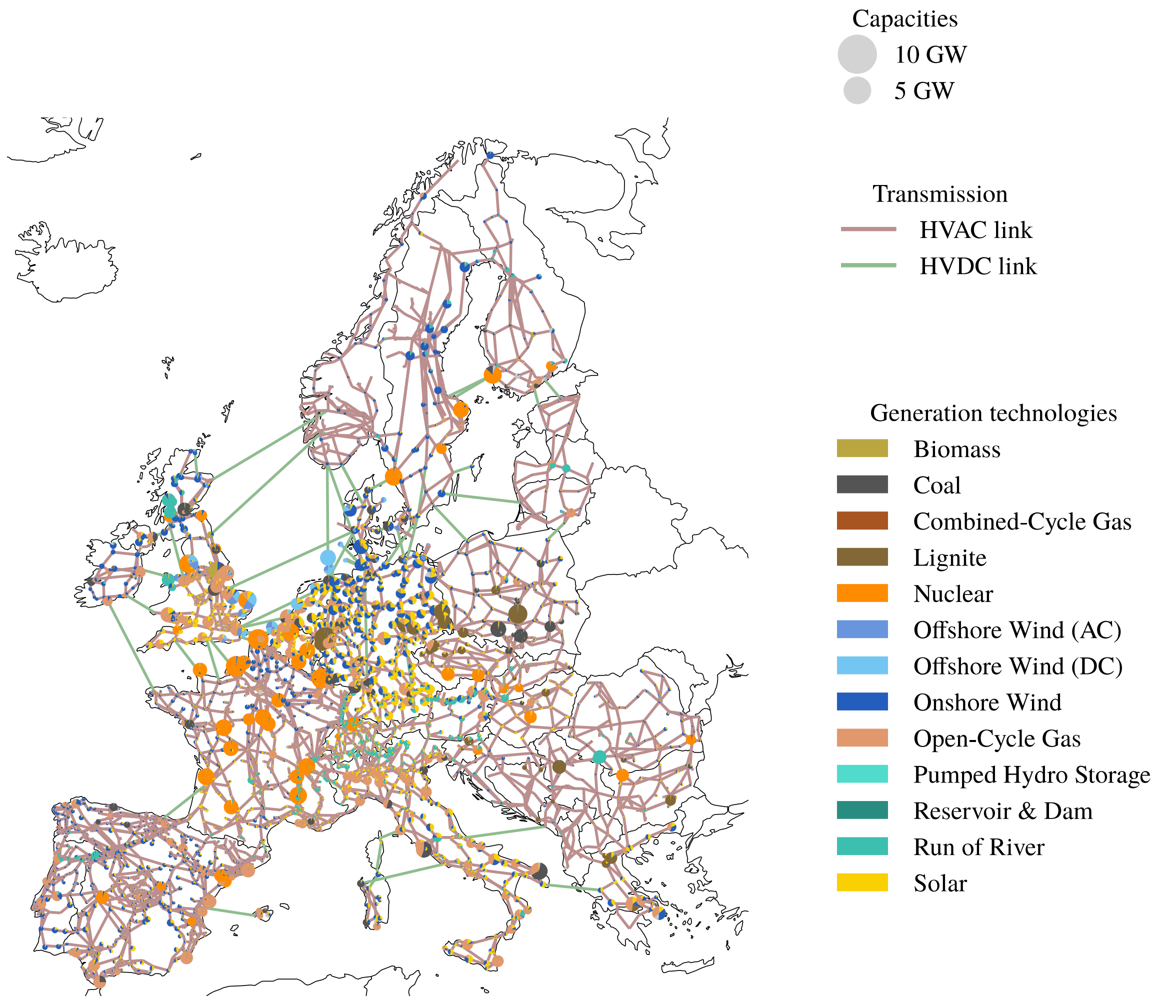
Aleksander Grochowicz

Lecture 13.1 – Challenging cost-optimality in modelling

Learning goals

- Critique existing paradigms in scientific disciplines
- Set-up alternative modelling approaches to cost optimisation
- Assess different assumptions and uncertainties when modelling real-world systems
- Use near-optimal solutions as an alternative perspective to energy planning
- Discuss complexities and trade-offs in policy as well as decision-making

Cost optimisations for long-term transition plans



- European perspective
  - interconnected system
  - central planner
  - large models depend on quantifiable data
- Assumptions
  - full information
  - perfectly competitive markets

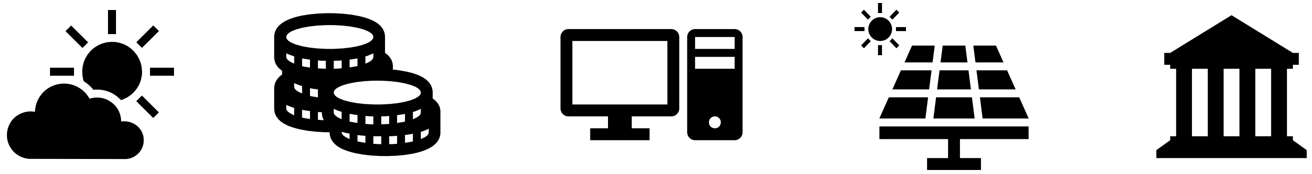
Cost optimisations for long-term transition plans

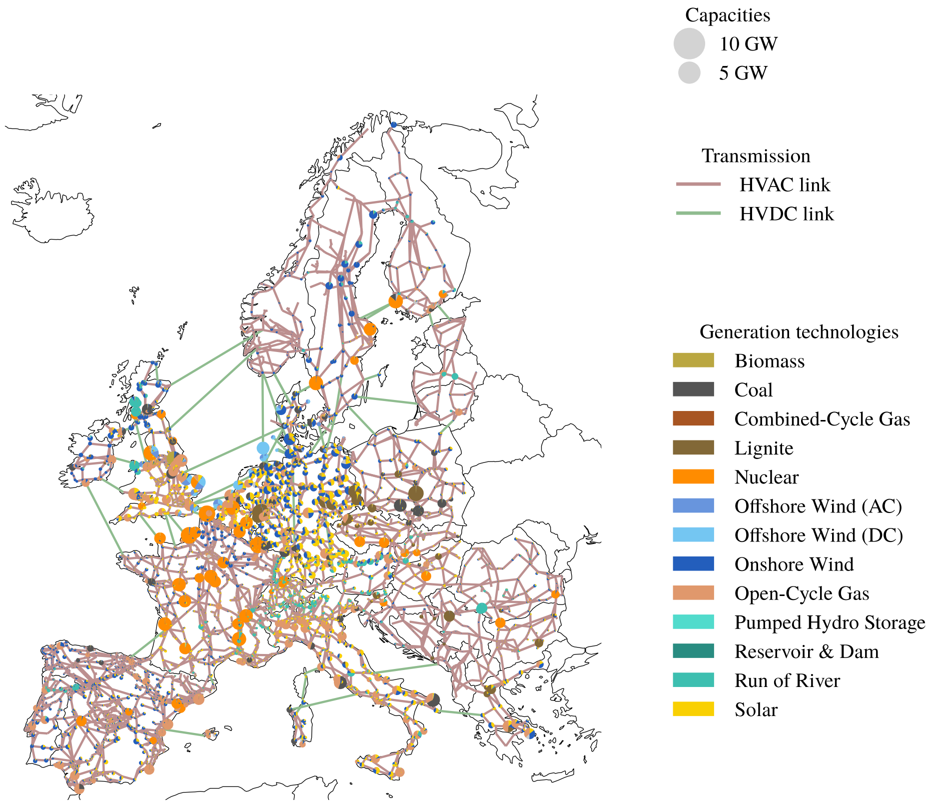
So far, we have looked at the cost-optimal solution mathematically:

$$\min_{x \in \mathbb{R}^N} \; c \cdot x, \qquad c \in \mathbb{R}^N \text{ (cost vector)}, \; x \in \mathbb{R}^N \text{ (decision variables)}$$

$$\text{s.t. } \; Ax \le b, \qquad A \in \mathbb{R}^{M \times N}, \; b \in \mathbb{R}^M \text{ (defining the constraints)}$$

Major uncertainties





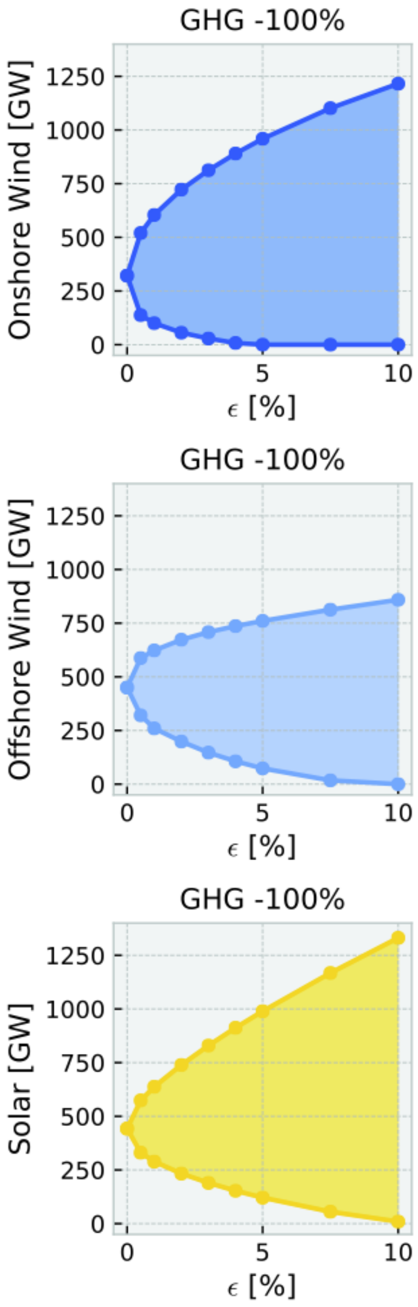
Is social acceptance a bigger barrier than technology?

- Possible obstacles of cost-optimal solutions
  - Investment in unpopular technologies
  - NIMBYism or (perceived) injustice
  - Narrow focus on costs
  - Environmental or security concerns
- Policymakers need to consider trade-offs when they make decisions
- Our policies do not follow optimal pathways either*

* Hindcast studies for the UK show deviations of 9-23% from the cost optimum. Trutnevyte. Energy, 2016. https://doi.org/10.1016/j.energy.2016.03.038

What can we do instead?

- Shift focus from strict cost optimisations, and consider other objectives
- Investigate many reasonable outcomes whose benefits can be weighted against another
- Internalise the complicated reality of uncertainties, trade-offs, and conflicting priorities
- Use technique called **modelling-to-generate-alternatives (MGA)**



Neumann and Brown. EPSR, 2021. https://doi.org/10.1016/j.epsr.2020.106690

Near-optimal solutions

Definition

Let $\varepsilon > 0$; for a linear program

$$\min_{x \in \mathbb{R}^N} \; c \cdot x$$
$$\text{s.t.} \;\; Ax \leq b,$$

the ε**-near-optimal feasible space** is given by all x

$$\begin{aligned} \text{s.t.} \;\; & Ax \leq b, \\ & c \cdot x \leq (1 + \varepsilon) \cdot c \cdot x^*, \end{aligned}$$

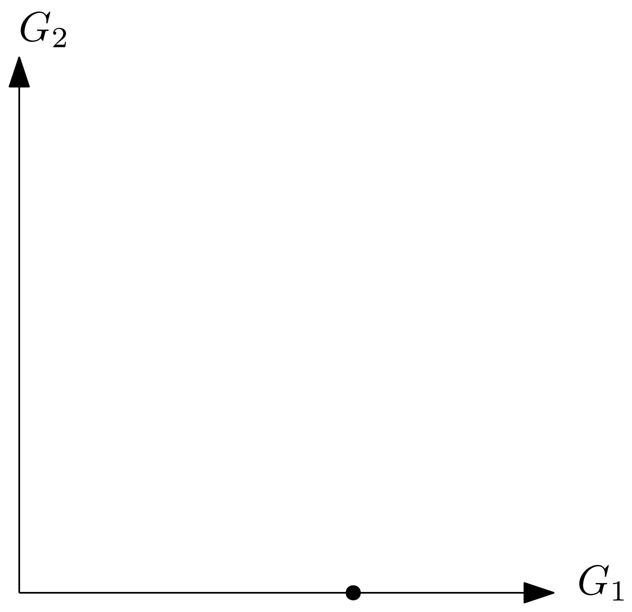
where x^* is the optimal solution to the initial linear program.

Intuition: We look for a ***feasible*** solutions within a pre-defined cost increase.

Mathematically: Turn objective function (with cost relaxation) into a constraint and find an alternative objective function for the optimisation.

Example for near-optimal spaces

Assume we are given a demand of 50 MW and two generators G_1, G_2 with the same capital cost; fuel costs o_1 for G_1 are 100 EUR/MWh, and o_2 for G_2 are 110 EUR/MWh.



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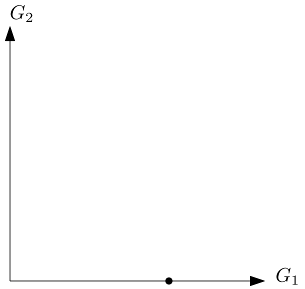
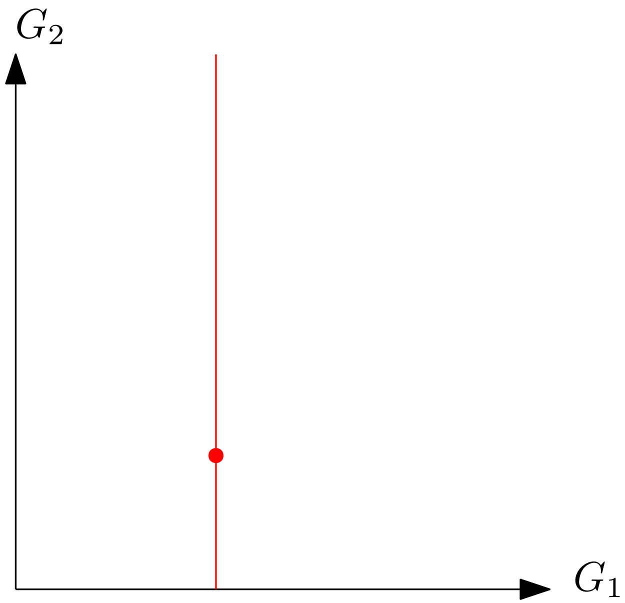


(optimum)



(land use limitation)

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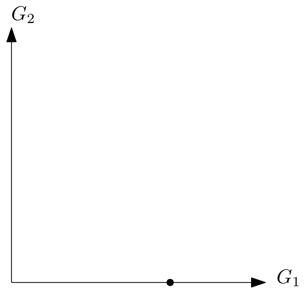

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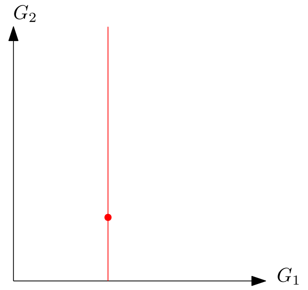

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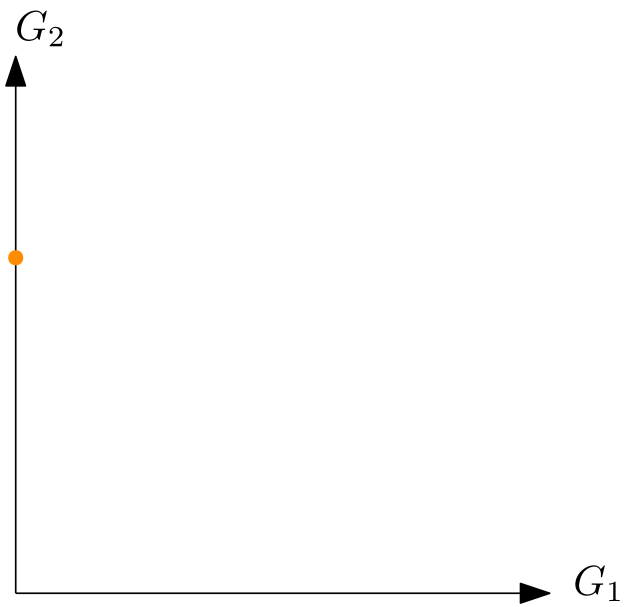

(subsidy)

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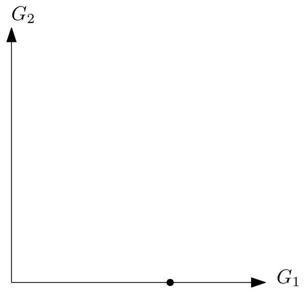

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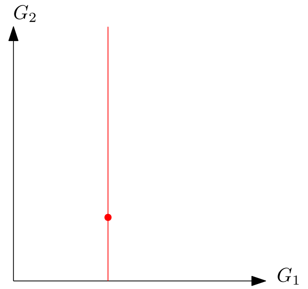

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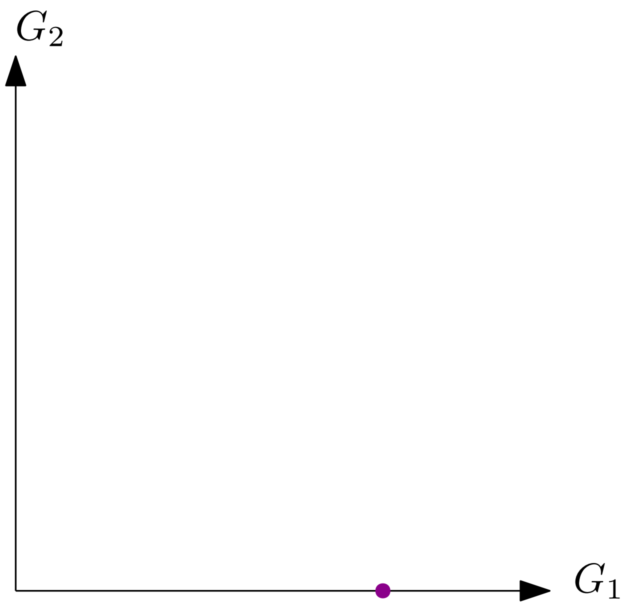
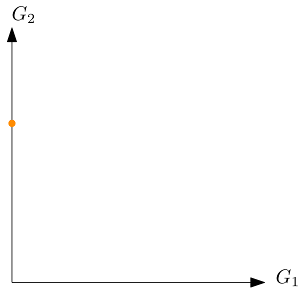


(demand uncertainty)



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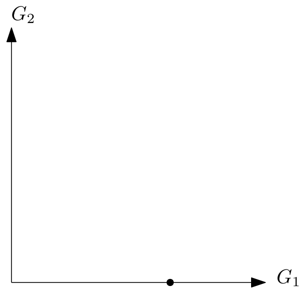

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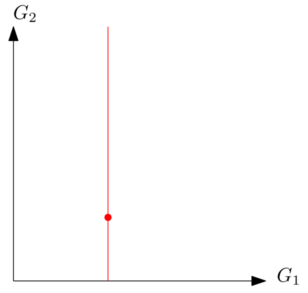

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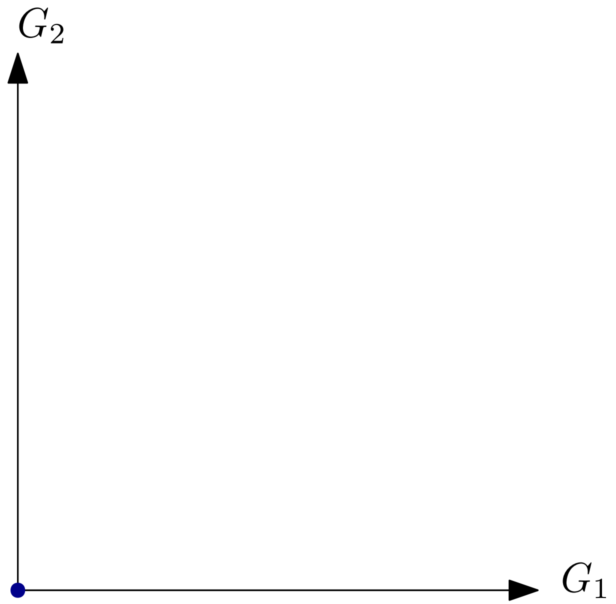
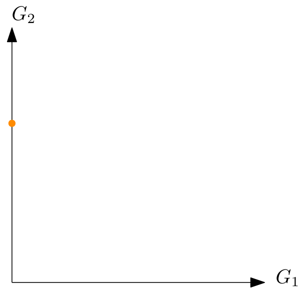


(technological uncertainty)



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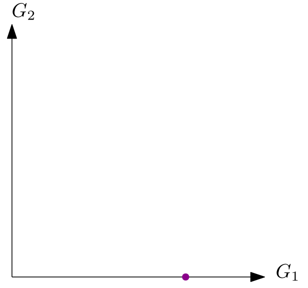

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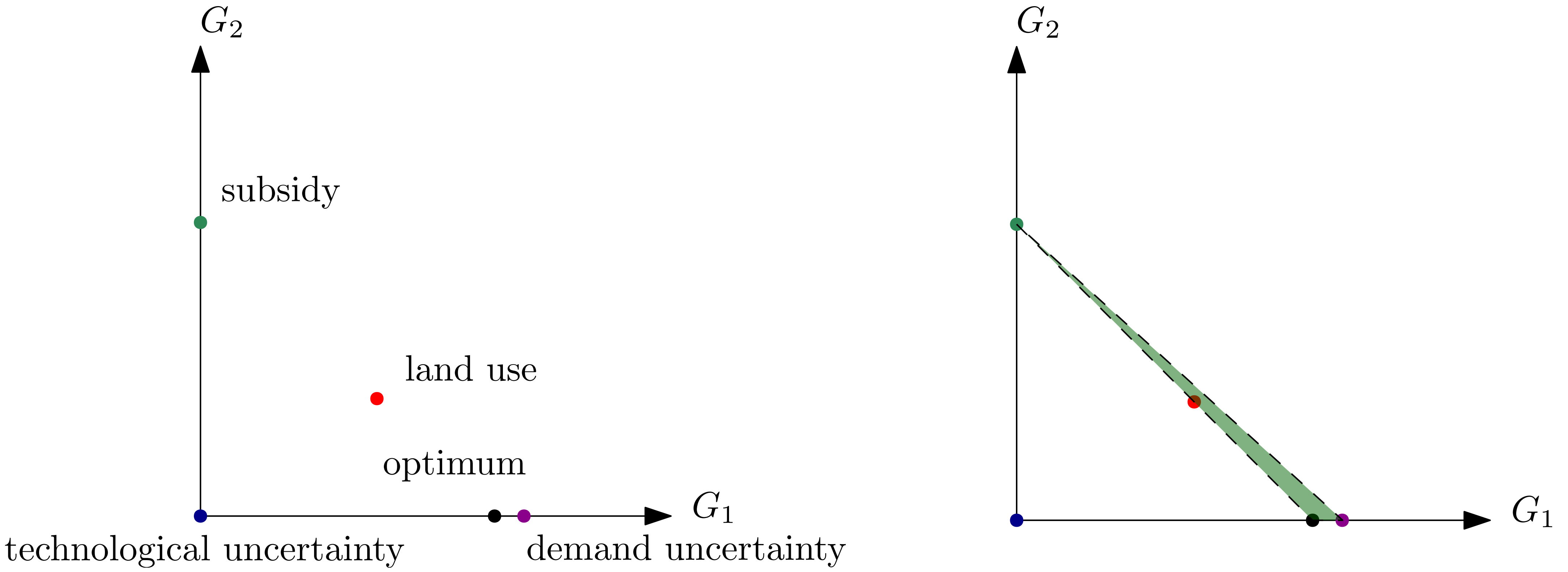

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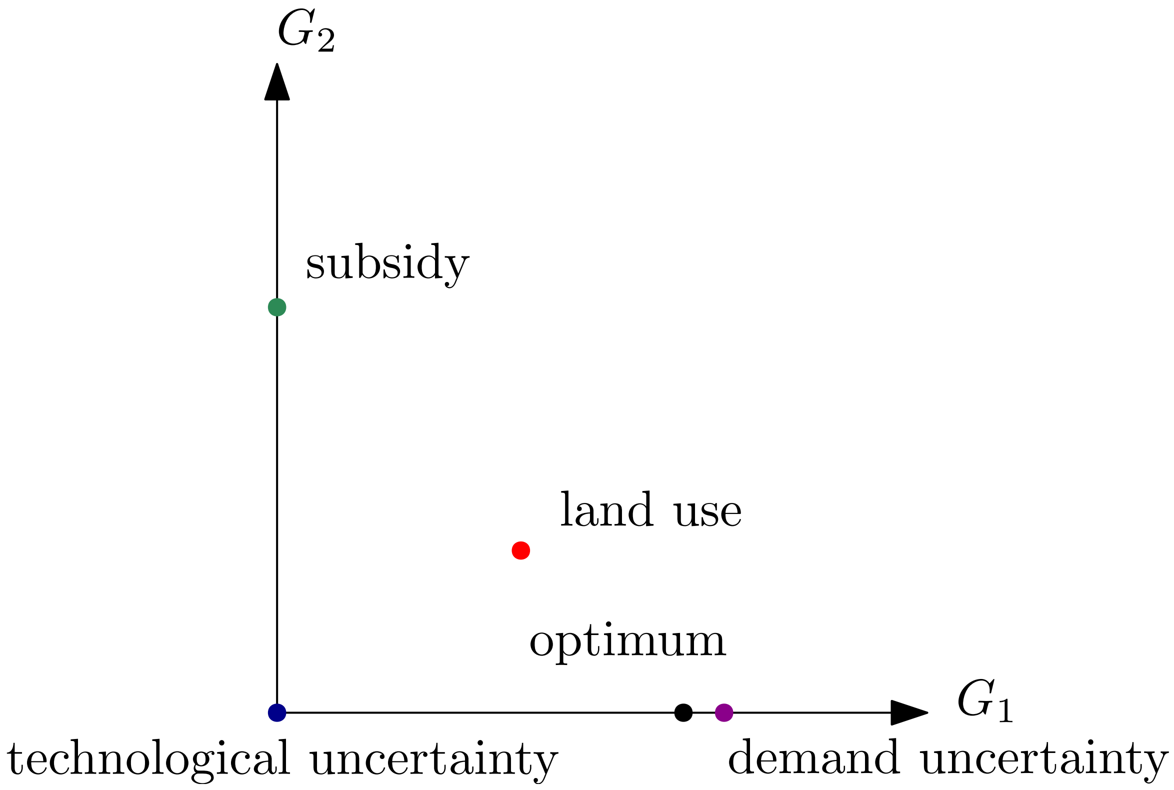
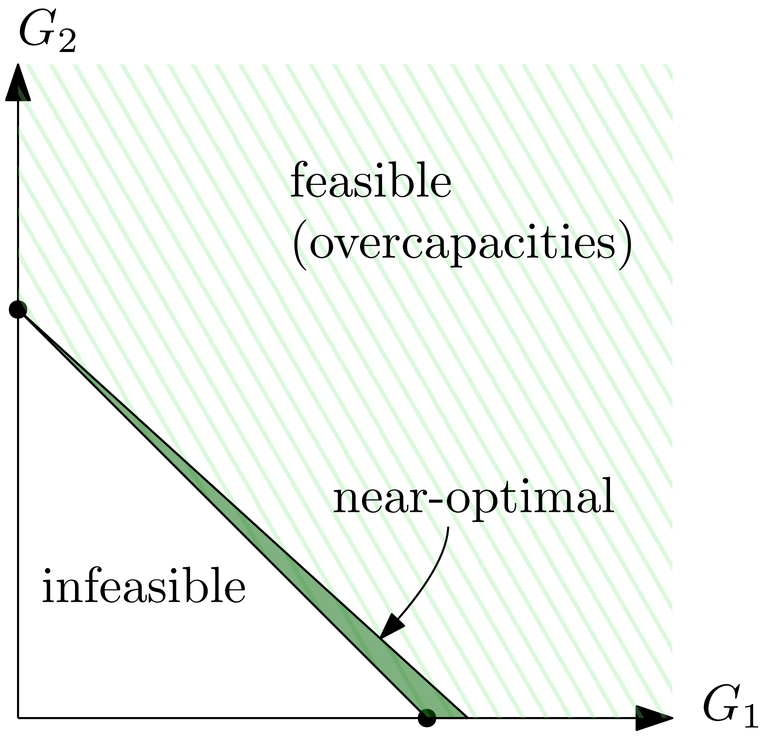
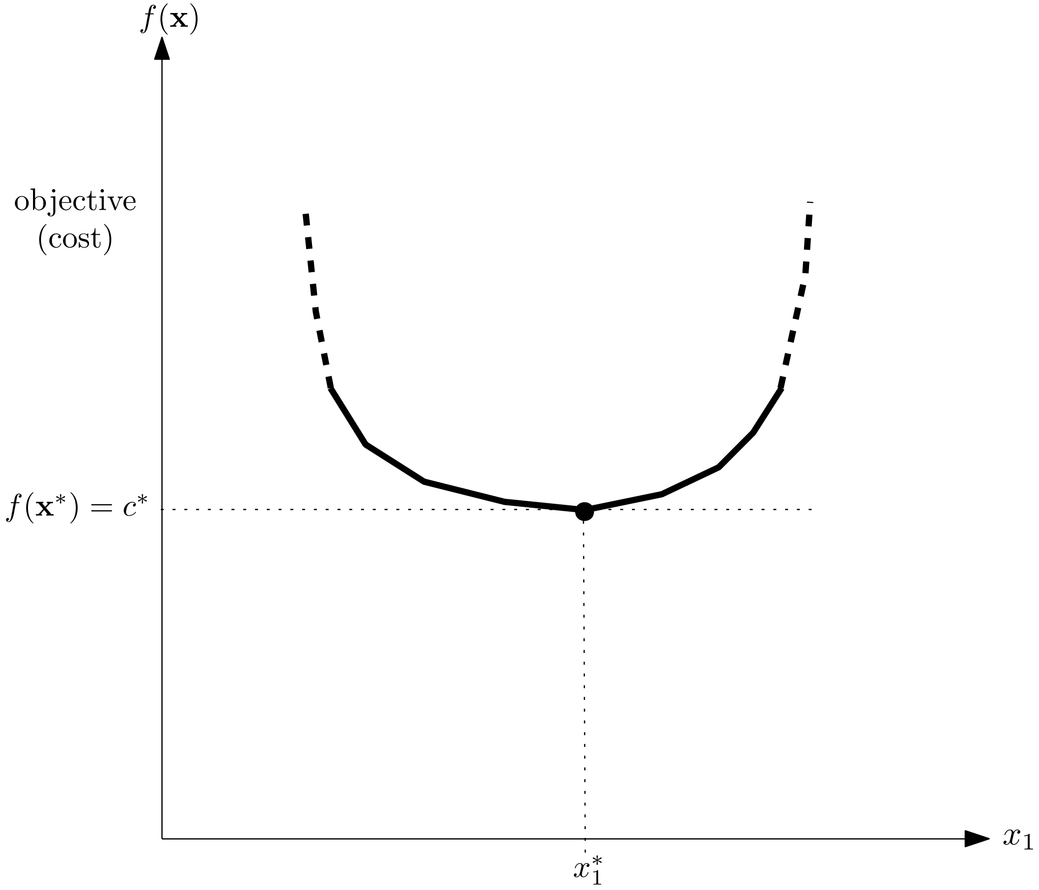




Geometrical illustration of near-optimal spaces



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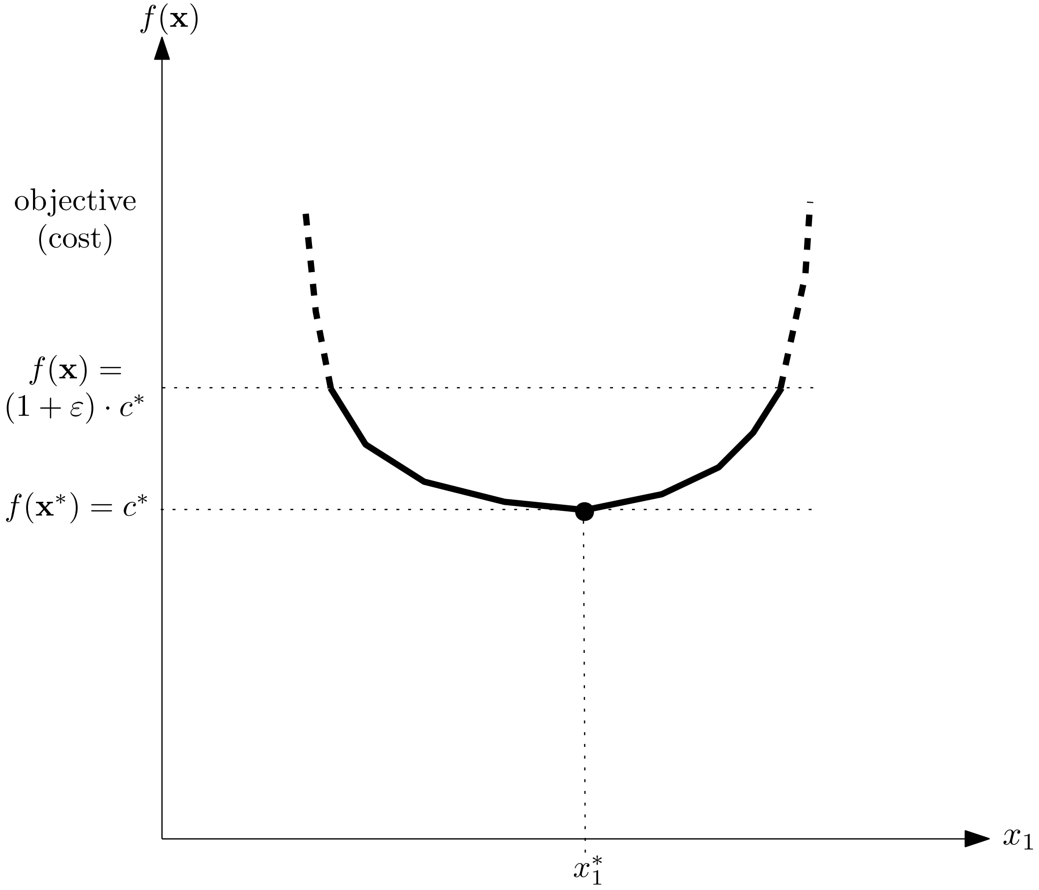

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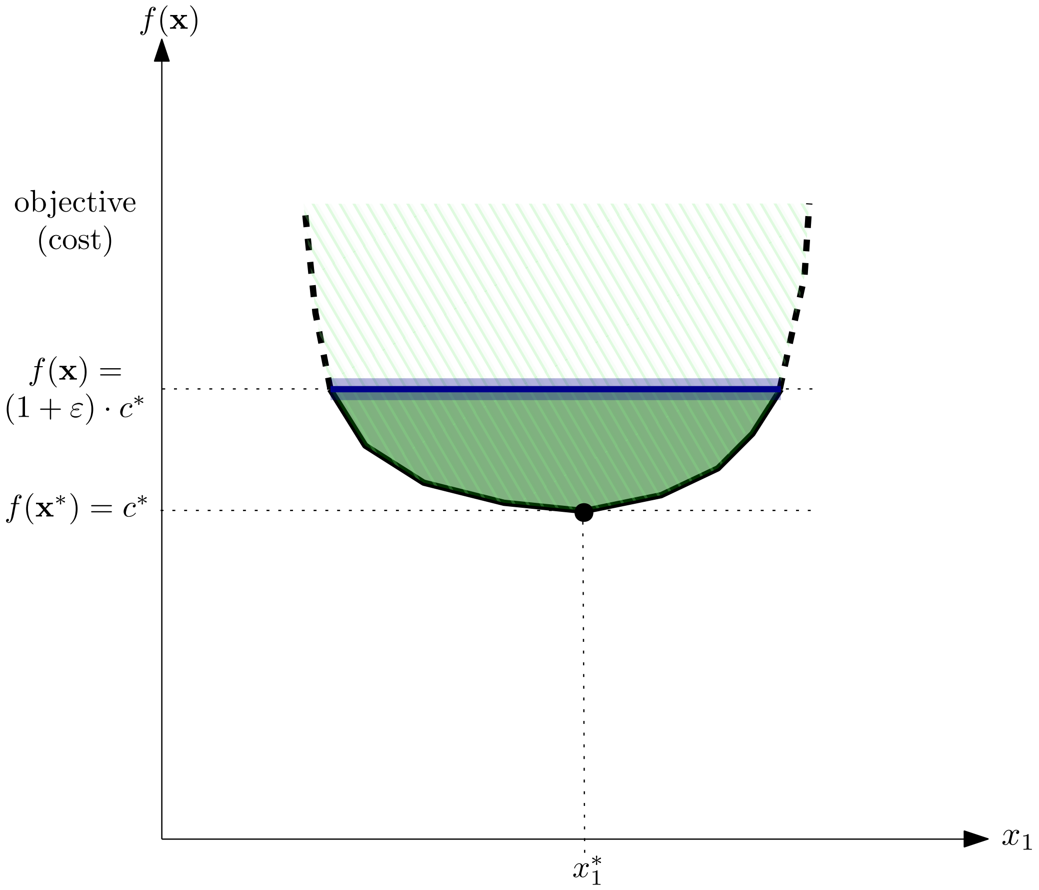

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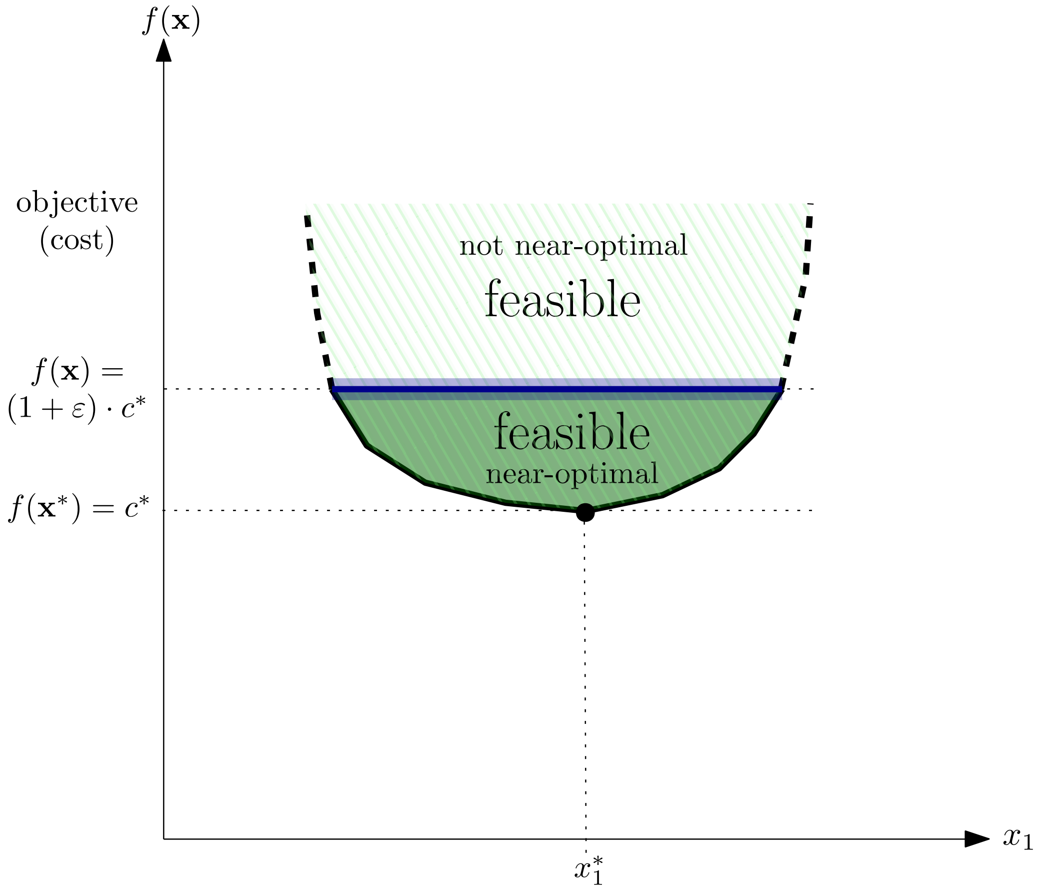

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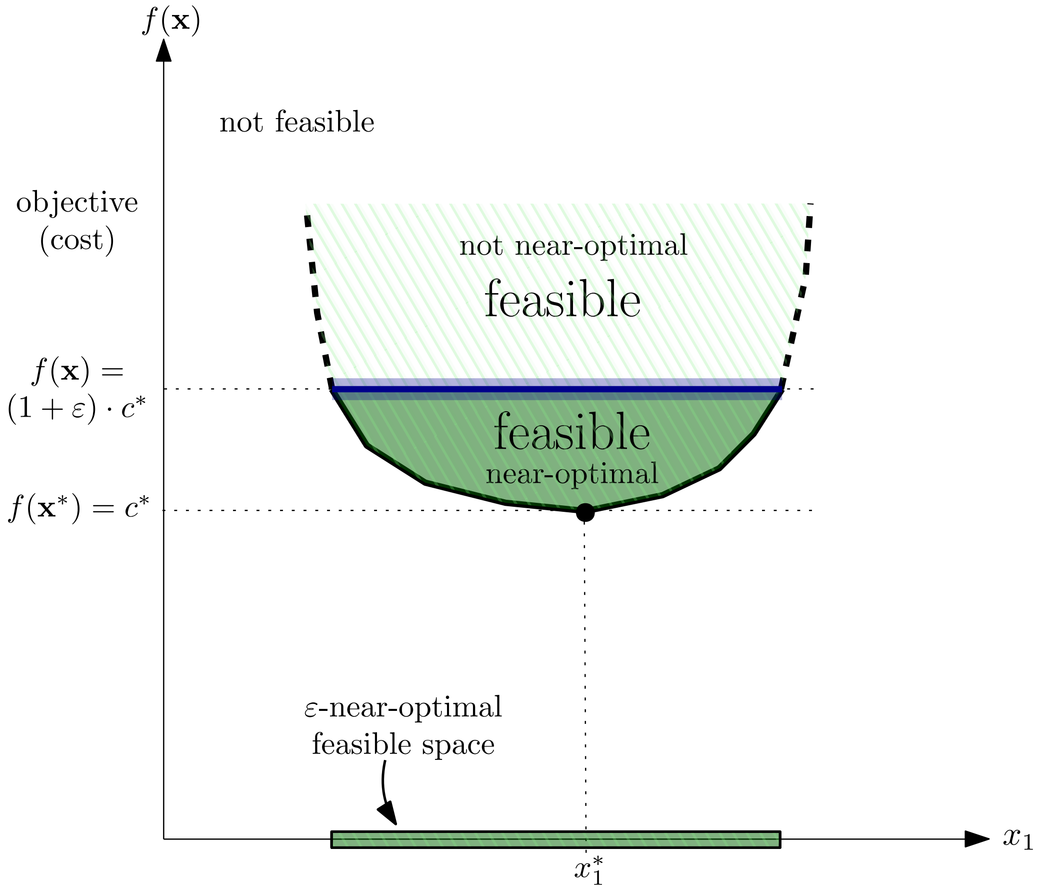

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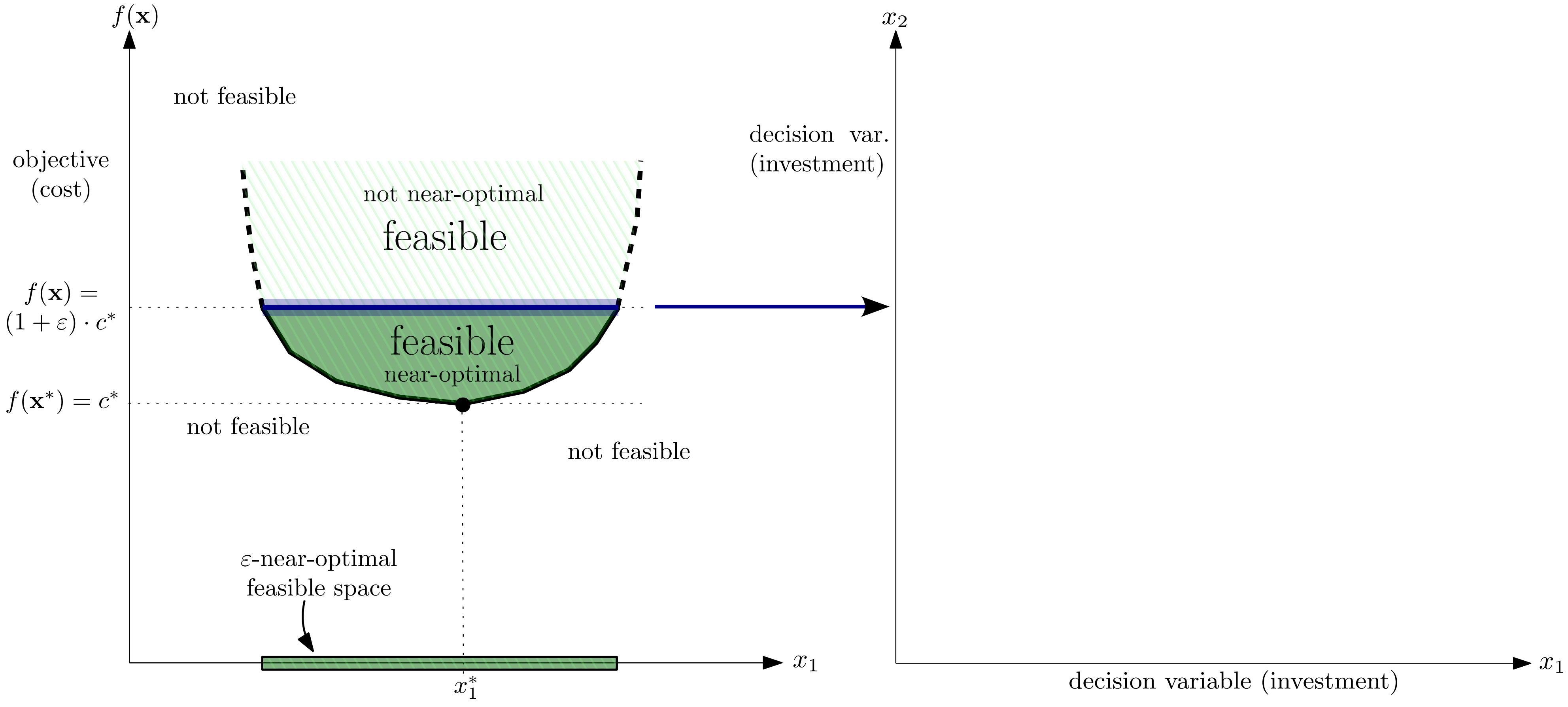

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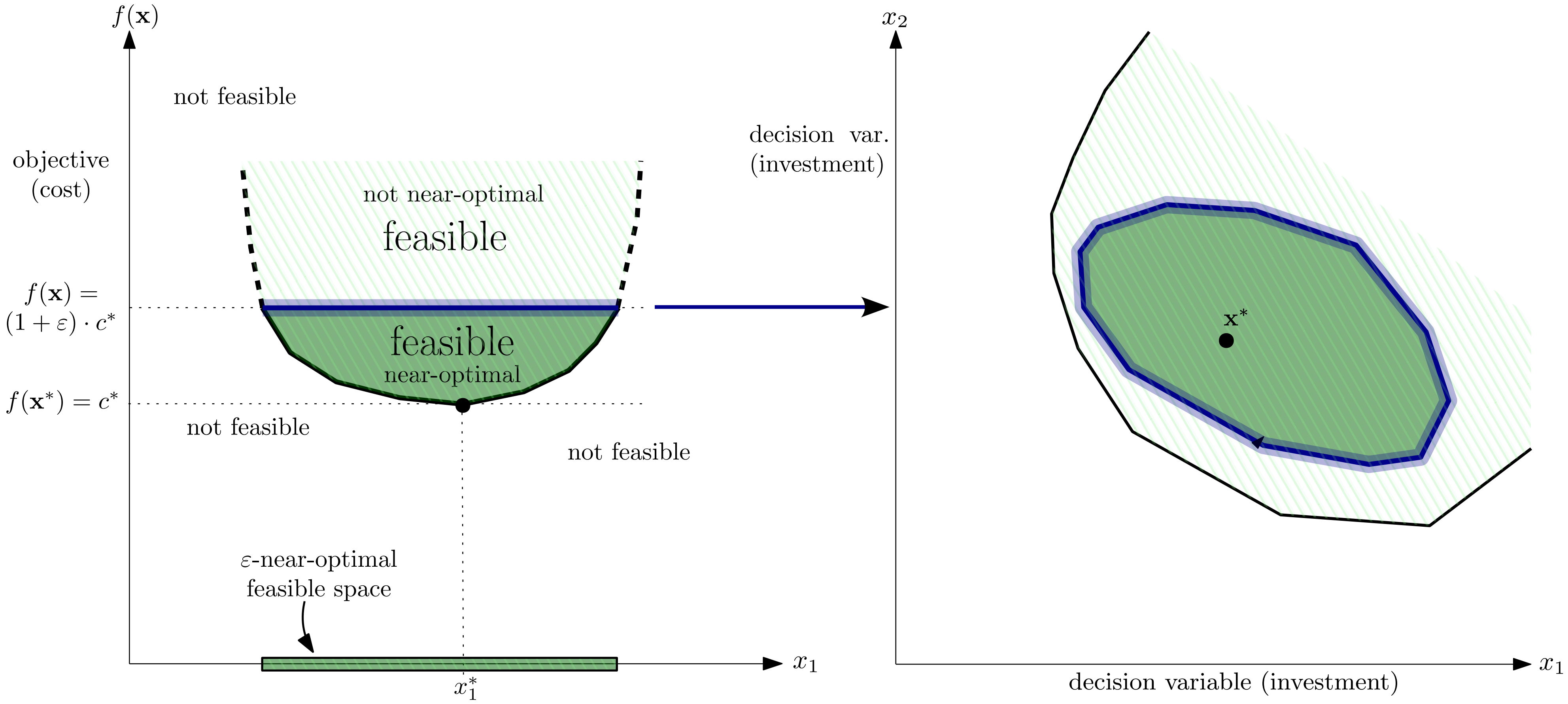

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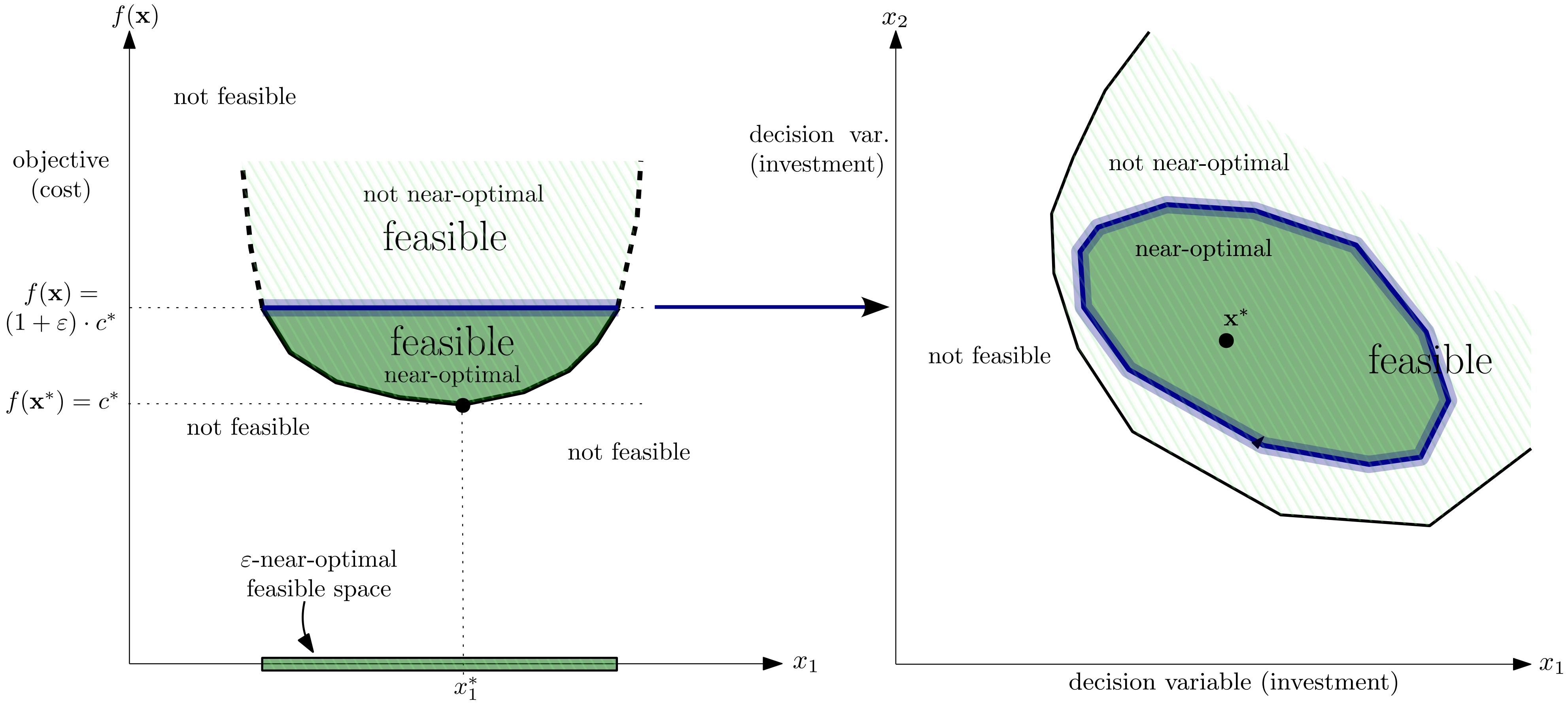


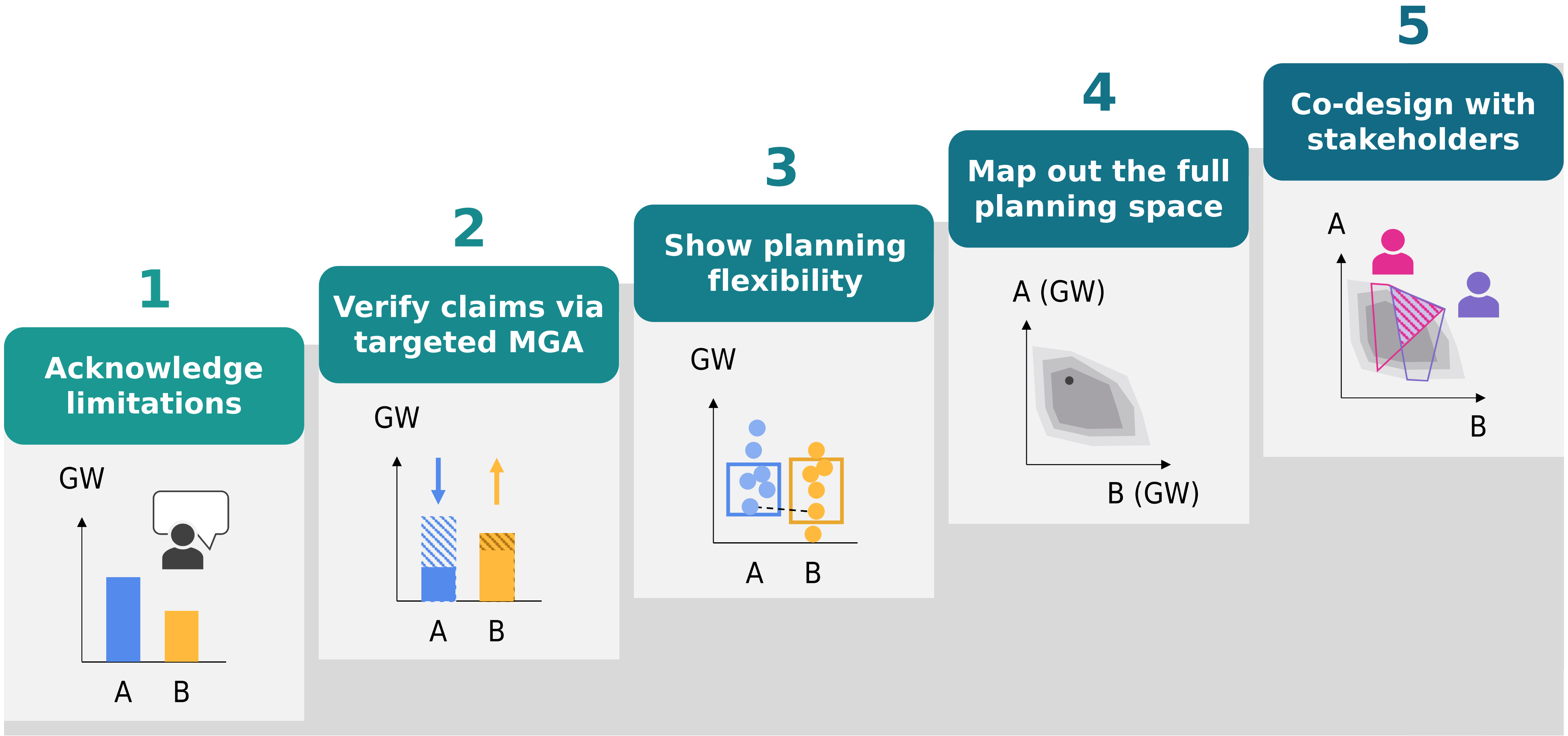
Pros and cons of near-optimal modelling

- Can compare cost-effective strategies
- Can assess non-monetary priorities and different scenarios under uncertainty
- Can hedge against market shifts or policy
- Increases robustness of results

- Computationally expensive (many optimisations required)
- Can only focus on a few variables or spatial dimensions (in large models)

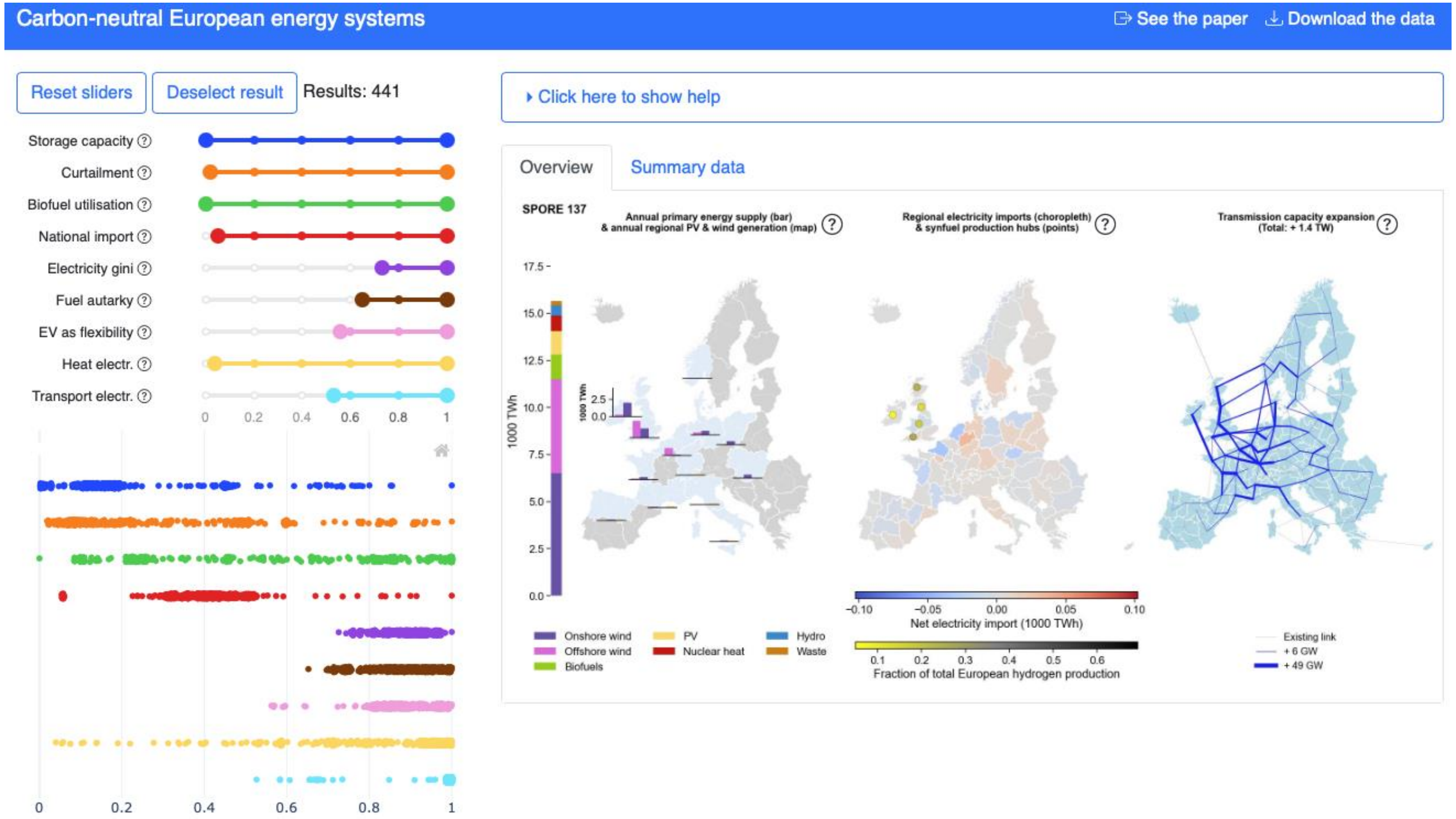
Key challenge: communication of results!

Research results: Suggested order of action



Lombardi, van Greevenbroek, Grochowicz et al., Under Review, 2025.

Showing planning flexibility

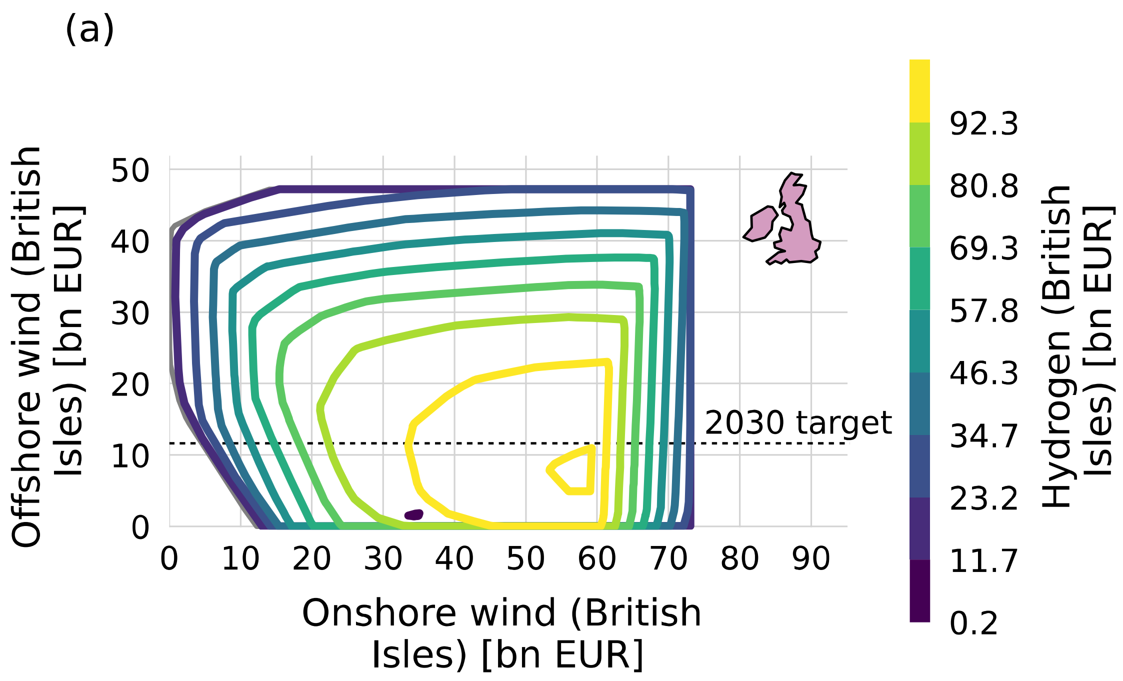


Interaction with explore.callio.pe

Pickering, Lombardi, Pfenninger. Joule, 2022. https://doi.org/10.1016/j.joule.2022.05.009

Mapping out the full planning space

- Can use geometry of near-optimal solutions to find spaces of cost-efficient investment combinations
- Decision-making process consists of trade-offs and might restrict flexibility or range of choices
- Flexibility with even small cost increases tends to be large, giving policymakers many options to choose from
- Have minimum investment levels in renewables, rather than single technologies



van Greevenbroek, Grochowicz, Benth, Zeyringer. Nature Sustainability, 2025. https://www.nature.com/articles/s41893-025-01556-2

Open questions

- How much additional cost is socially acceptable if we can achieve other desirable targets?
- Can we construct near-optimal transition pathways that keep the number of options large?
- How can we integrate policymakers, stakeholders, and their preferences into near-optimal modelling?
- How do we communicate and present results of near-optimal alternatives clearly?

Recommended literature

- Methods to explore near-optimal spaces

Pedersen, Victoria, Rasmussen, Andresen. Modeling all alternative solutions for highly renewable energy systems, Energy (2021). https://doi.org/10.1016/j.energy.2021.121294

Lau, Wang, Patankar, Jenkins. Modelling to Generate Continuous Alternatives: Enabling Real-Time Feasible Portfolio Generation in Convex Planning Models, pre-print (2024). https://doi.org/10.48550/arXiv.2411.16887

- Participatory modelling with stakeholders

Vågerö, van Greevenbroek, Grochowicz, Roithner. Exploring near-optimal energy systems with stakeholders: a novel approach for participatory modelling, pre-print (2025). https://doi.org/10.48550/arXiv.2501.05280

- Exploring potential and role of technologies

Millinger et al. Diversity of biomass usage pathways to achieve emissions targets in the European energy system, Nature Energy (2025). https://doi.org/10.1038/s41560-024-01693-6

- Weather uncertainty

Grochowicz, van Greevenbroek, Benth, Zeyringer. Intersecting near-optimal spaces: European power systems with more resilience to weather variability, Energy Economics (2023). https://doi.org/10.1016/j.eneco.2022.106496

- Review paper

Lau, Patankar, Jenkins. Measuring exploration: evaluation of modelling to generate alternatives methods in capacity expansion models, Environmental Research Energy (2024). https://doi.org/10.1088/2753-3751/ad7d10

- Justice and equity considerations

Sasse, Trutnevyte. A low-carbon electricity sector in Europe risks sustaining regional inequalities in benefits and vulnerabilities, Nature Communications (2023). https://doi.org/10.1038/s41467-023-37946-3

Vågerö, Zeyringer. Can we optimise for justice? Reviewing the inclusion of energy justice in energy system optimisation models, Energy Research & Social Science (2023). https://doi.org/10.1016/j.erss.2022.102913