TECHNISCHE UNIVERSITÄT DRESDEN

Faculty of Business and Economics, Chair of Energy Economics, Prof. Dr. Möst

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The Influence of Voltage Stability on Congestion Management Cost in a Changing Electricity System

Fabian Hinz

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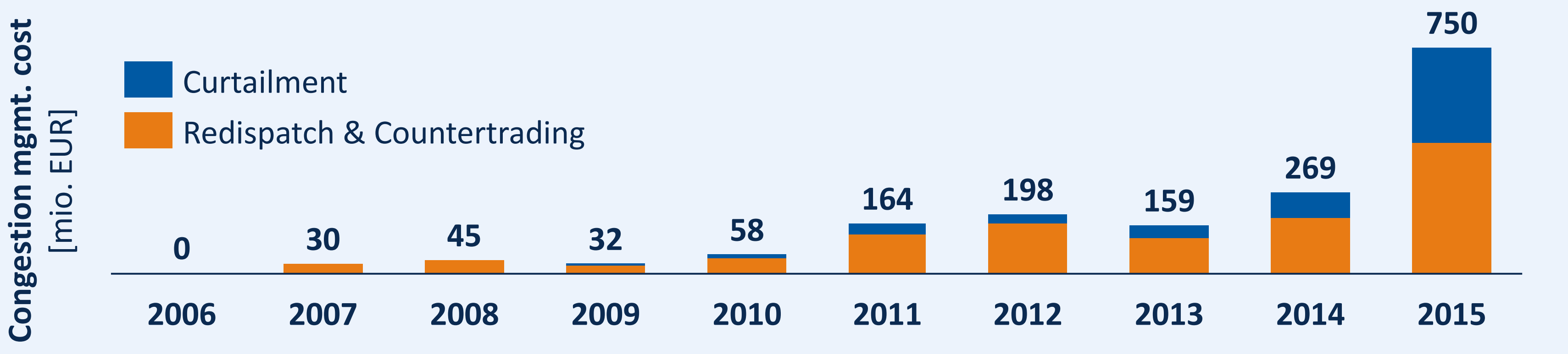
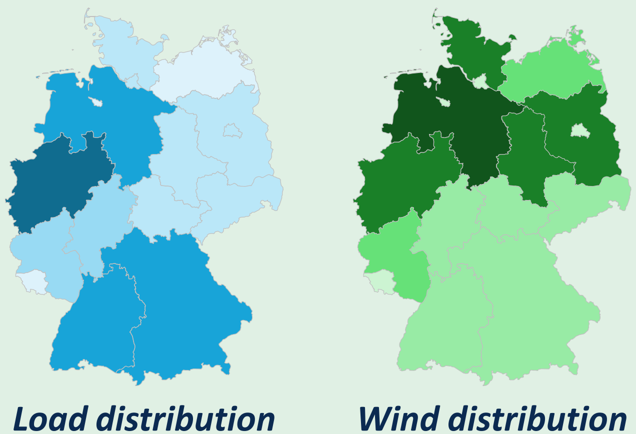
Congestion management causes high cost

Challenge
Current / Real power

Development of congestion mgmt. cost, causes



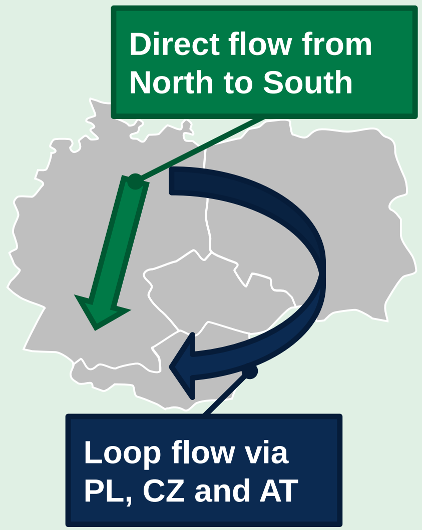
Load vs. generation



- Load concentrated in the South and West
- Wind concentrated in the North

Loop flows

- Power flows from North to South cause loop flows via Eastern Europe
- Phase shifting transformers being installed



Source: BNetzA Monitoring Reports 2007 - 2016

Availability of reactive power in the transmission grid declines

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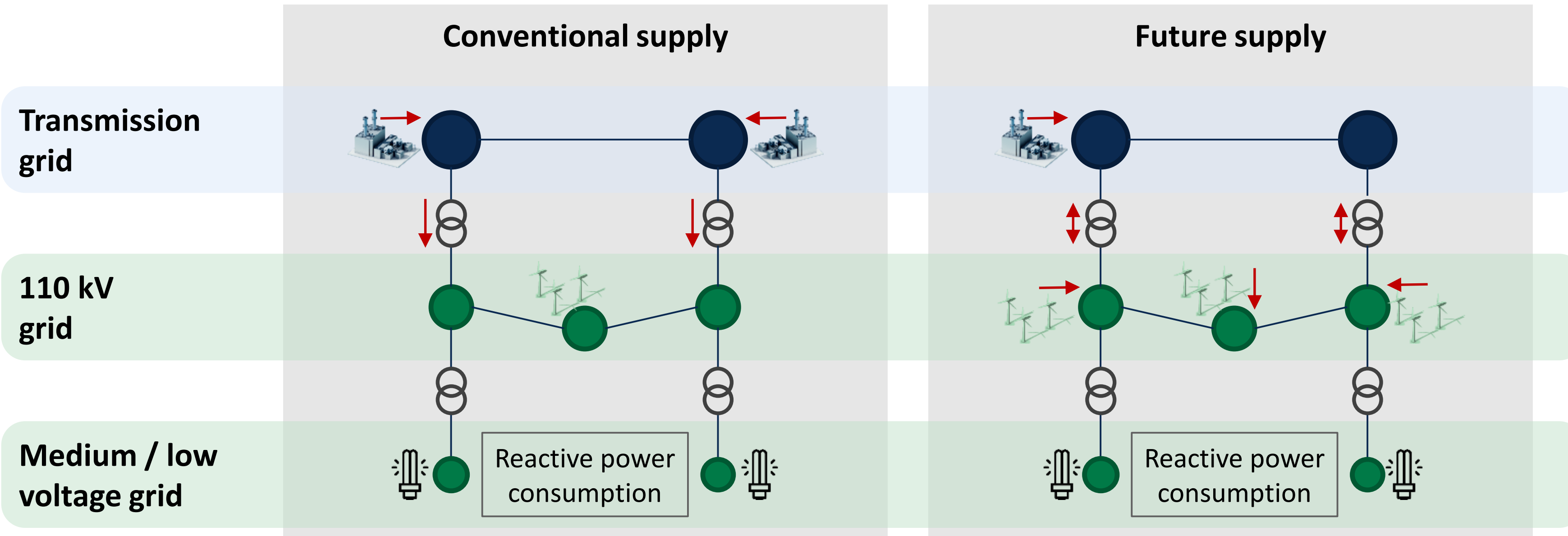
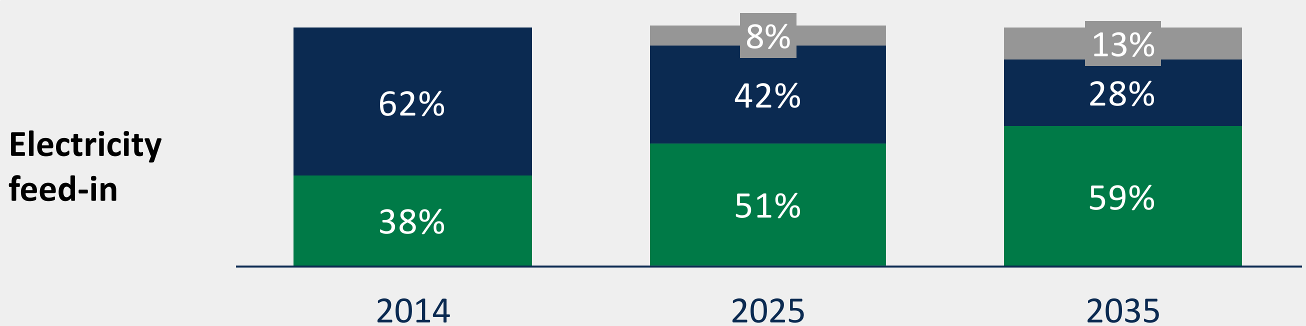
Reactive power supply: conventional and future scenario





Reactive power supply

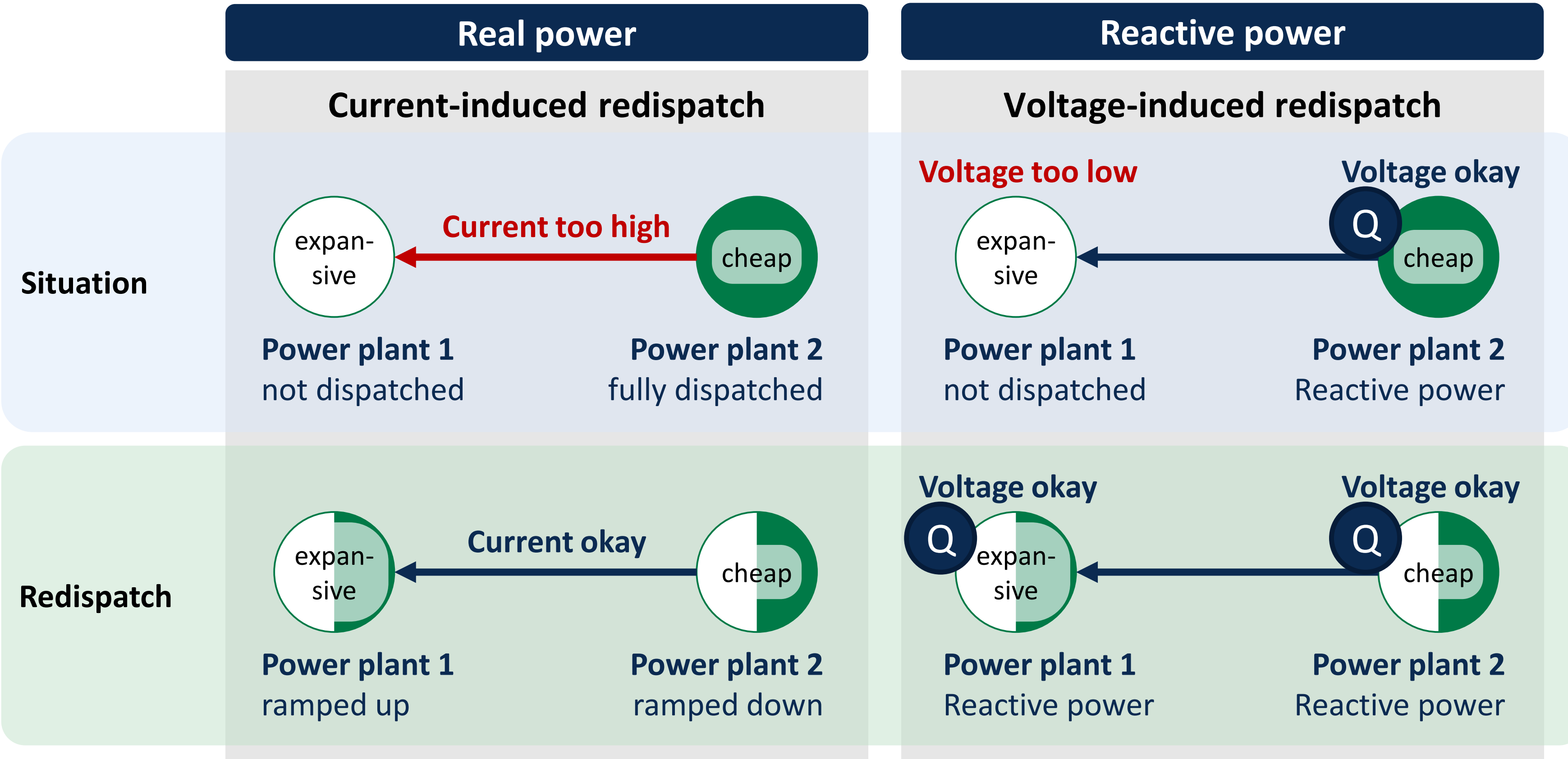
- Conventional supply through large power plants
- Availability in the transmission grid decreases
- Supply can be replaced by RES in the distribution grid

Controllable reactive power | Offshore | TSO | DSO

Source: Kraftwerksliste BNetA 2015, Netzentwicklungsplan 2015

Redispatch measures conducted in order to solve current and voltage problems

Current- and voltage-induced redispatch



More expansive power plant ramped up in order to alleviate transmission line

More expansive power plant ramped up in order to provide reactive power

→ Redispatch cost

Redispatch cost calculated in a 3-step approach

Model approach

Step 1
Market model

- **Electricity market model** (copper plate) for Germany and neighboring countries to generate **power plant dispatch**
- **NTC-based** trade between market zones
- Only **real power** (P) dispatch

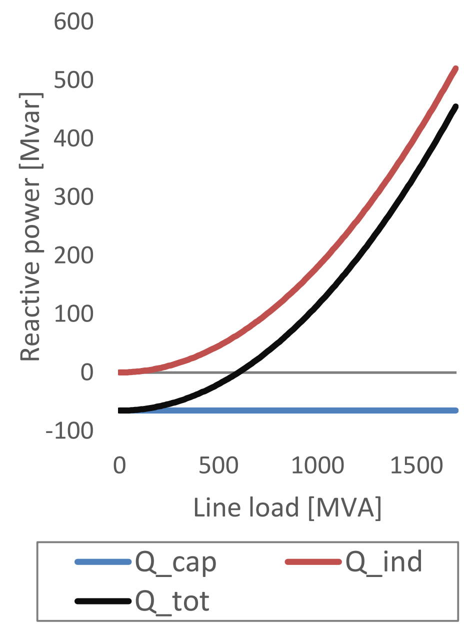
Step 2
Real power: current-induced redispatch

- Estimation of current-induced redispatch based on a **transmission & 110 kV distribution grid** model
- Usage of **ELMOD** to calculate load flows, overloads and **least-cost redispatch**
- Penalty cost for international redispatch

Step 3
Reactive power: voltage-induced redispatch

- Estimation of **reactive power dispatch** and voltage-induced redispatch
- Usage of **ELMOD LinAC**, a linearized AC model to account for voltage stability and reactive power flows
- **Iterative approach** to account for **quadratic reactive power behavior** of electricity lines

Reactive power behavior of 380 KV line



Iterative calculation of quadratic inductive reactive power behavior

Redispatch models use linearized real and reactive power flow calculations

Simplified model formulation of redispatch models

Market model → **Current-induced Redispatch** → **Voltage-induced Redispatch**

Target function

$$\text{Min} \sum_{n \in N} cost_n^{marg} \cdot \left(Gen_n^P - gen_n^{P,market}\right)$$

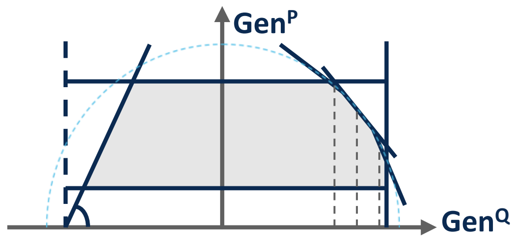
Restrictions

Thermal limit: $LineCurrent_l \leq Thermallimit_l$

Voltage TS: $0,97\ p.u. \leq U_n \leq 1,03\ p.u.$

Voltage DS: $0,94\ p.u. \leq U_n \leq 1,06\ p.u$

$$\begin{pmatrix} Gen_n^P, \\ Gen_n^Q \end{pmatrix} \in$$



Grid balance

Real power: $Gen_n^P - Dem_n^P = \sum_{m \in N}\left(g_{n,m}(U_n - U_m) - b_{n,m}(\theta_n - \theta_m)\right)$

Iterative calculation

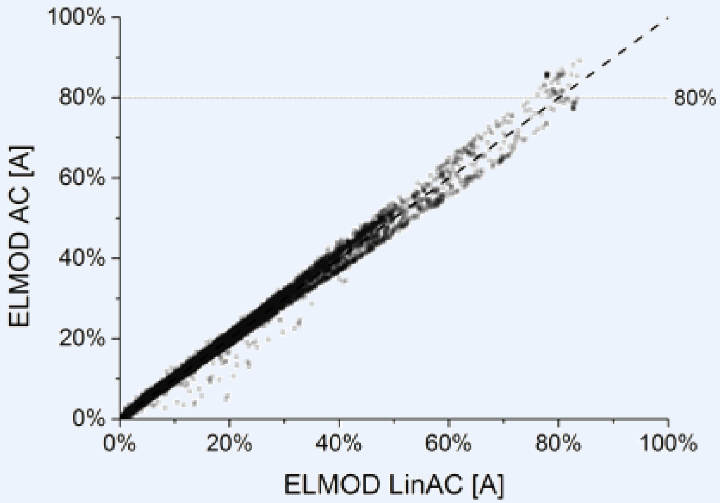
Reactive power: $Gen_n^Q - Dem_n^Q - Loss_n^Q = \sum_{m \in N}\left(-b_{n,m}(U_n - U_m) - g_{n,m}(\theta_n - \theta_m)\right)$

1) U_n / U_m... Voltage magnitude at node n / m Θ_n / Θ_m... Voltage angle at node n / m $g_{n,m}$ / $b_{n,m}$... Conductance / susceptance between node n and m

Current and voltage are represented reasonably well by the redispatch model

Model quality of ELMOD AC and ELMOD LinAC

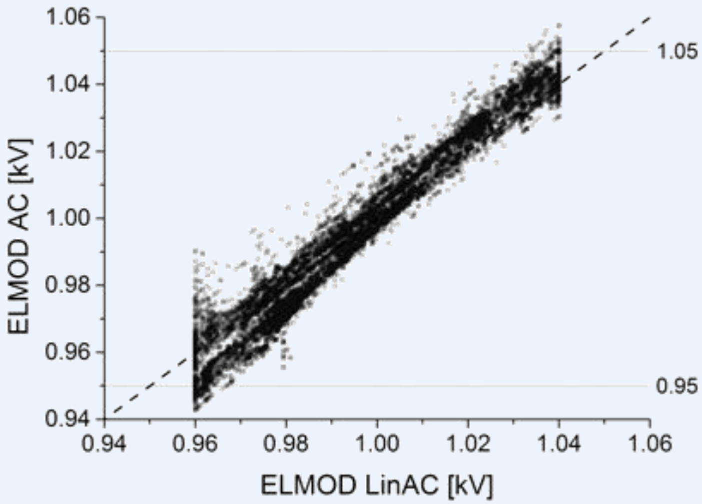
Current [A]



LinAC	MAE	RSME	aMAPE[1)]
I [A]	22.9	39.6	0.69%

Good fit for current

Voltage [p.u.]



LinAC	MAE	RSME	aMAPE[1)]
U [kV][2)]	2.0	2.5	0.53%

Reasonable fit for voltage

Comparison between redispatch model (ELMOD LinAC) and AC load flow model (ELMOD AC), Germany, 16 grid situations

1) Adjusted Mean Absolute Percentage Error: adjusted in relation to nominal voltage / thermal limit 2) On 380 kV level

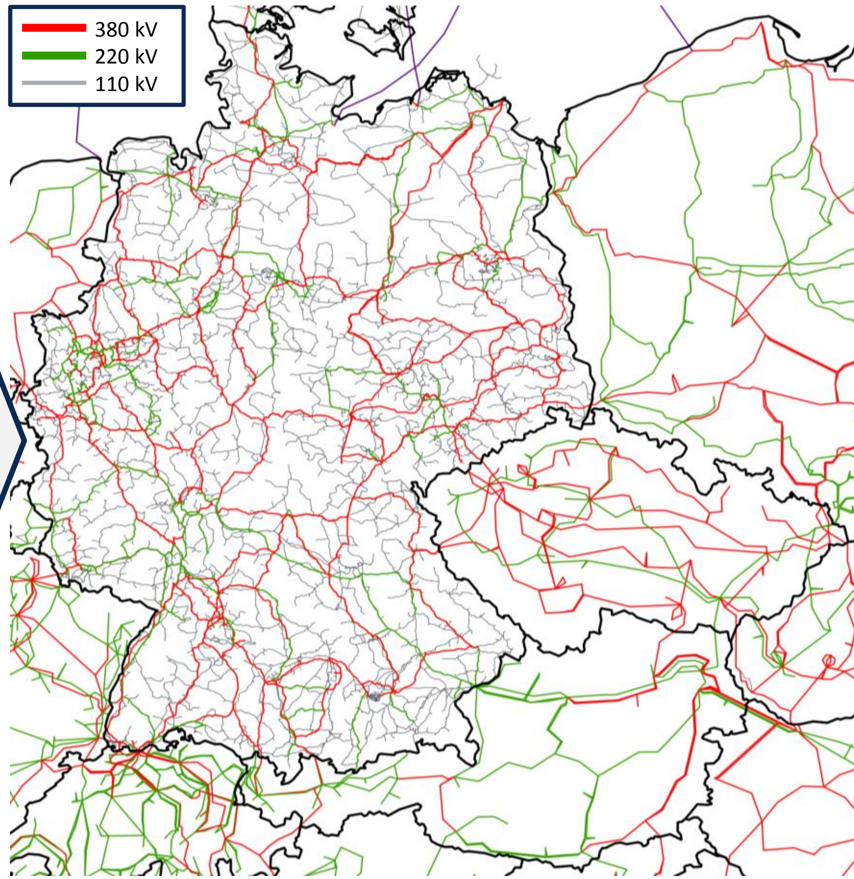
110 kV grid set developed based on OSM data and other public sources

Data set for grid model

OSM data

- **Substations**
  380 / 220 / 110 kV
- **Electricity lines**
  380 / 220 / 110 kV

- **Nodes** with generation and demand
- **Auxiliary nodes**
- **Lines** start / end, technical parameters
  updated with TSO static grid models
- **Transformers**
  380 / 110 kV
  220 / 110 kV



Power plants / RES

Attribution to nodes

- **Plants:** based on addresses and coordinates
- **RES:** based on OSM data / RES database

Load

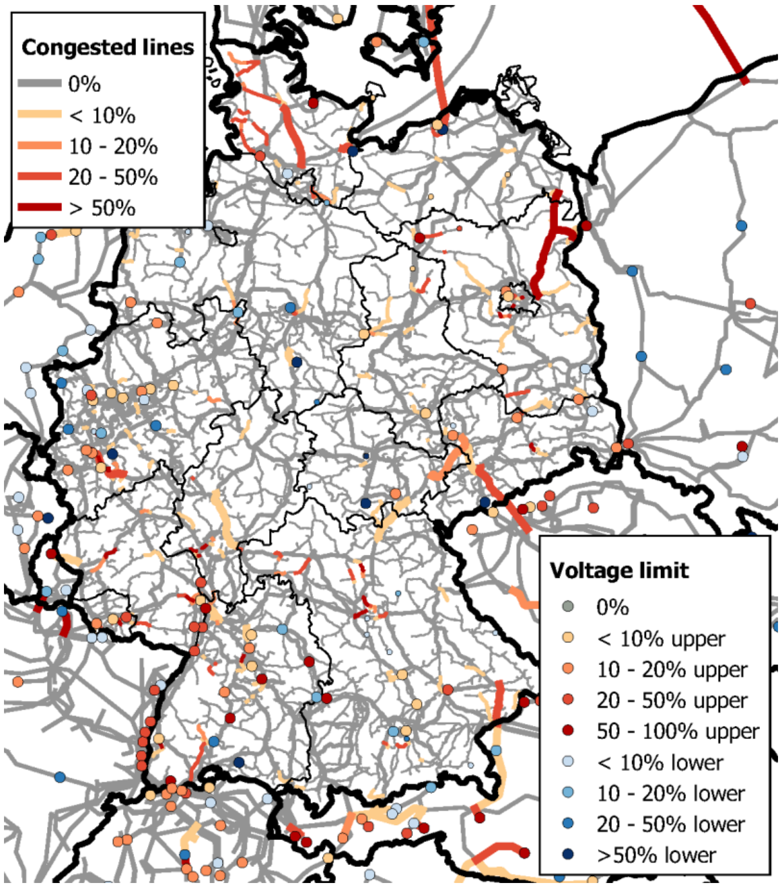
- Attribution based on GDP and population of surrounding area

Nodes:	~5700
Lines:	~6500
Substations:	~370

Good fit between congestions in model and reality

Congested grid elements: Model results vs. reality

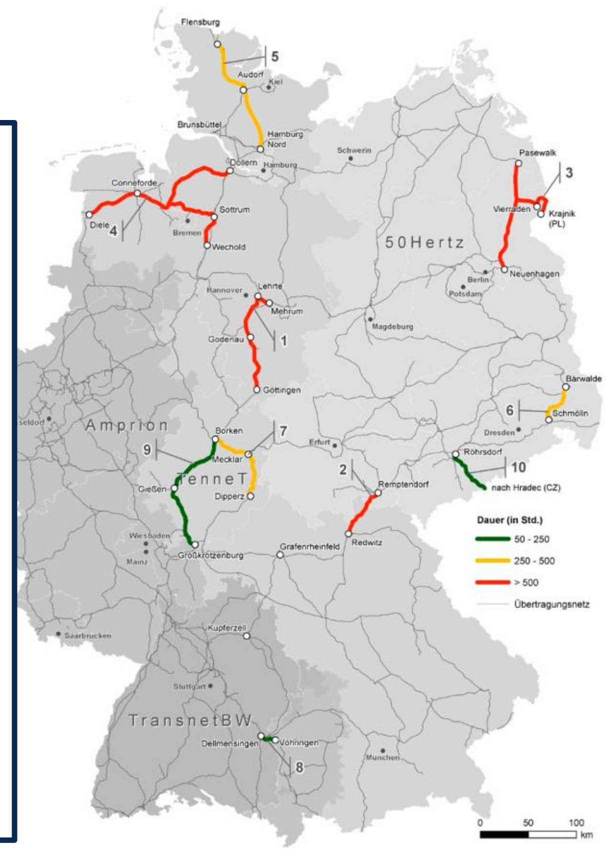
Model results 2014



Frequency of congested grid elements

- Good fit between for border areas to Poland, Czech Republic and Denmark
- Fit for Remptendorf-Redwitz line
- Congestions in the North West and Center not reliably recognized
- Distribution grid congestions in the North fit local curtailment compensation

Monitoring report 2014

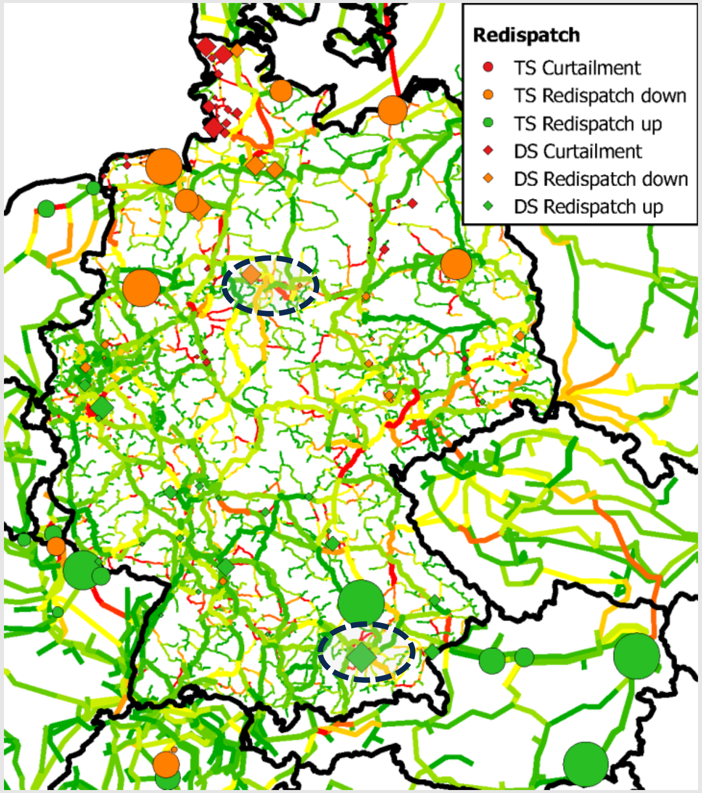


Source: BNetzA Monitoring Report 2015

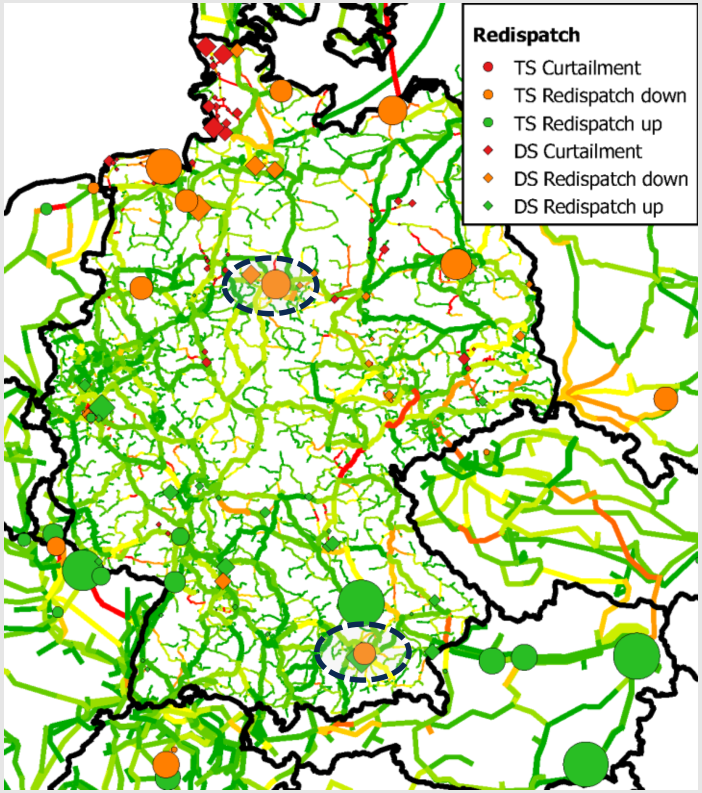
Taking into account voltage stability, redispatch patterns change

High load and high wind feed-in situation: current- and voltage-induced redispatch

Current-induced



Current- and voltage induced



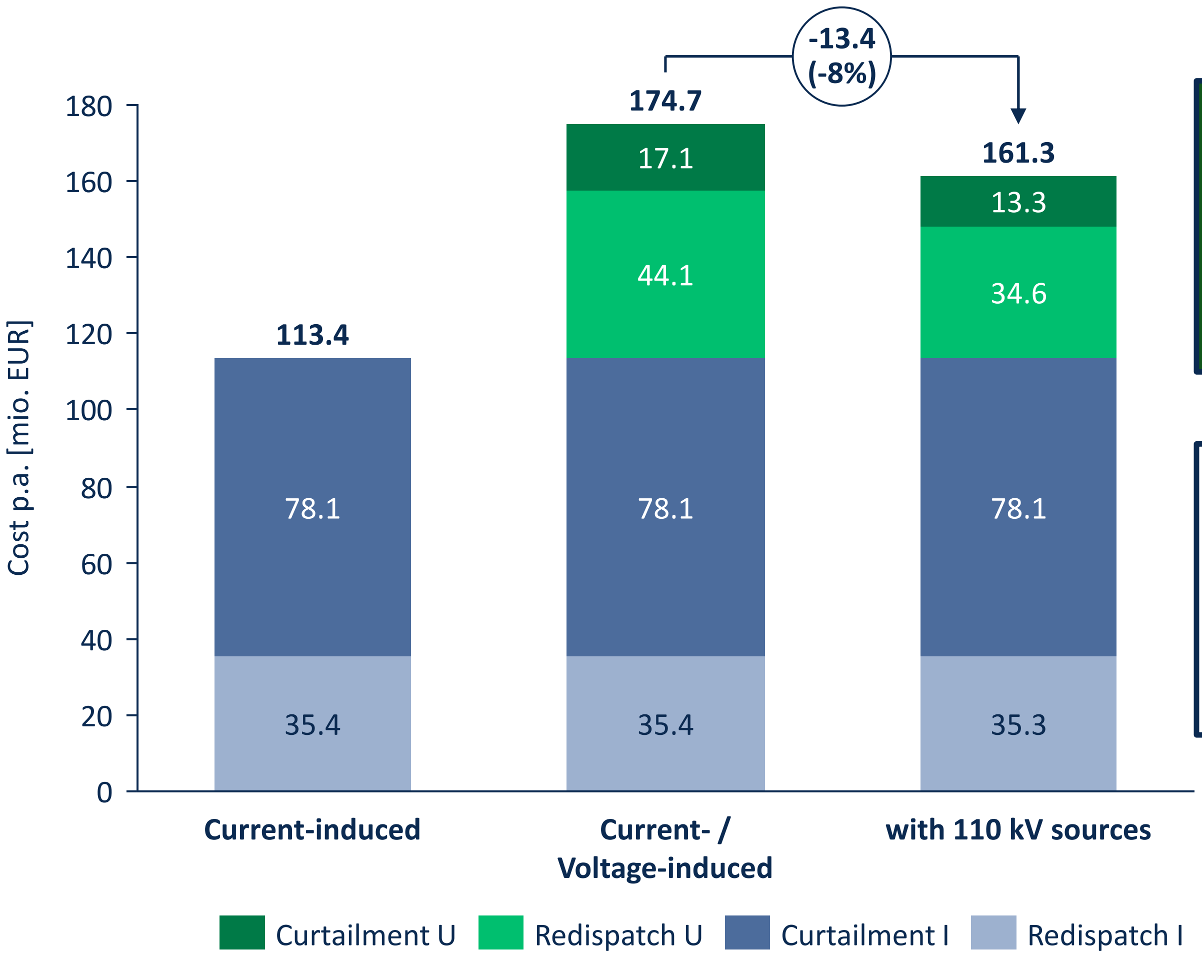
Results

- Ramp-down of power plants in the North
- Curtailment mainly in Schleswig-Holstein
- Ramp-up in the South and Austria

- Additional redispatch in the South to cover reactive power requirements
- Additional ramp-downs in the North

Reactive power from the 110 kV grid decreases voltage-induced redispatch cost

Redispatch costs 2014 in Germany



Redispatch cost Germany 2014

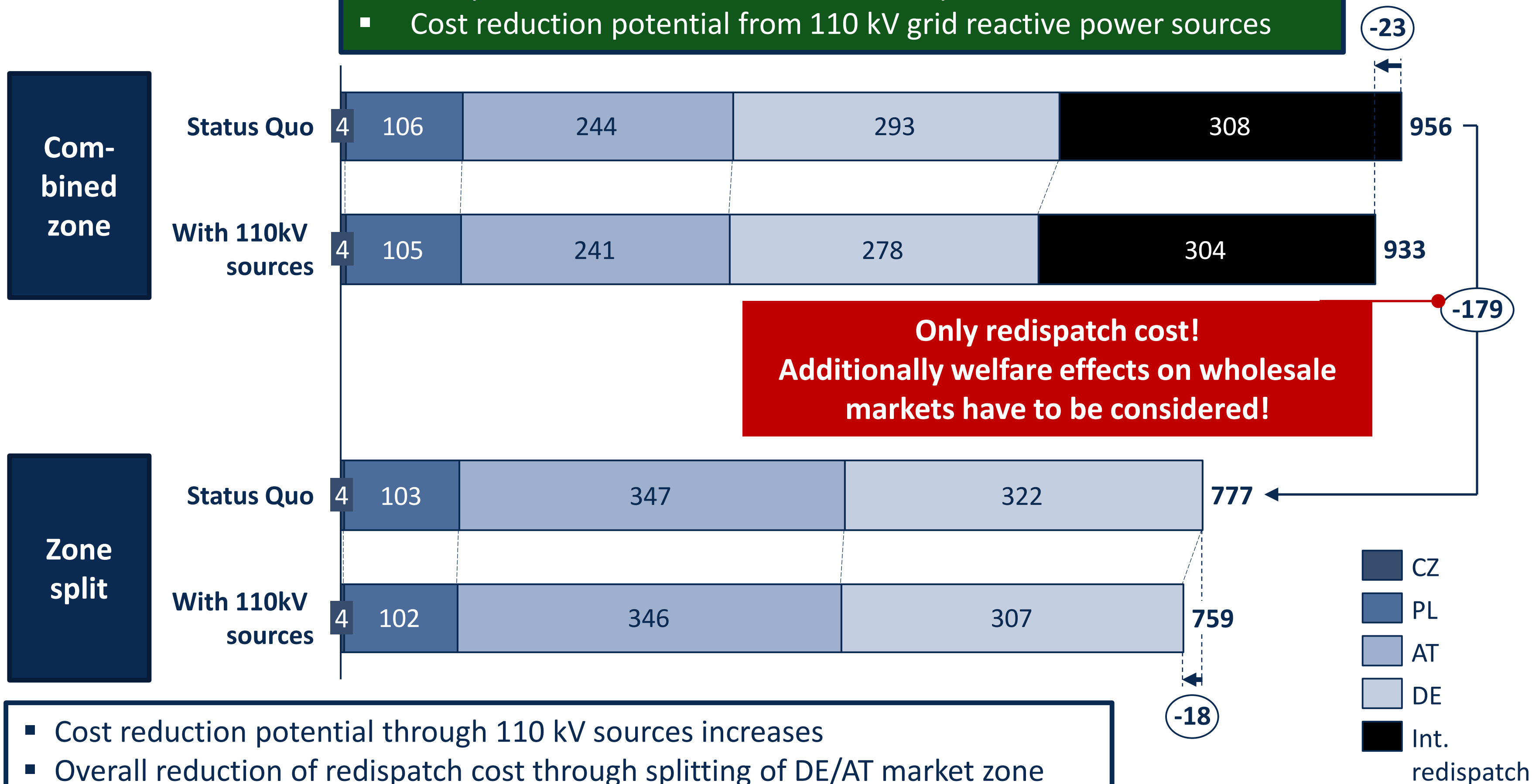
- Comparison of voltage- / current- induced redispatch
- Cost reduction potential from 110 kV grid reactive power sources

- Redispatch and curtailment cost is mainly current-induced
- 8% reduction possible through reactive power from the distribution grid

Market zone split decreases redispatch cost more than 110 kV reactive power

Redispatch costs 2025 under full grid extension, combined and split DE/AT market zone

Redispatch cost 2025
- Comparison of DE/AT market zone and split
- Cost reduction potential from 110 kV grid reactive power sources



- Cost reduction potential through 110 kV sources increases
- Overall reduction of redispatch cost through splitting of DE/AT market zone

Considerably higher cost under grid extension delay – savings potential increases

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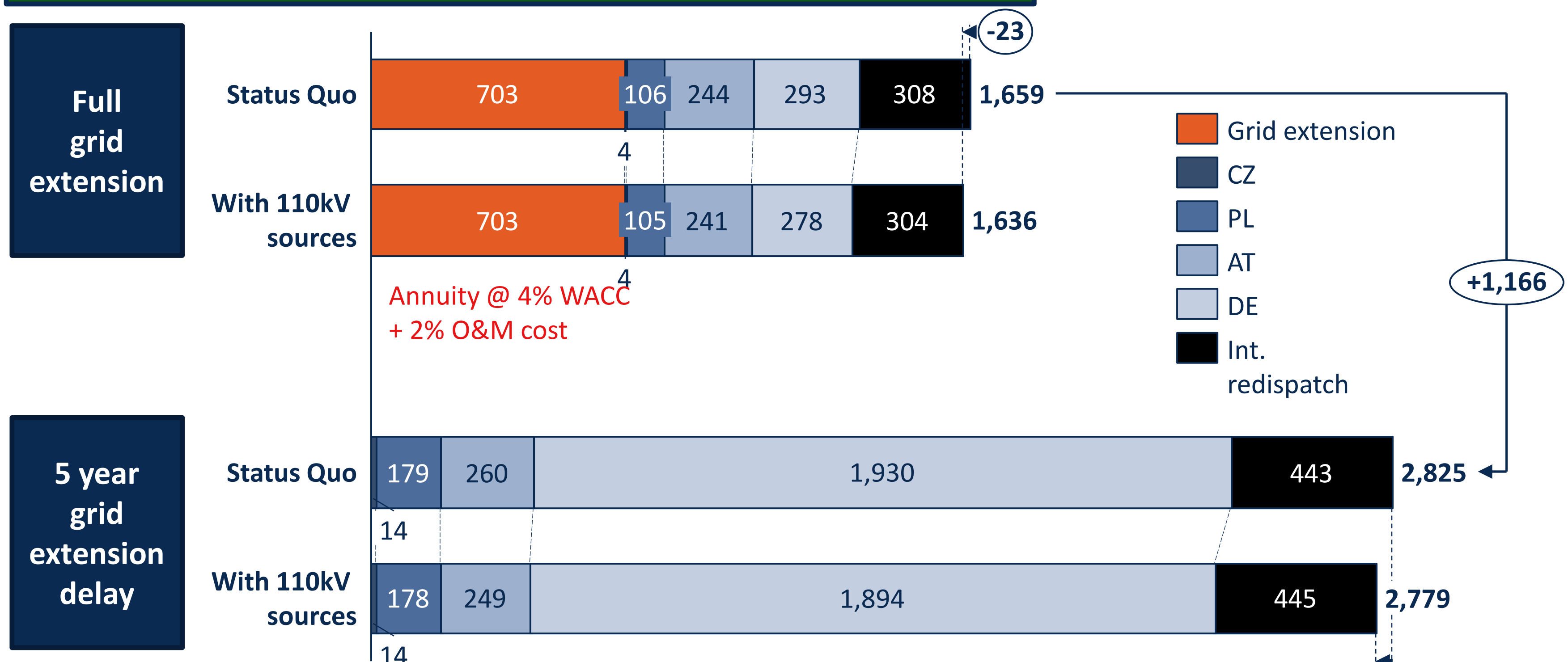
Redispatch costs 2025 under full and delayed grid extension

Redispatch cost 2025
- Comparison of full and delayed grid extension
- Cost reduction potential from 110 kV grid reactive power sources



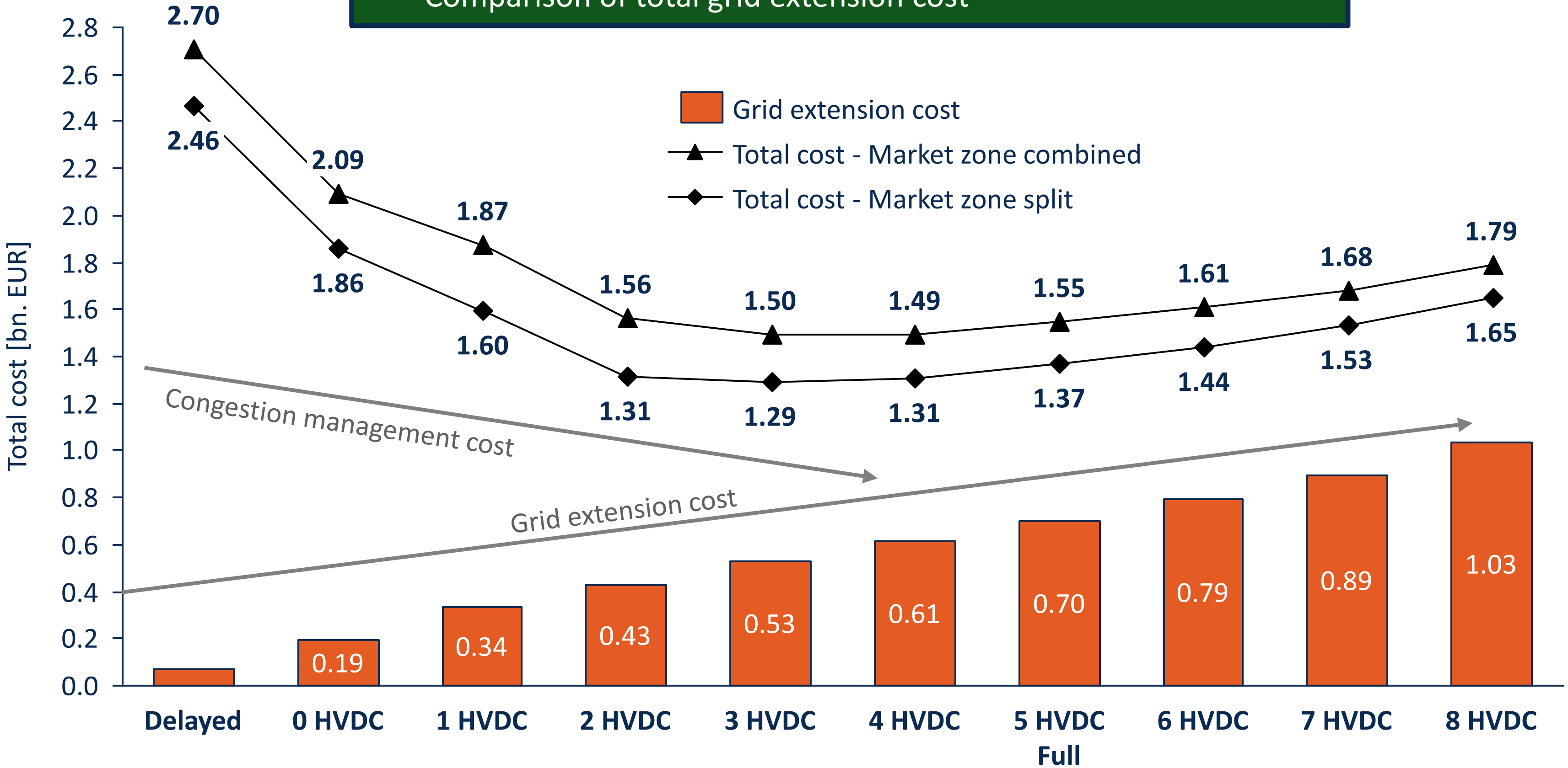
- Considerably higher cost under grid extension delay
- Under grid extension delay , the cost reduction potential from 110 kV sources increases

Which degree of grid extension is economically reasonable?

Relationship between grid extension and redispatch cost

Redispatch cost 2025

- Alteration of grid extension level (# of HVDC links)
- Comparison of total grid extension cost



Conclusions

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Key take-aways

- Current- and voltage induced **redispatch** will play an **important role in future** electricity systems
- Usage of **110 kV reactive power sources** can **slightly limit** redispatch costs
- **Market zone layout** has a much **higher impact**
- **Grid extensions** required to **impede extreme cost** increases – number of **HVDC links** in grid development plan seems **reasonable**

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Thank you for your attention!

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Dipl. Wi.-Ing. Fabian Hinz
Chair of Energy Economics
Faculty of Business and Economics
TU Dresden
Email: fabian.hinz@tu-dresden.de
Phone: +49 351 463 39896

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