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Designing Europe’s Future Power System: A Techno-Economic Evaluation of Design Options Facilitating Renewable and Flexibility Integration in Austria and Beyond

POWER SYSTEM SECURITY 2030+

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TU WIEN

APG

AIT

Outline of presentation

Background and scope

- Status quo and challenges
- Literature review
- Research questions

Methodology and data

- Overview of model structure
- Deep dives
- Data preparation

Results and discussion

- Preliminary results
- Outlook on next steps
- Questions and feedback

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Starting point of this work: PSS2030+ project

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Research

University

Industry

System Design

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Overall task: Develop solutions – spanning planning, markets, operation and protection - that enable a secure, resilient and fully renewable power system for Austria within the European context

PV & Batteries: Benefits & drawbacks

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! Status Quo

Austrian goal: Produce **100% net renewable electricity** by 2030+

PV and batteries as **key drivers** of electricity transition

Decentralized structure: Dominant share is **small- and medium-scale**

? Challenges

Variability of solar generation

Misaligned **incentives** (feed-in tariffs)

Unused flexibility potential

Problems

Costly **redispatch** measures

Congestion in electricity grids

Curtailment

Optimal system design?

Stakeholders tried to counteract these problems using different system design approaches:

Market-based option:
Real-time pricing

ElWG: Dynamic retail pricing legally anchored

Widespread implementation in NO, DK, ES, DE

Regulatory option:
PV Peak-Shaving

ElWG: Fixed (max. 70%) or dynamic export limits

Non-firm access schemes across EU countries

Regulatory option:
Capacity tariff

ElWG: Energy-, capacity- or time-variant grid charges

Increasing attention to hybrid/system-peak designs

However there exists no general answer to which system design in best!

- Depends on **aspects** of **system-friendliness** that are targeted
- **Grid-friendly behavior** is in the focus of this work
- **Economic aspects** are of great importance as well

State of the art in literature

RTP

Improves prosumer profits, induces load shifting and incentivizes flexibility use (Hao et al., 2024; Stute & Kühnbach, 2023)

Peak-Shaving

Static and dynamic export limits significantly increase PV hosting capacity especially when combined with storage (Konrad et al., 2025)

Capacity-Tariff

Hybrid and system-peak-oriented capacity tariffs reduce synchronized peak behaviour (Gunkel et al., 2023; Hofmann et al., 2025)

Gap

Isolated analysis: Instruments are mostly studied individually

Distribution-level focus: No system-wide evaluation

Lack of **unified benchmarking** across congestion welfare dimensions

Research Questions

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System-level impacts on high-voltage networks, cross-border power flows, and welfare effects remain largely unexplored

How does the integration of PV installations and battery storage under different instruments affect power system operation, particularly high-voltage and cross-border transmission networks?

What are the resulting economic and welfare impacts of instruments compared to status quo schemes?

Do instruments provide stronger incentives for battery deployment and operation?

Does system adequacy improve under instrument use PV and battery feed-in?

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Model I

Key Insights

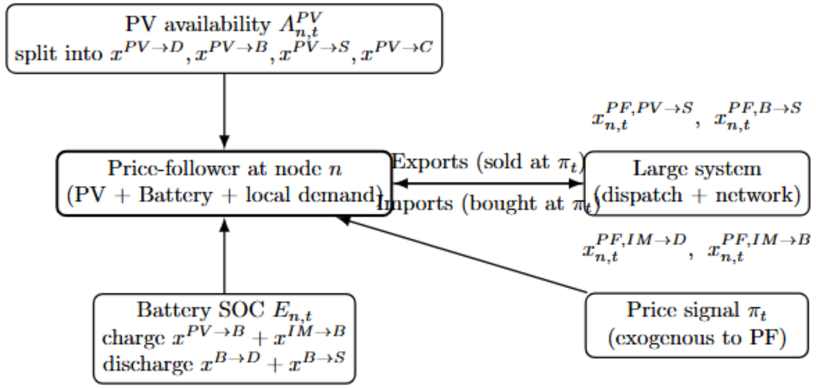
2 **LPs** (Linear Programs): Follower and system model

Follower: Instrument given; Imports from and exports to system model

System: Grid model, demand equilibrium, cost-minimization

Outcome: **Flows, congestion, curtailment, welfare**

Model structure



Model II | Deep Dive

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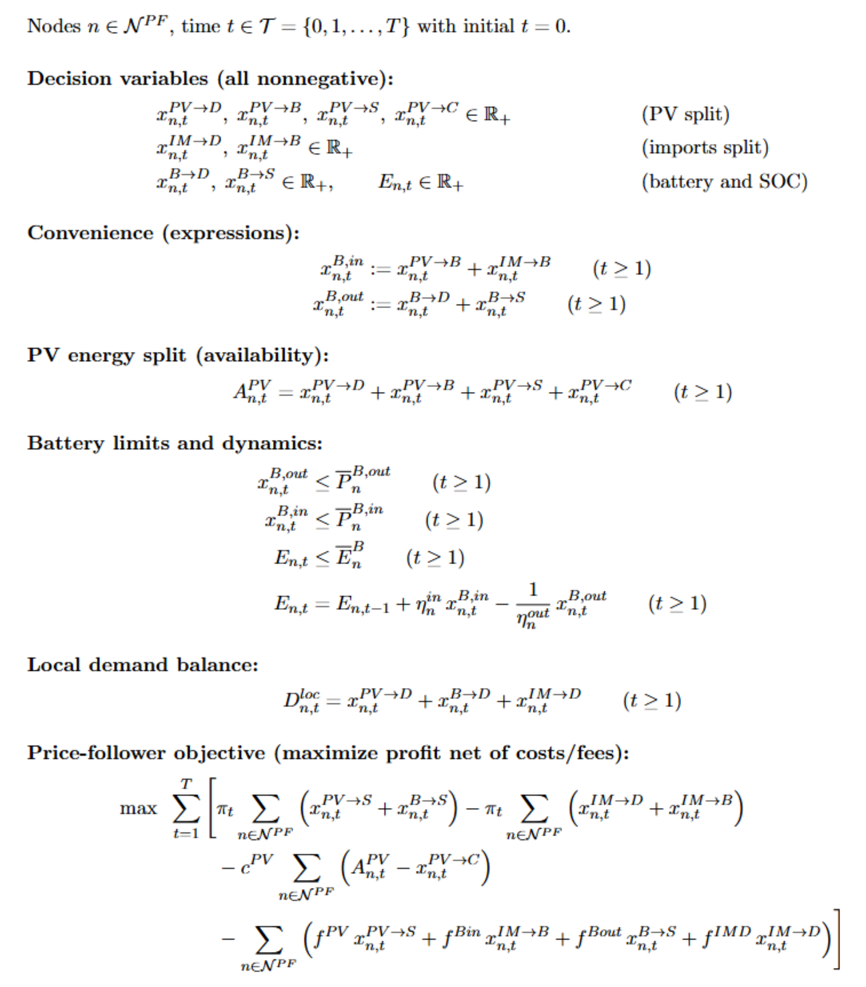
Decision variables determine power flows

Available PV energy is allocated to:
Local demand, battery, exports

Local demand is met by:
Local PV, battery discharge, imports

Profit maximization; Objective reflects **profits, costs and fees**



Nodes $n \in \mathcal{N}^{PF}$, time $t \in \mathcal{T} = \{0, 1, \dots, T\}$ with initial $t = 0$.

Decision variables (all nonnegative):

$$\begin{aligned} & x_{n,t}^{PV\to D},\ x_{n,t}^{PV\to B},\ x_{n,t}^{PV\to S},\ x_{n,t}^{PV\to C} \in \mathbb{R}_+ && \text{(PV split)} \\ & x_{n,t}^{IM\to D},\ x_{n,t}^{IM\to B} \in \mathbb{R}_+ && \text{(imports split)} \\ & x_{n,t}^{B\to D},\ x_{n,t}^{B\to S} \in \mathbb{R}_+, \qquad E_{n,t} \in \mathbb{R}_+ && \text{(battery and SOC)} \end{aligned}$$

Convenience (expressions):

$$x_{n,t}^{B,in} := x_{n,t}^{PV\to B} + x_{n,t}^{IM\to B} \qquad (t \geq 1)$$

$$x_{n,t}^{B,out} := x_{n,t}^{B\to D} + x_{n,t}^{B\to S} \qquad (t \geq 1)$$

PV energy split (availability):

$$A_{n,t}^{PV} = x_{n,t}^{PV\to D} + x_{n,t}^{PV\to B} + x_{n,t}^{PV\to S} + x_{n,t}^{PV\to C} \qquad (t \geq 1)$$

Battery limits and dynamics:

$$x_{n,t}^{B,out} \leq \overline{P}_n^{B,out} \qquad (t \geq 1)$$

$$x_{n,t}^{B,in} \leq \overline{P}_n^{B,in} \qquad (t \geq 1)$$

$$E_{n,t} \leq \overline{E}_n^{B} \qquad (t \geq 1)$$

$$E_{n,t} = E_{n,t-1} + \eta_n^{in}\, x_{n,t}^{B,in} - \frac{1}{\eta_n^{out}}\, x_{n,t}^{B,out} \qquad (t \geq 1)$$

Local demand balance:

$$D_{n,t}^{loc} = x_{n,t}^{PV\to D} + x_{n,t}^{B\to D} + x_{n,t}^{IM\to D} \qquad (t \geq 1)$$

Price-follower objective (maximize profit net of costs/fees):

$$\begin{aligned} \max \sum_{t=1}^{T} \Bigg[& \pi_t \sum_{n\in\mathcal{N}^{PF}} \left(x_{n,t}^{PV\to S} + x_{n,t}^{B\to S} \right) - \pi_t \sum_{n\in\mathcal{N}^{PF}} \left(x_{n,t}^{IM\to D} + x_{n,t}^{IM\to B} \right) \\ & - c^{PV} \sum_{n\in\mathcal{N}^{PF}} \left(A_{n,t}^{PV} - x_{n,t}^{PV\to C} \right) \\ & - \sum_{n\in\mathcal{N}^{PF}} \left(f^{PV}\, x_{n,t}^{PV\to S} + f^{Bin}\, x_{n,t}^{IM\to B} + f^{Bout}\, x_{n,t}^{B\to S} + f^{IMD}\, x_{n,t}^{IM\to D} \right) \Bigg] \end{aligned}$$

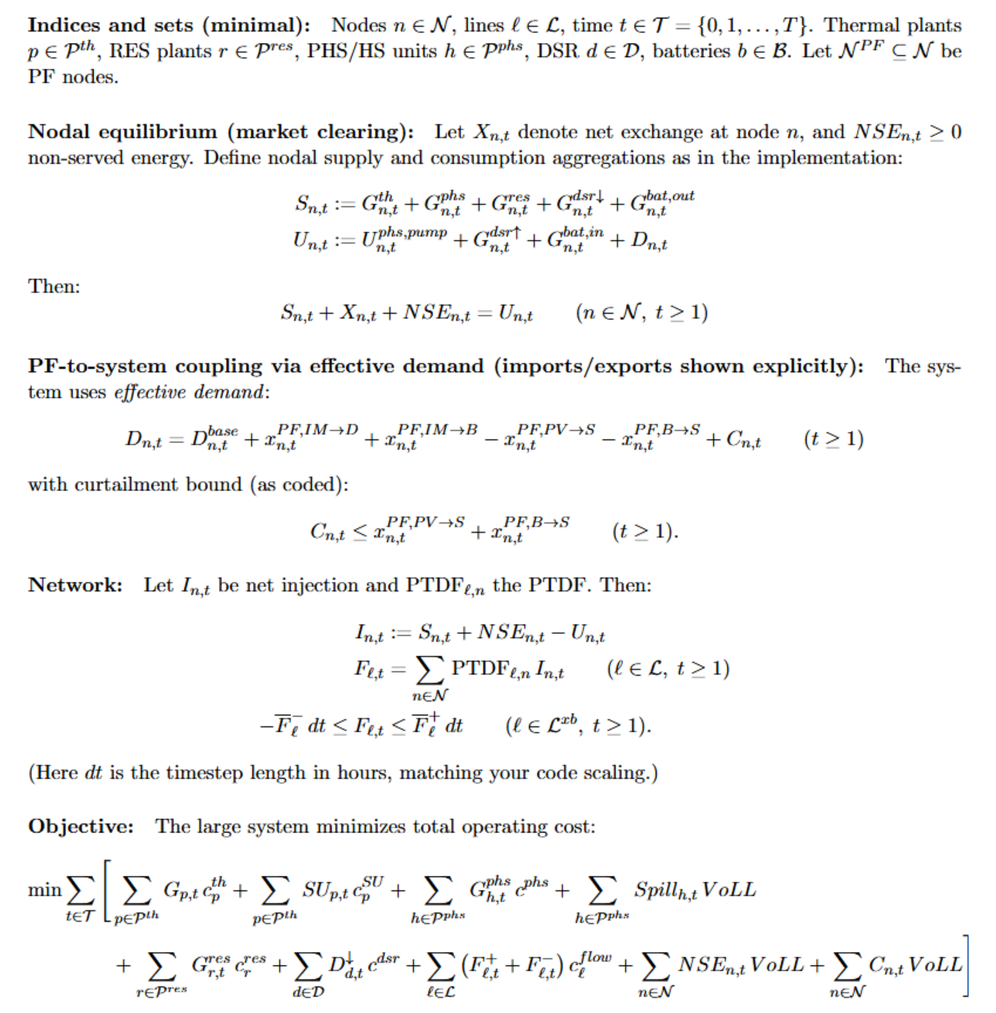
Model III | Deep Dive

Large system minimizes total **operating cost**

Thermal, hydro, renewable, flex **dispatch** modelled

Demand balance includes imports/exports from/to follower

Transmission network modelled via FBMC approach



Indices and sets (minimal): Nodes $n \in \mathcal{N}$, lines $\ell \in \mathcal{L}$, time $t \in \mathcal{T} = \{0, 1, \dots, T\}$. Thermal plants $p \in \mathcal{P}^{th}$, RES plants $r \in \mathcal{P}^{res}$, PHS/HS units $h \in \mathcal{P}^{phs}$, DSR $d \in \mathcal{D}$, batteries $b \in \mathcal{B}$. Let $\mathcal{N}^{PF} \subseteq \mathcal{N}$ be PF nodes.

Nodal equilibrium (market clearing): Let $X_{n,t}$ denote net exchange at node n, and $NSE_{n,t} \geq 0$ non-served energy. Define nodal supply and consumption aggregations as in the implementation:

$$
\begin{aligned}
S_{n,t} &:= G^{th}_{n,t} + G^{phs}_{n,t} + G^{res}_{n,t} + G^{dsr\downarrow}_{n,t} + G^{bat,out}_{n,t} \\
U_{n,t} &:= U^{phs,pump}_{n,t} + G^{dsr\uparrow}_{n,t} + G^{bat,in}_{n,t} + D_{n,t}
\end{aligned}
$$

Then:

$$
S_{n,t} + X_{n,t} + NSE_{n,t} = U_{n,t} \qquad (n \in \mathcal{N},\ t \geq 1)
$$

PF-to-system coupling via effective demand (imports/exports shown explicitly): The system uses *effective demand*:

$$
D_{n,t} = D^{base}_{n,t} + x^{PF,IM\to D}_{n,t} + x^{PF,IM\to B}_{n,t} - x^{PF,PV\to S}_{n,t} - x^{PF,B\to S}_{n,t} + C_{n,t} \qquad (t \geq 1)
$$

with curtailment bound (as coded):

$$
C_{n,t} \leq x^{PF,PV\to S}_{n,t} + x^{PF,B\to S}_{n,t} \qquad (t \geq 1).
$$

Network: Let $I_{n,t}$ be net injection and $\mathrm{PTDF}_{\ell,n}$ the PTDF. Then:

$$
\begin{aligned}
I_{n,t} &:= S_{n,t} + NSE_{n,t} - U_{n,t} \\
F_{\ell,t} &= \sum_{n \in \mathcal{N}} \mathrm{PTDF}_{\ell,n}\, I_{n,t} \qquad (\ell \in \mathcal{L},\ t \geq 1) \\
-\overline{F}^{-}_{\ell}\, dt \leq F_{\ell,t} &\leq \overline{F}^{+}_{\ell}\, dt \qquad (\ell \in \mathcal{L}^{xb},\ t \geq 1).
\end{aligned}
$$

(Here dt is the timestep length in hours, matching your code scaling.)

Objective: The large system minimizes total operating cost:

$$
\begin{aligned}
\min \sum_{t \in \mathcal{T}} \Bigg[& \sum_{p \in \mathcal{P}^{th}} G_{p,t}\, c^{th}_{p} + \sum_{p \in \mathcal{P}^{th}} SU_{p,t}\, c^{SU}_{p} + \sum_{h \in \mathcal{P}^{phs}} G^{phs}_{h,t}\, c^{phs} + \sum_{h \in \mathcal{P}^{phs}} Spill_{h,t}\, VoLL \\
& + \sum_{r \in \mathcal{P}^{res}} G^{res}_{r,t}\, c^{res}_{r} + \sum_{d \in \mathcal{D}} D^{\downarrow}_{d,t}\, c^{dsr} + \sum_{\ell \in \mathcal{L}} \left(F^{+}_{\ell,t} + F^{-}_{\ell,t}\right) c^{flow}_{\ell} + \sum_{n \in \mathcal{N}} NSE_{n,t}\, VoLL + \sum_{n \in \mathcal{N}} C_{n,t}\, VoLL \Bigg]
\end{aligned}
$$

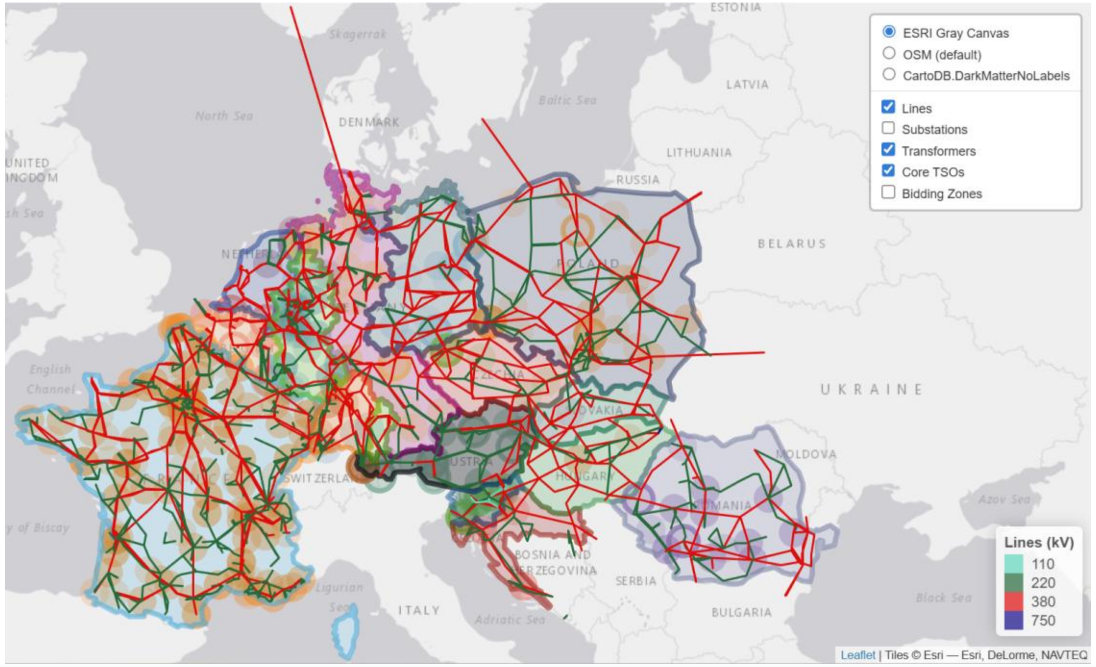
Data Preparation

Data assumptions

Data published by Joint Allocation Service (JAO) for **grid topology** and line parameters

TYNDP 2030 projections for generation and consumption capacities & RES profiles

AT, BE, CH, CZ, DE, FR, HU, IT, NL, PL, SI, SK modelled; Later onwards: **Greater Focus on AT**



● ESRI Gray Canvas
○ OSM (default)
○ CartoDB.DarkMatterNoLabels

☑ Lines
☐ Substations
☑ Transformers
☑ Core TSOs
☐ Bidding Zones

Source: Static Grid Model from JAO-Website

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Preliminary results I

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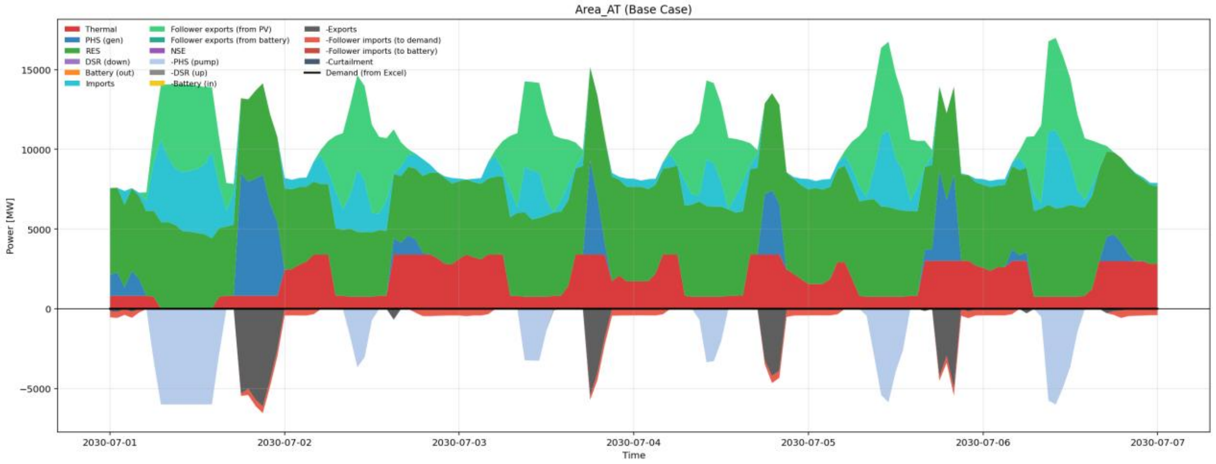

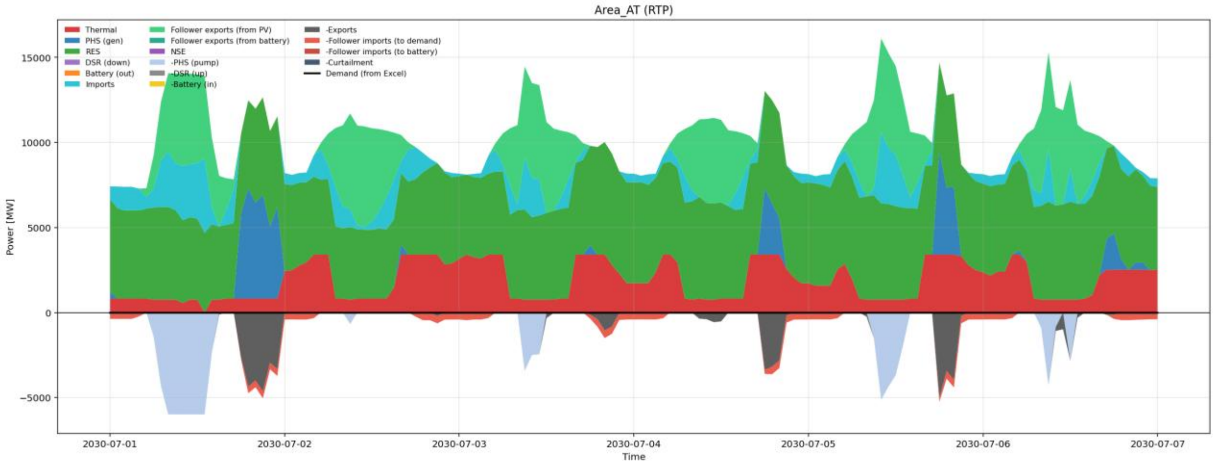

- System behaviour (generation, consumption) differs markedly between base and instruments
- Instruments induce heterogeneous effects that are difficult to evaluate without KPIs
- Outcomes are country-specific and depend on generation mix (especially ratio of PV & battery)

Preliminary results II

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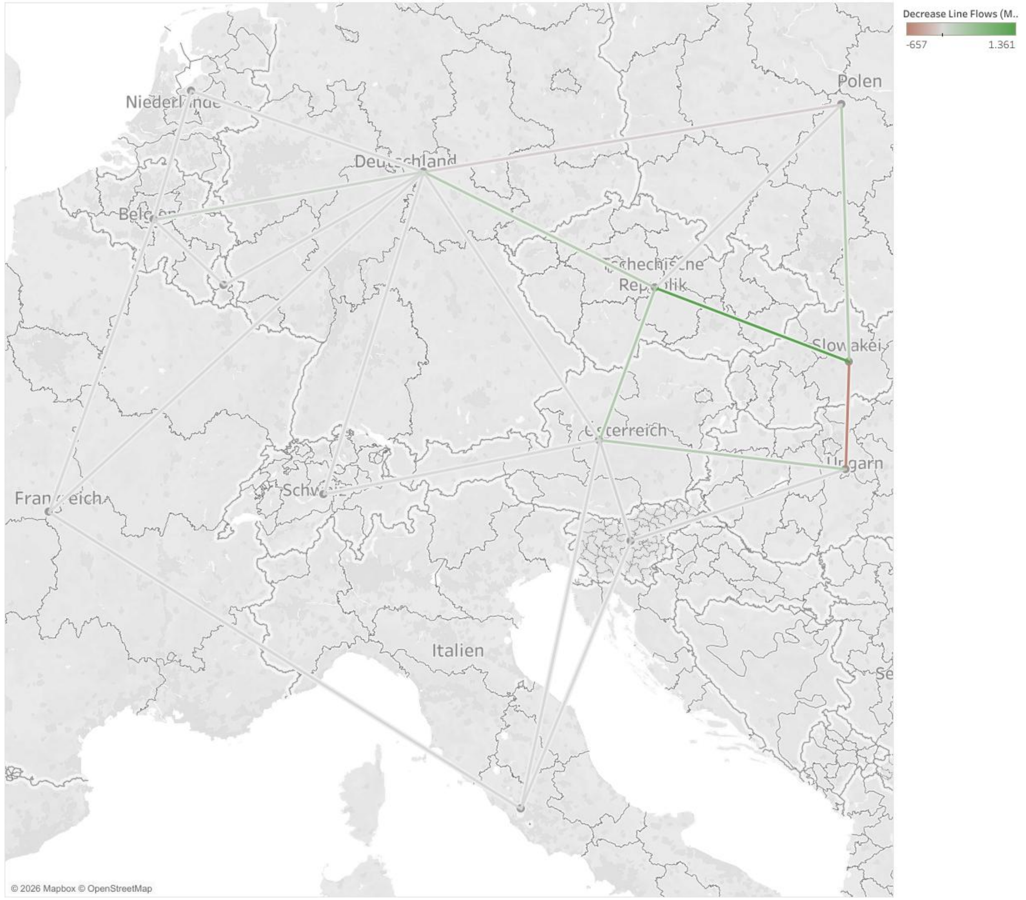
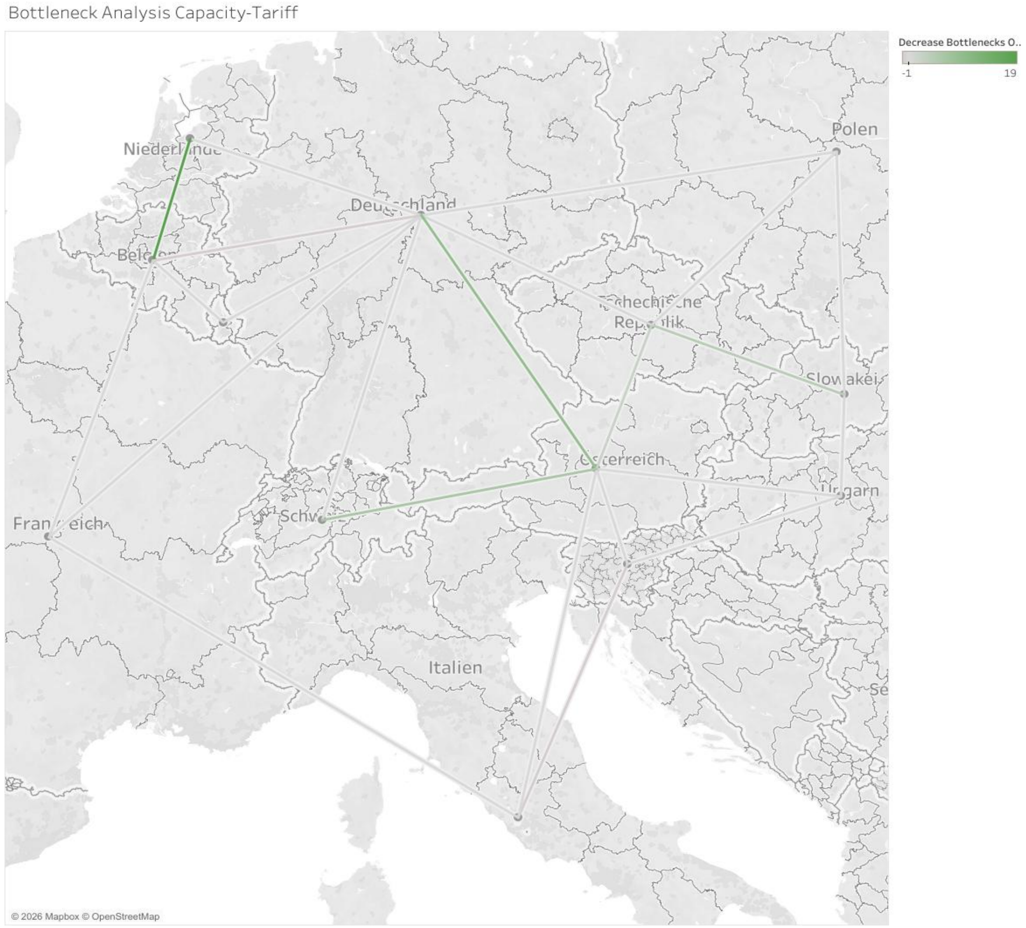
Flow Analysis RTP



- Snapshot analysis of cross-border flows at summer midday under alternative instrument designs
- Predominantly declining flows are observed across interconnectors; overall effects remain ambiguous
- RTP exhibits the strongest improvements, though further analysis is required

Preliminary results III


Bottleneck Analysis Capacity-Tariff

- Total number of congestion events over the considered time horizon (one year, hourly resolution)
- All instruments contribute to congestion reduction, though impacts vary across individual lines
- Capacity Tariff demonstrates the strongest improvements; sensitivity analysis possible

Preliminary results IV

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AT:

*KPIs**	*RTP*	*Peak-Shaving*	*Capacity-Tariff*
Export Revenue	+	=	−
Cost Import	+	=	+
Curtailment	=	=	=
Peak Export	+	−	−
Peak Import	+	−	−

**KPIs rel. to base case*

- RTP increases export revenues but is associated with higher import costs; it raises peak exports and imports
- Capacity tariff lowers export revenues and substantially reduces both peak exports and peak imports
- Peak shaving moderately reduces both peak imports and exports, while revenues and costs remain largely unchanged
- Effects differ markedly across countries; particularly pronounced in systems with high PV–battery shares

Outlook on next steps

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Limitations

Current focus on Austria: **Increased spatial granularity** is required

Additional **validation** steps need to be undertaken

Sensitivity analysis of key parameter assumptions possible

Future developments

Integration of **more detailed** grid/generation model for Austria

Explicit consideration of **TYNDP grid expansion** projects

Consolidation of results and preparation for **publication**

Thank you for your attention!

Questions & feedback

Literature

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