Heuristics for Transmission Expansion Planning in Low-Carbon Energy System Models

Fabian Neumann and Tom Brown

fabian.neumann@kit.edu
Institute for Automation and Applied Informatics
Karlsruhe Institute of Technology (KIT)

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HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

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Introduction

To investigate the most cost-effective pathways to reduce greenhouse gas emissions researchers build large and computationally challenging optimisation models.

$$\textbf{Minimise}\left(\begin{array}{c}\textbf{Yearly}\\ \textbf{system costs}\end{array}\right) = \sum_{n}\left(\begin{array}{c}\textbf{Annualised}\\ \textbf{capital costs}\end{array}\right) + \sum_{n,t}\left(\begin{array}{c}\textbf{Marginal}\\ \textbf{costs}\end{array}\right)$$

subject to **linear optimal power flow** constraints
and the **variability & potentials** of renewable energy.

Simultaneous investment planning of generation, storage and **transmission** infrastructure is indispensable to consider the whole multitude of trade-offs.

Linearised Power Flow without capacity expansion

$$\overbrace{|f_{ij,t}|}^{\text{power flow between nodes i and j at time t}} \leq \overbrace{F_{ij,t}}^{\text{line capacity}}$$

$$f_{ij,t} = \overbrace{b_{ij}}^{\substack{\text{line susceptance} \\ b_{ij}=\frac{1}{x_{ij}}}} \cdot \overbrace{(\theta_{i,t} - \theta_{j,t})}^{\text{voltage angle difference}}$$

Transmission Expansion Planning Problem **(MINLP)**

If line capacity can be **extended** discretely, the problem becomes **nonconvex**...

$$|f_{ij,t}| \leq \overbrace{\left(1 + \frac{\Gamma_{ij}}{\tilde{\gamma}_{ij}}\right)}^{\text{scaling via integer } (\mathbb{N}) \text{ investment variable}} \cdot \overbrace{\tilde{F}_{ij}}^{\text{original capacity}}$$

... and **nonlinear** ...

$$f_{ij,t} = \overbrace{\left(1 + \frac{\Gamma_{ij}}{\tilde{\gamma}_{ij}}\right) \tilde{b}_{ij}}^{b_{ij}} \cdot (\theta_{i,t} - \theta_{j,t})$$

... which we can transform to an **MILP** using a **Big-M disjunctive relaxation**.

Heuristic 1: Relaxation of Line Investment Variables

Discrete investment decisions — heur-int

$$\Gamma_{ij} \in \mathbb{N}_{\geq 0}$$

are relaxed to allow each line to be **expanded continuously**, i.e. — heur

$$\Gamma_{ij} \in \mathbb{R}$$

Heuristic 2a: Iterative Update of Line Impedances

Pursue an **iterative** approach

iter

$$f_{ij,t} = \overbrace{\left(1 + \frac{\Gamma_{ij}}{\tilde{\gamma}_{ij}}\right)\tilde{b}_{ij}}^{b_{ij}} \cdot (\theta_{i,t} - \theta_{j,t}) \quad \longrightarrow \quad f_{ij,t} = b_{ij}^{(k)} \cdot (\theta_{i,t} - \theta_{j,t})$$

where in the first iteration the **initial susceptances** are used

$$b_{ij}^{(1)} = \tilde{b}_{ij}$$

while for subsequent iterations $k+1$ the **optimal line investment $\Gamma_{ij}^{*(k)}$ of the previous iteration k** determines the physical line attributes

$$b_{ij}^{(k+1)} = \left(1 + \frac{\Gamma_{ij}^{*(k)}}{\tilde{\gamma}_{ij}}\right)\tilde{b}_{ij} \qquad \forall k > 1$$

Heuristic 2b: Discretized Iterative Update of Line Impedances

Instead of adjusting the susceptances to values corresponding to fractional line capacities, another variant is to round any $\Gamma_{ij}^{*(k)} \in \mathbb{R}$ to their nearest integer value for **faster convergence**.

iter-seqdisc

$$b_{ij}^{(k+1)} = \left(1 + \frac{\left\lfloor \Gamma_{ij}^{*(k)} \right\rceil}{\tilde{\gamma}_{ij}}\right) \tilde{b}_{ij} \qquad \forall k > 1$$

Stopping Criteria

- no further change in line investment
- pre-defined iteration limit

Heuristic 3: Post-facto Discretization of Line Investment Variables

Following the iteration loop, fractional investment decisions from relaxation must be **fitted to valid investment choices**:

postdisc

1. Round optimal line capacities nearest candidate (with threshold $z = 0.3$)
2. Fix line capacities & rerun generation expansion only.

Optionally:

postdisc_mult

3. Repeat for multiple discretization thresholds (z) & choose configuration with lowest costs.

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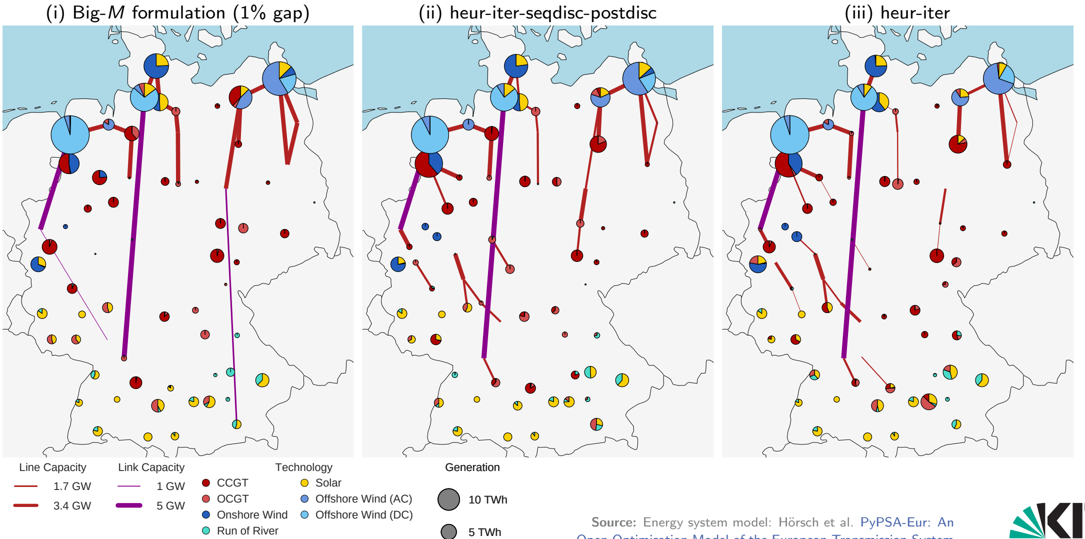
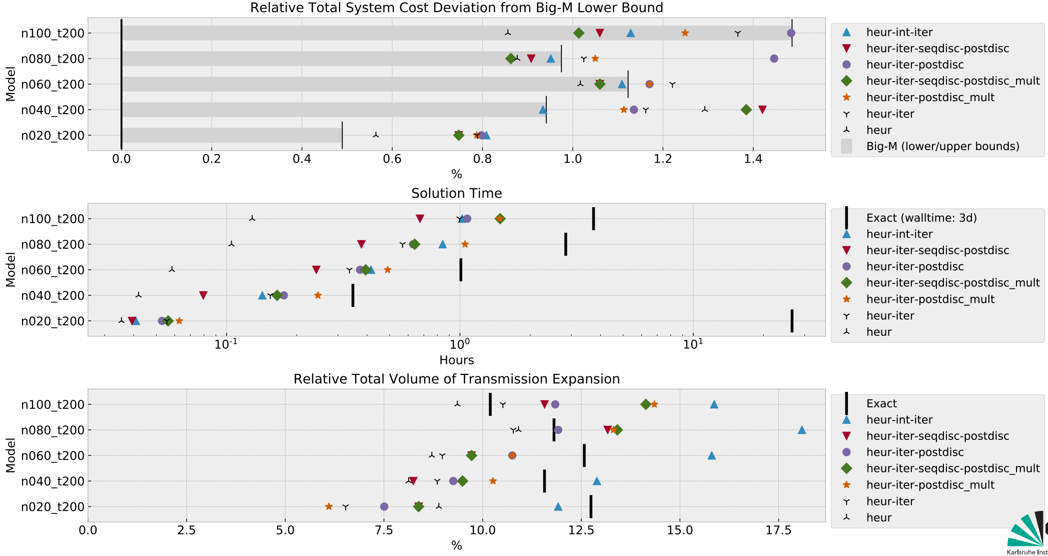
Results: Generation and Transmission Expansion



Source: Energy system model: Hörsch et al. PyPSA-Eur: An Open Optimisation Model of the European Transmission System

Results: Accuracy & Speed



Conclusion

When **co-optimizing** generation, transmission and storage infrastructure
with high spatial and temporal resolution,
discrete line expansion is **computationally prohibitive**.

The shown heuristics **closely mirror optimal integer line investment**
of the exact MINLP with **considerable time savings** for policy-relevant models.

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Resources and Copyright

Find the slides:

https://neumann.fyi/assets/eem19-tepheuristics.pdf

Send an email:

fabian.neumann@kit.edu

Find the energy system model:

Code: https://github.com/pypsa/pypsa-eur

Documentation: https://pypsa-eur.readthedocs.io