Trade-offs between system cost and supply security in energy system design

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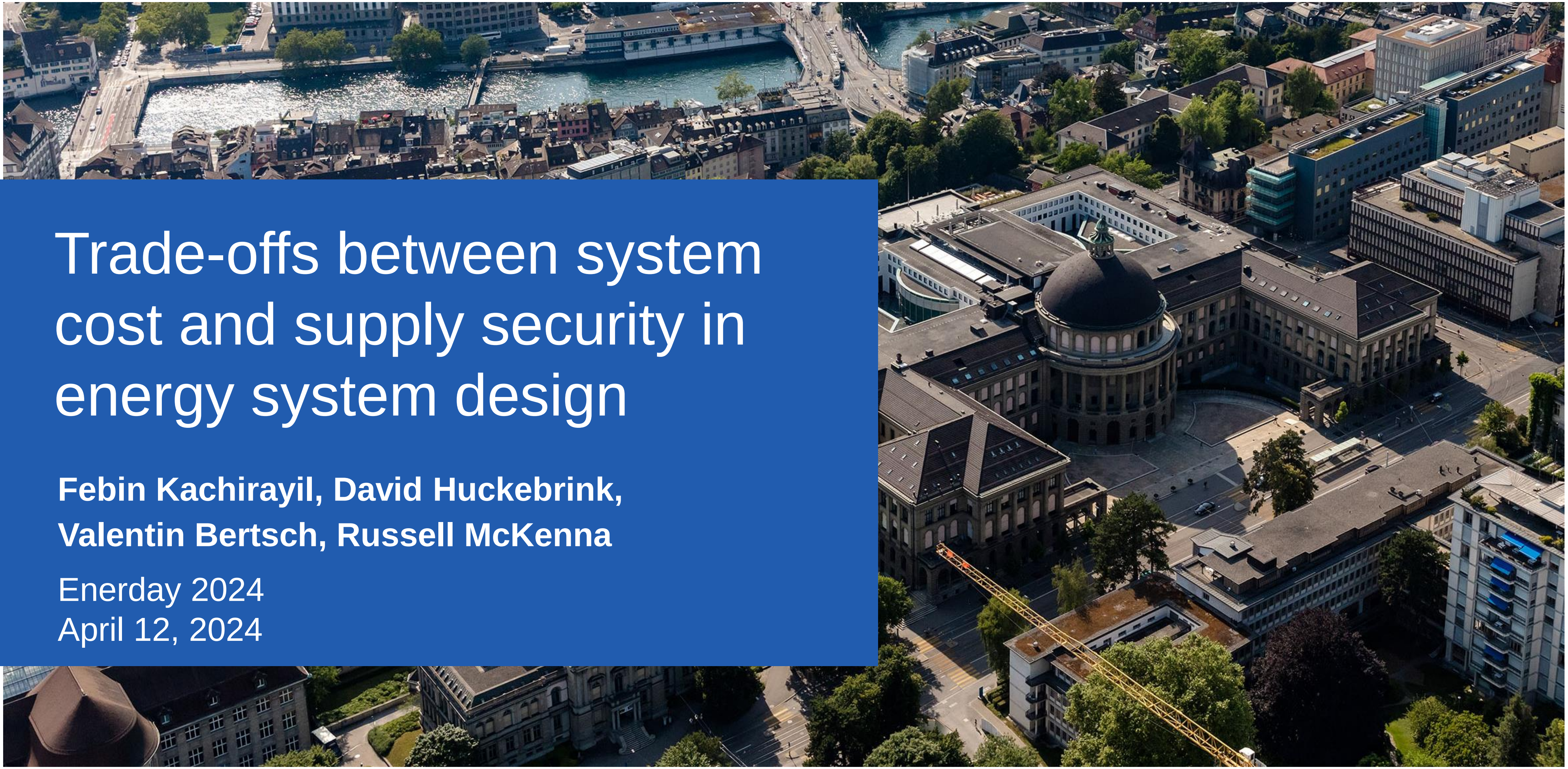


Context

- EU directive 2019/943 prescribes the use of the Value of Lost Load (VOLL) to determine national reliability standards.
- VOLL: Economic cost of unserved load based on welfare loss from an outage
- Wide range in estimates despite common methodology (ACER, 2022)
- System-level reliability indicators:
  - Expected Energy Not Served (EENS)
  - Loss of Load Expectation (LOLE)

Motivation & Aims

- Single average VOLL per country masks temporal and regional variations in the VOLL, potentially impacting optimal reliability levels

- Case study in Germany, which is at risk of reduced supply security (ENTSO-E, 2021) and has a wide range of VOLL estimates from 0.5-15€/kWh (BMWK, 2019) to over 20€/kWh (ACER, 2022)

→ Determine hourly VOLL for every county in Germany

→ Scenario analysis enabling load curtailment at different VOLL

→ Power system reliability is not driven by averages but by extremes

1. When is it useful to reduce demand?
2. How do different values impact the trade-off between system cost and reliability?

Using the production function to assess the residential VOLL

- VOLL based on the value of activities that cannot take place due to an outage (Wolf & Wenzel, 2016).
- The VOLL is determined (de Nooij et al., 2007):

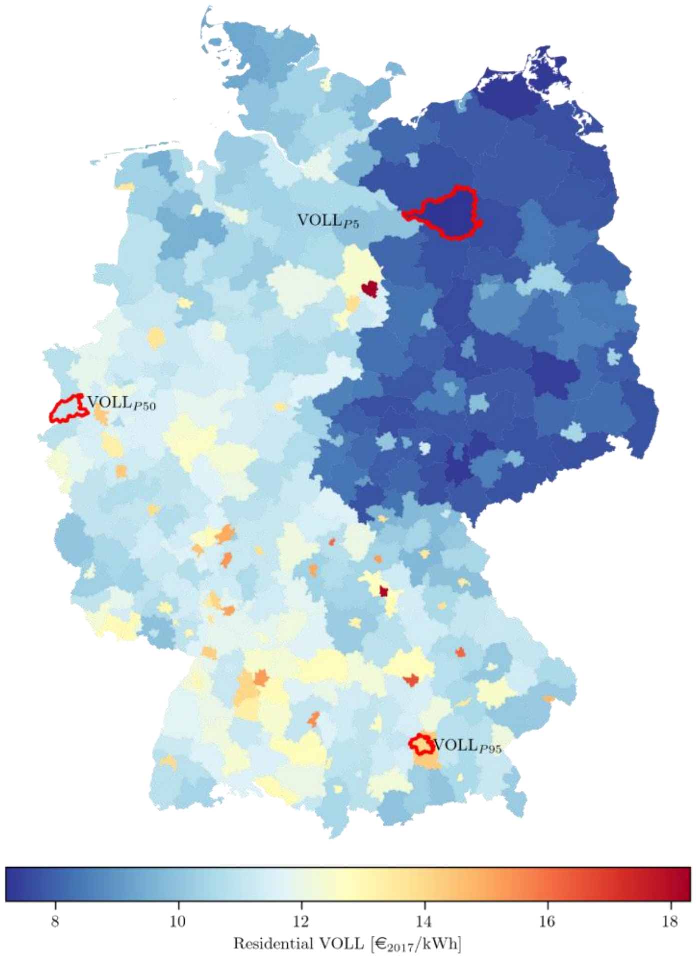
$$\text{VOLL} = \frac{\big((8760 - H_{PC} - H_{W}) \cdot W\big) \cdot E_{dep} \cdot (Pop_e + cf \cdot Pop_{ne})}{EC_a} \left[\frac{€}{kWh}\right]$$

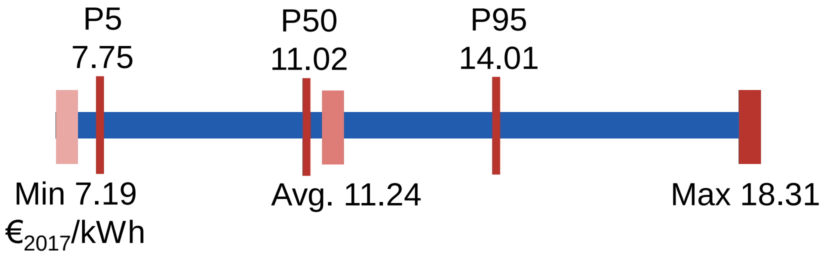
1. Total economic value of leisure time
2. Share of electricity-dependent activities
3. Total electricity consumption
4. Total (non-)employed population

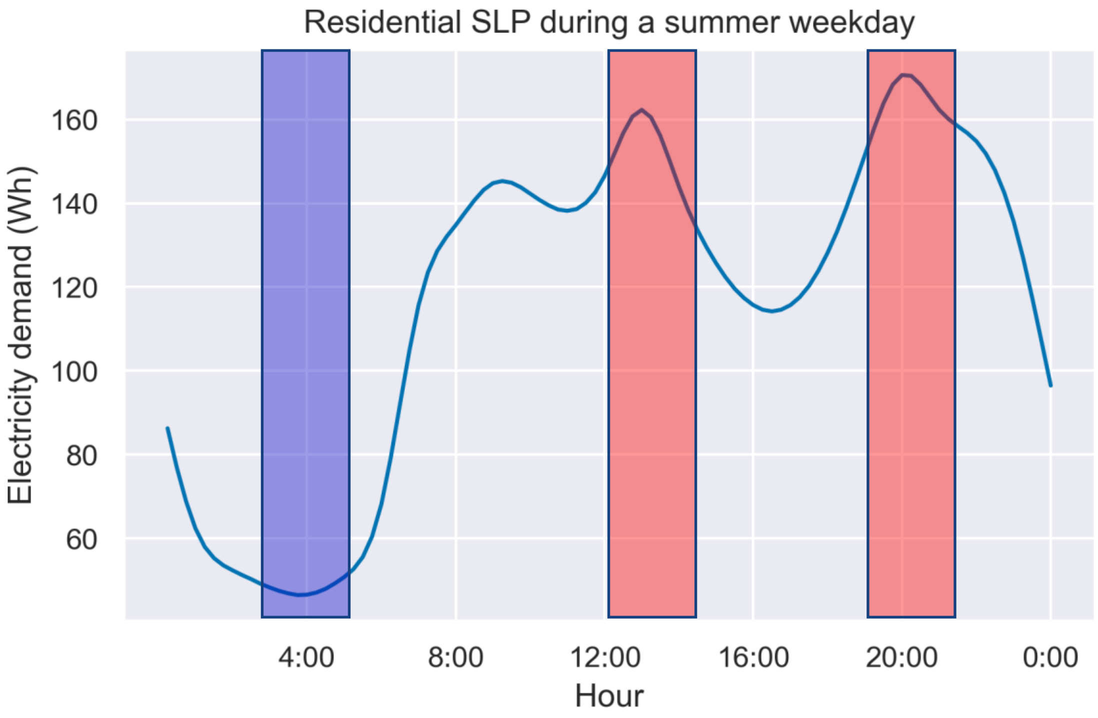
- Hourly scaling that conserves average VOLL using the residential standard load profile

$$VOLL_{t,c} = VOLL_c \cdot \frac{SLP_t}{SLP_{avg}}$$

A spatio-temporally resolved VOLL for Germany



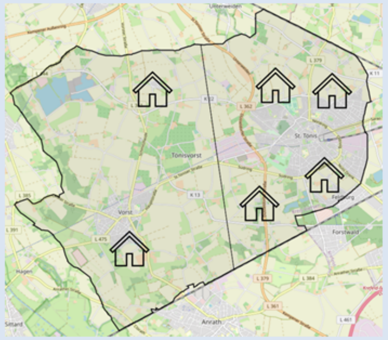




The RE^{3}ASON municipal energy system optimization model

Input data

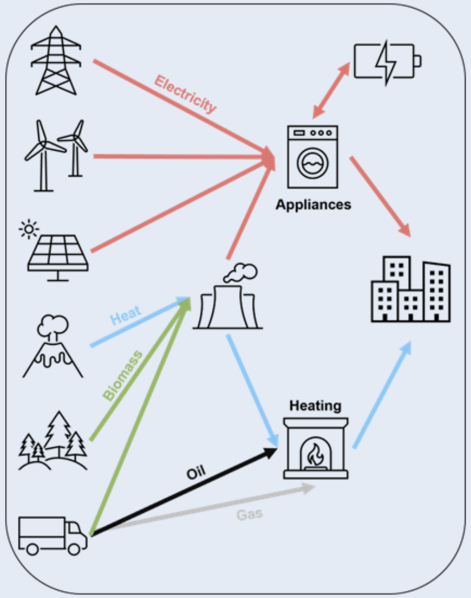
- Combining Bing maps, OpenStreetMap and German census data
- Residential focus
- Building archetypes based on age and type



- Simulating load profiles
- Techno-economic RE potential assessment
- Flexible temporal and spatial resolution

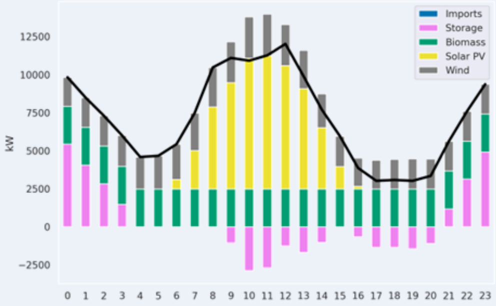
Optimization model

- MILP minimizing cost
- Optimal investment and operation decisions
- Hourly power balance, daily heat balance



Model outputs

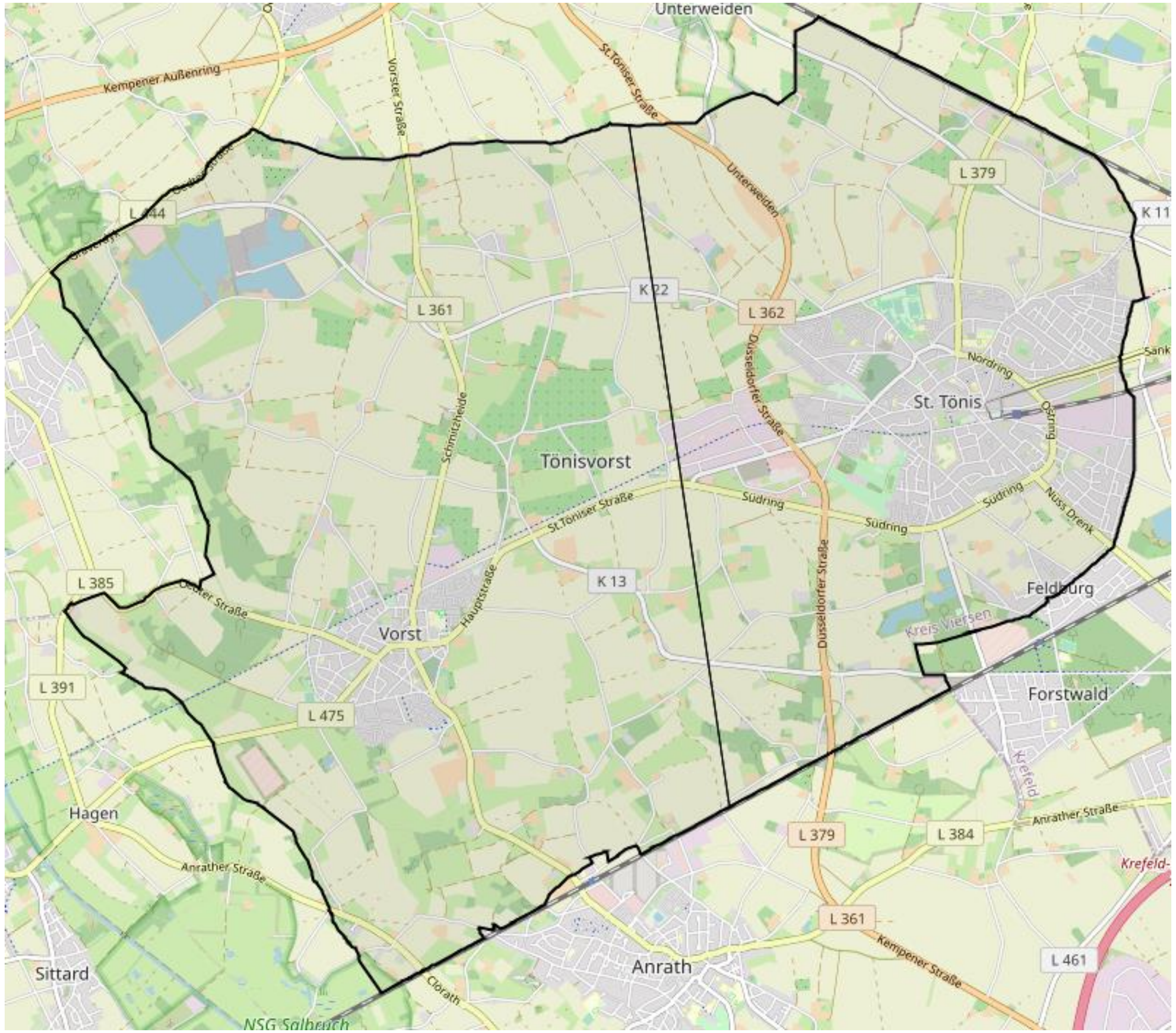
- Costs from annuities, O&M, energy flows etc.
- CO_2 and PM emissions
- Investment decisions on a building and district level
- Local generation and consumption of electricity and heat
- Energy flows (storage, import/export)



Model description & scenario analysis

- Median VOLL for case study:
  Tönisvorst (Viersen)
  Pop: 29'257, area: 44 km²
- Typical temporal resolution (2021-2050)
- Power shortage days defined by:
  - No intermittent generation
  - Peak loads
- Enable load curtailment at the cost of the VOLL
- Spatio-temporal detail - constant vs variable for:

Scenario	VOLL (€/kWh)
$VOLL_{low}$	7.75
$VOLL_{med}$	11.02
$VOLL_{high}$	14.01



Impacts on system design and operation

- 3% savings with median VOLL despite nearly identical system design
- Minimal demand reductions (0.12%, **only during power shortages**) can yield outsized cost savings
- Demand curtailment offsets storage investments

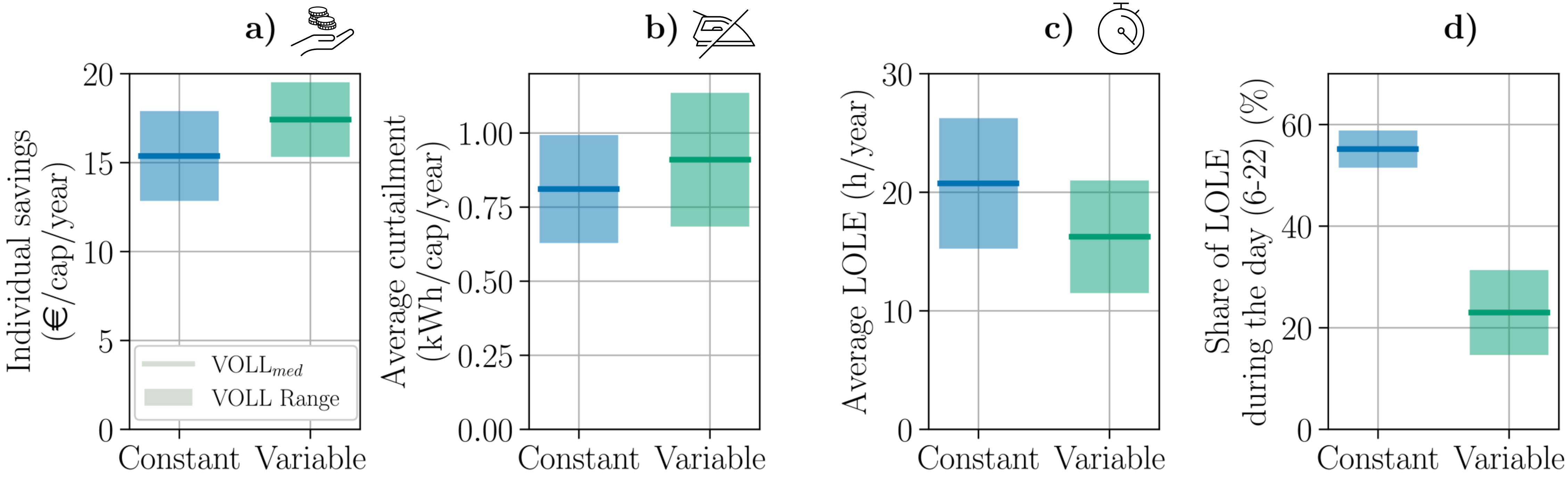
→ Load curtailment during power shortages lowers cost, regional differences with minimal impact

VOLL (€/kWh)	System cost (% of NoVoll)	EENS (%)	Max. LOLE (h/year)
NoVoll	100	0	0
7.75	96.5	0.15	32
11.02	97.1	0.12	28
14.01	97.5	0.09	20

The impact of temporal variations in the VOLL

- Total **EENS increases** as VOLL is lower during hours with load curtailment
- Temporal detail **reduces LOLE** and shifts load curtailment to the night

→ Optimal decision-making depends on the choice of indicators



Limitations and further research

Limitations

- VOLL calculation does not account for non-linear effect of advance notice
- Strict definition of power shortage events
- Incomplete consideration of flexibility options

Further research

→ Alternative tariff design options (e.g. critical peak pricing or curtailable contracts)

→ Technical barriers for residential demand-side management

→ Factors fostering social acceptability of load curtailment

Conclusion

- EU prescribes singular VOLL to determine reliability standard
- Transferable method to calculate the residential VOLL reveals important spatio-temporal variations for Germany (average of 11.24 €/kWh, range of 7.19 – 18.31 €/kWh)

- The analysis reveals that load curtailment is exclusively viable during power shortages
- Curtailment of 0.8 kWh per capita over 20 hours per year leads to savings of 15 € per person and year
- Temporal scaling of the VOLL enables less intrusive load curtailment decisions

- Consumers have expressed a readiness to reduce energy consumption and participate in demand-response programs
- Considering this willingness, we find system-level benefits from residential load curtailment

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Thank you for your attention!

Looking forward to your questions

Backup slides

Applying the production function

- Validating assumption on the share of electricity-dependent activities and time for personal care [1]
- Annual working hours by county [2]
- (Non-)employed population by county [3]
- Annual household electricity consumption by county [4]
- Wage calculation using:
  - Median monthly gross wage by county [5]
  - Tax payments by county [6]
  - Social security contributions [7]

$$W_{net,d} = W_{gross,d} \qquad , \forall d \in D$$

[1] Statistisches Bundesamt. (2015). *Zeitverwendungserhebung* [Data set]. https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Einkommen-Konsum-Lebensbedingungen/Zeitverwendung/Publikationen/Downloads-Zeitverwendung/zeitverwendung-5639102139004.html
[2] Statistische Ämter des Bundes und der Länder. (2021). *Erwerbstätgienrechnung* [Data set]. https://www.statistikportal.de/sites/default/files/2021-06/ETR_R2B2_2019_j_0.pdf
[3] Statistisches Bundesamt. (2018). Daten aus dem Gemeindeverzeichnis Kreisfreie Städte und Landkreise nach Fläche, Bevölkerung und Bevölkerungsdichte [Data set]. In *Statistisches Bundesamt*. https://www.destatis.de/DE/Themen/Laender-Regionen/Regionales/Gemeindeverzeichnis/_inhalt.html
[4] FfE, Statistische Ämter des Bundes und der Länder, & Bundesministerium für Wirtschaft und Energie. (2019). *Electricity Consumption of Private Households per Country (German Districts)* [Data set]. http://opendata.ffe.de/dataset/electricity-consumption-of-private-households-german-districts/
[5] Bundesagentur für Arbeit. (2018). *Sozialversicherungspflichtige Bruttoarbeitsentgelte – Deutschland, West/Ost, Länder und Kreise (Jahreszahlen)* [Data set]. https://statistik.arbeitsagentur.de/SiteGlobals/Forms/Suche/Einzelheftsuche_Formular.html?nn=1592932&topic_f=beschaeftigung-entgelt-entgelt&dateOfRevision=201712-201712
[6] Statistische Ämter des Bundes und der Länder. (2022). *Lohn- und Einkommensteuerpflichtige, Gesamtbetrag der Einkünfte, Lohn- und Einkommensteuer—Jahressumme—Regionale Tiefe: Kreise und krfr. Städte* [Text]. https://www.regionalstatistik.de/genesis/online?operation=table&code=73111-01-01-4#astructure
[7] Vereinigte Lohnsteuerhilfe. (2022). *Das wird Arbeitnehmern vom Lohn abgezogen*. https://www.vlh.de/arbeiten-pendeln/beruf/das-wird-arbeitnehmern-vom-lohn-abgezogen.html

Comparing our results to literature

Study	Estimate (€/kWh)	Year	VOLL ($€_{2017}$/kWh)
Wolf & Wenzel (2016)	6.56 - 15.11	2010	7.17 – 16.52
Our results	**11.24**	**2017**	**11.24**
CEPA (2018)	12.41	2013	12.84
Shivakumar et al. (2017)	12.64	2015	12.89
Growtisch et al. (2013)	11.92	2007	13.57
Röpke (2013)	15.05	2008 - 2010	16.64
Praktiknjo et al. (2011)[1]	15.70	2007	17.87

[1] Only study using surveys rather than a production function

The Value of Lost Load

1. **Surveys**
   - Willingness-to-Pay or -to-Accept
   - Labor-intense, hard to scale

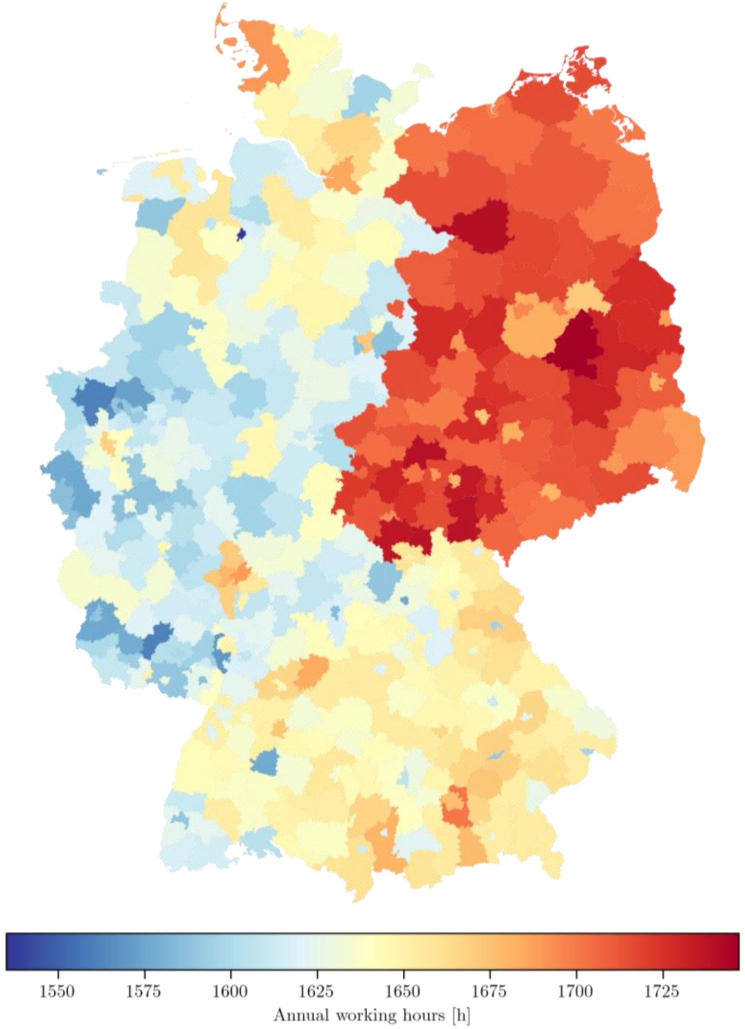
2. **Calculation by proxy**
   - Production function
   - Cannot easily capture non-linearities

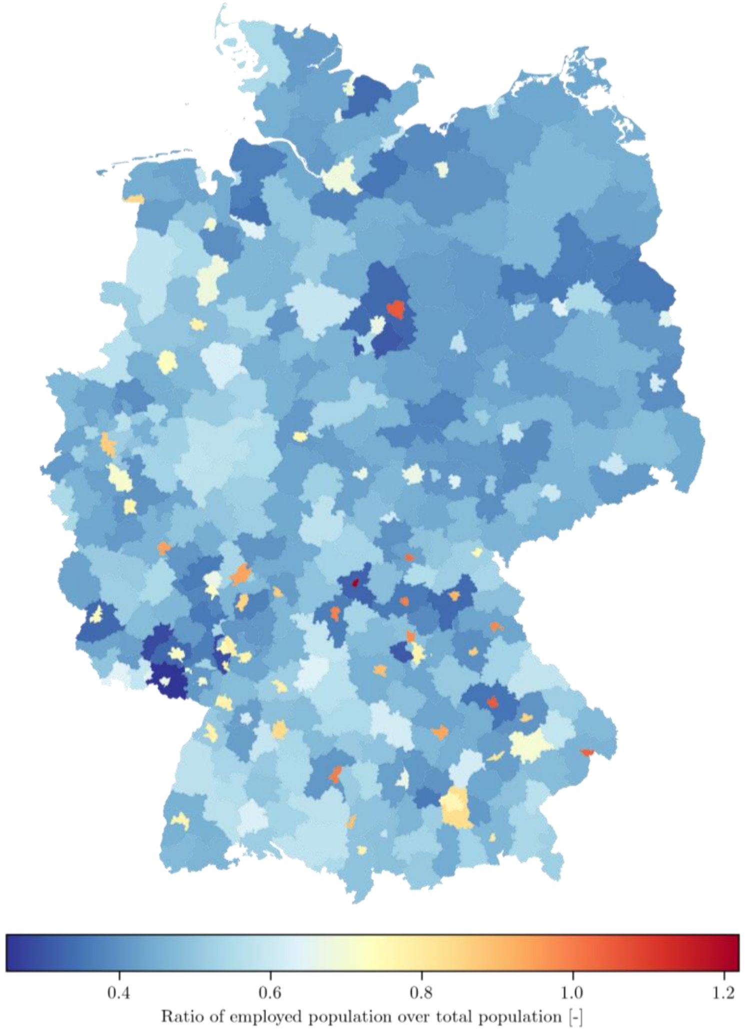
3. **Revealed preferences**
   - Market behavior or past outage events
   - Not suitable if high supply security

	Importance
Sector	++
Duration	
Timing	+
Frequency	
Region	+
Advance notice	++

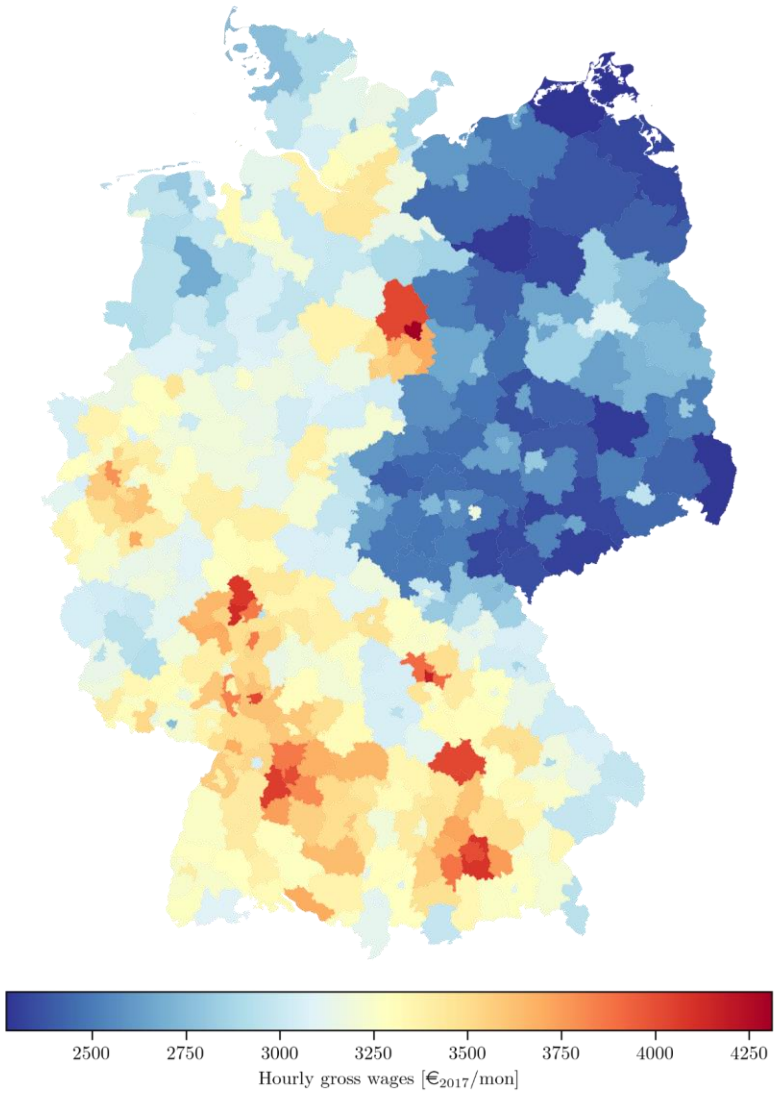
* Factors requested by EU Regulation 2019/943

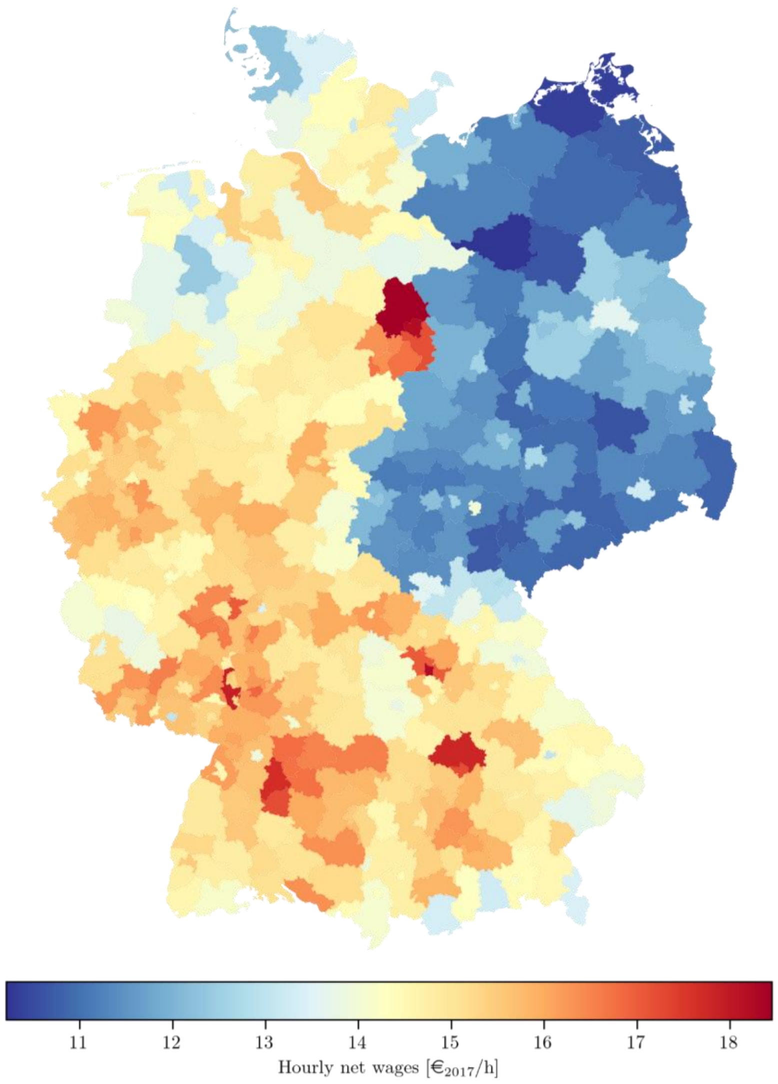
Annual working hours and employment ratio by region



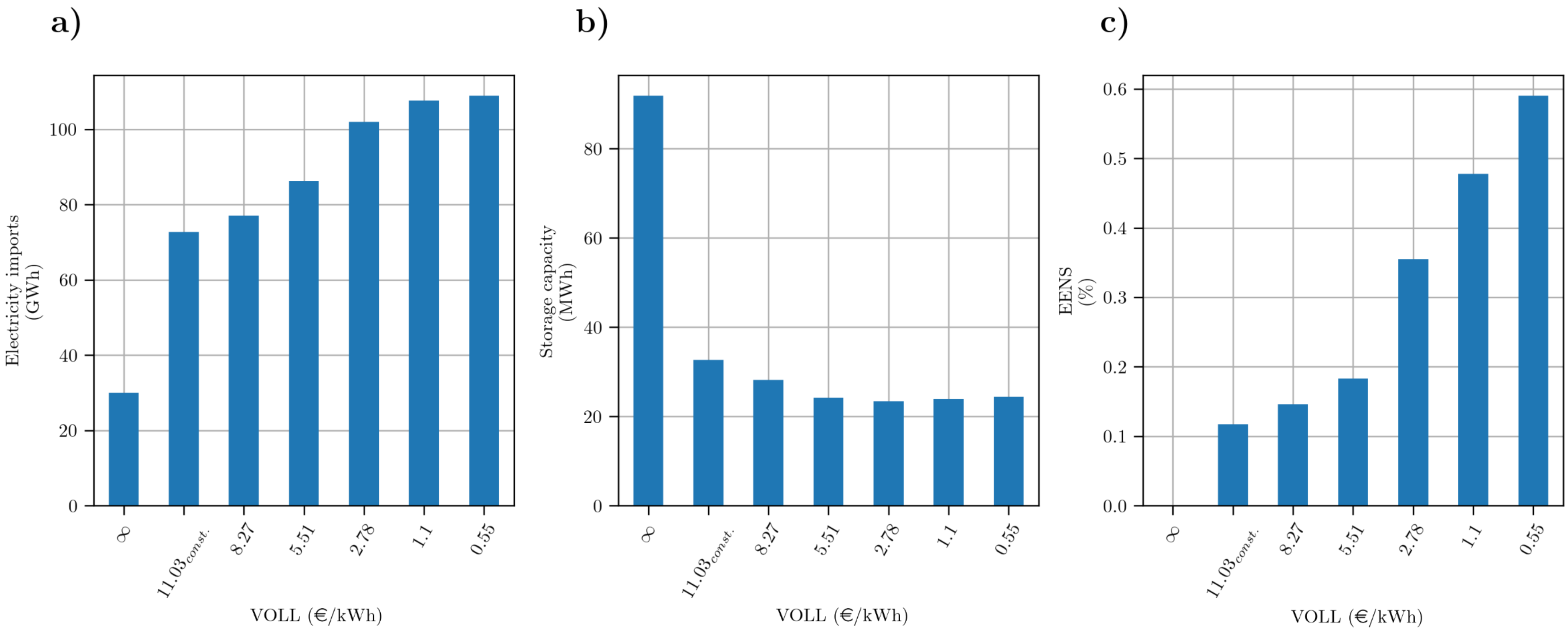


Gross and net wages by region

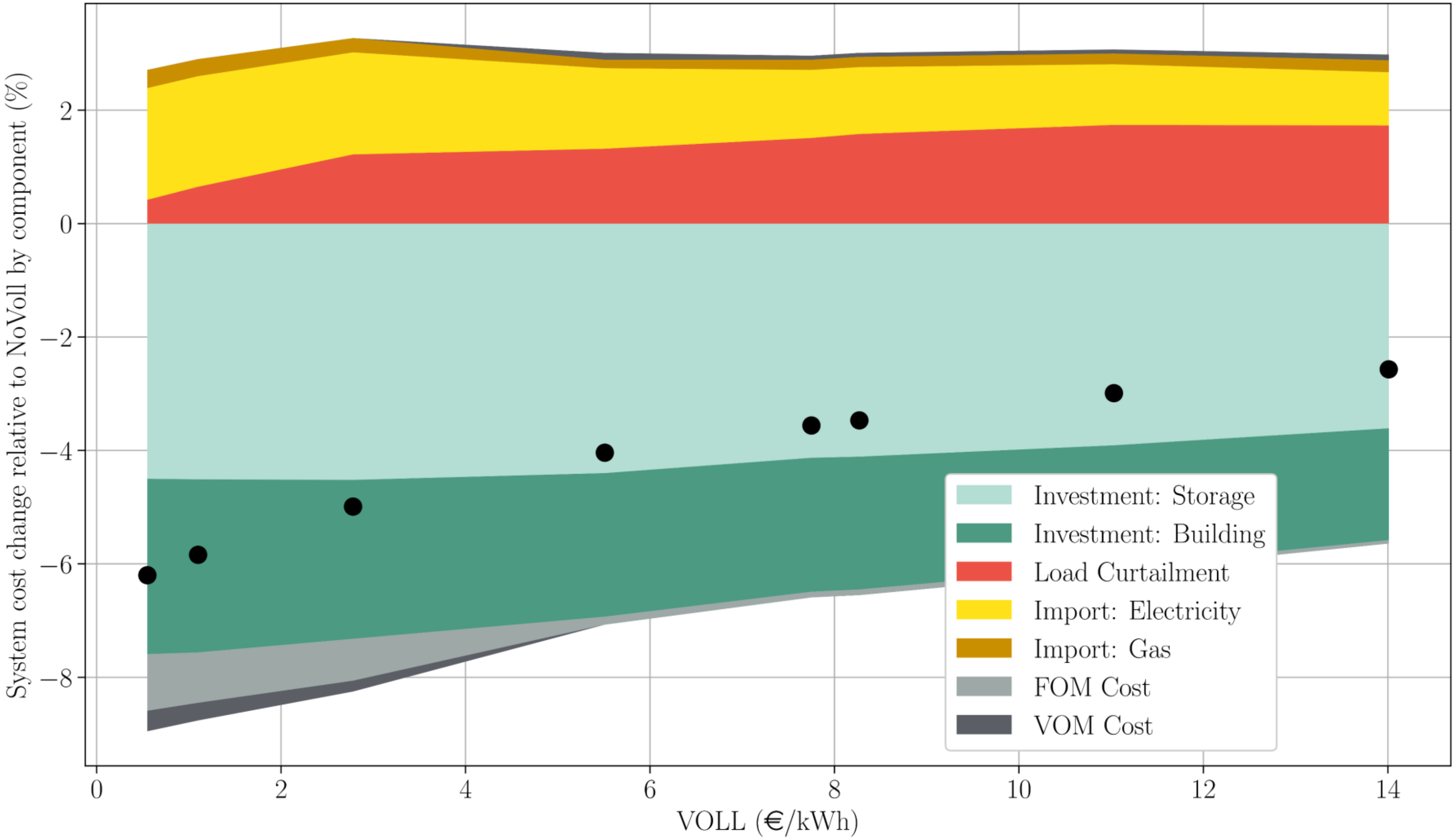




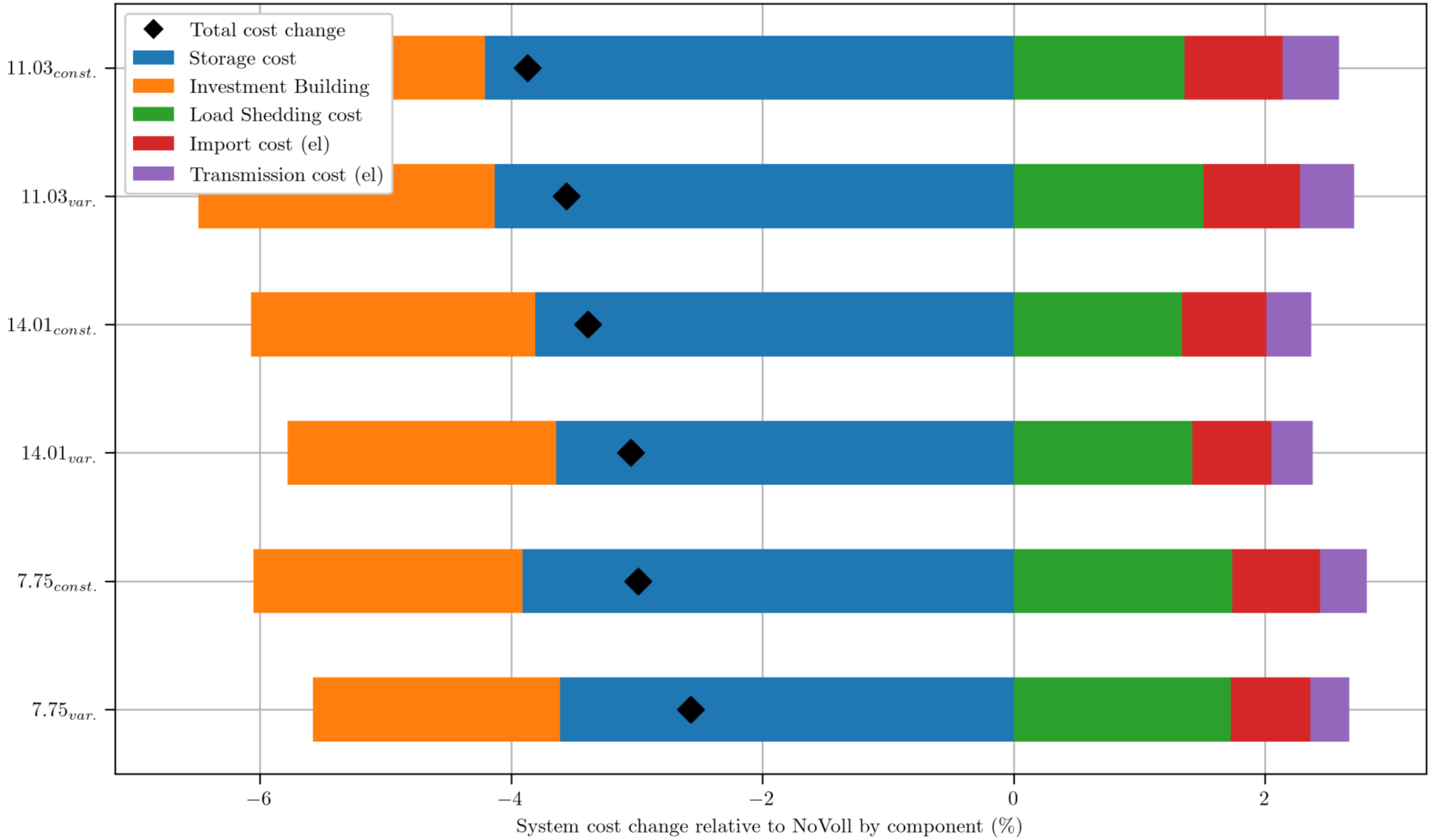
Use of flexibility options (import, storage, curtailment)



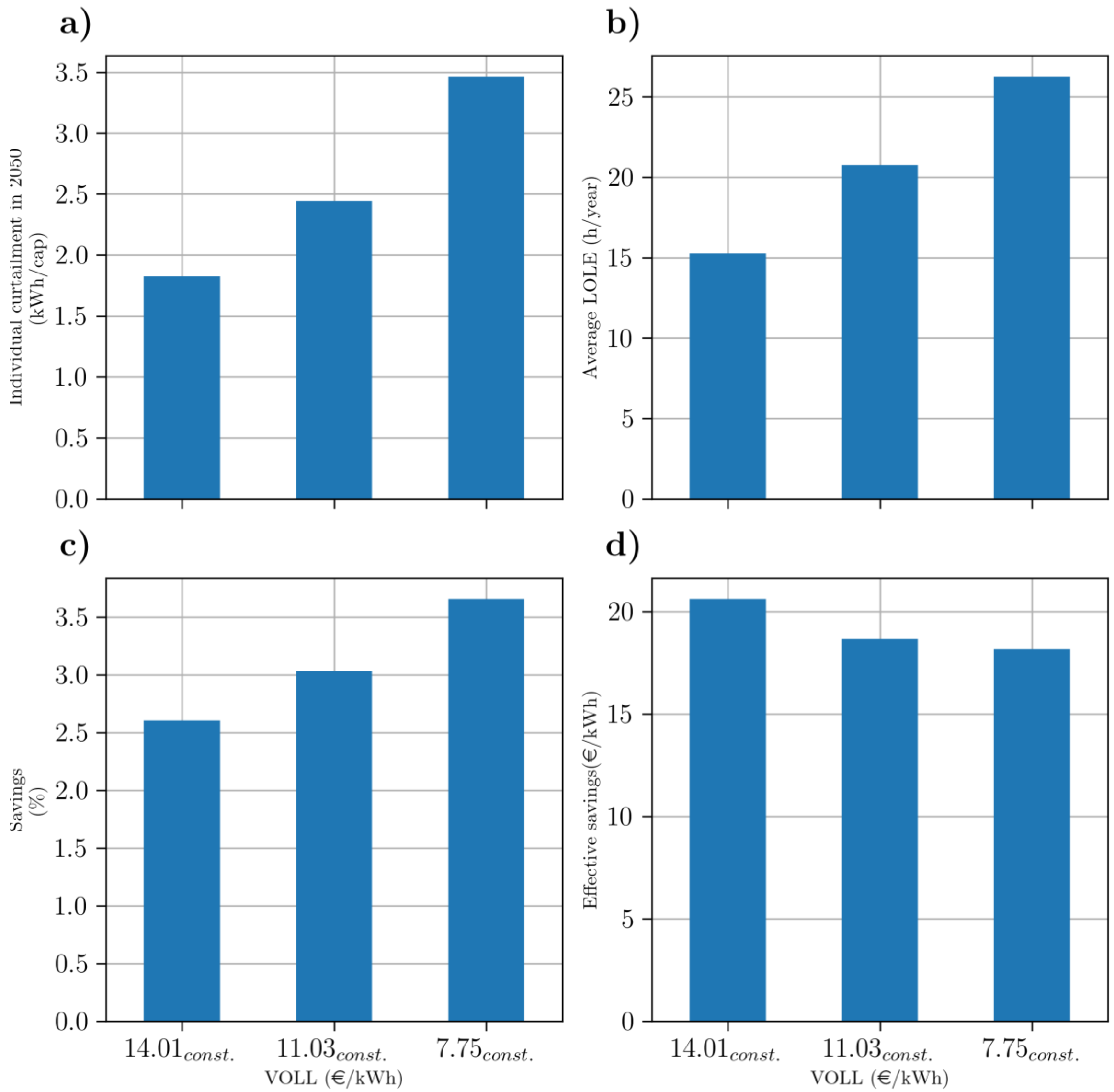
Source of cost savings pt.1 – sensitivity to chosen VOLL



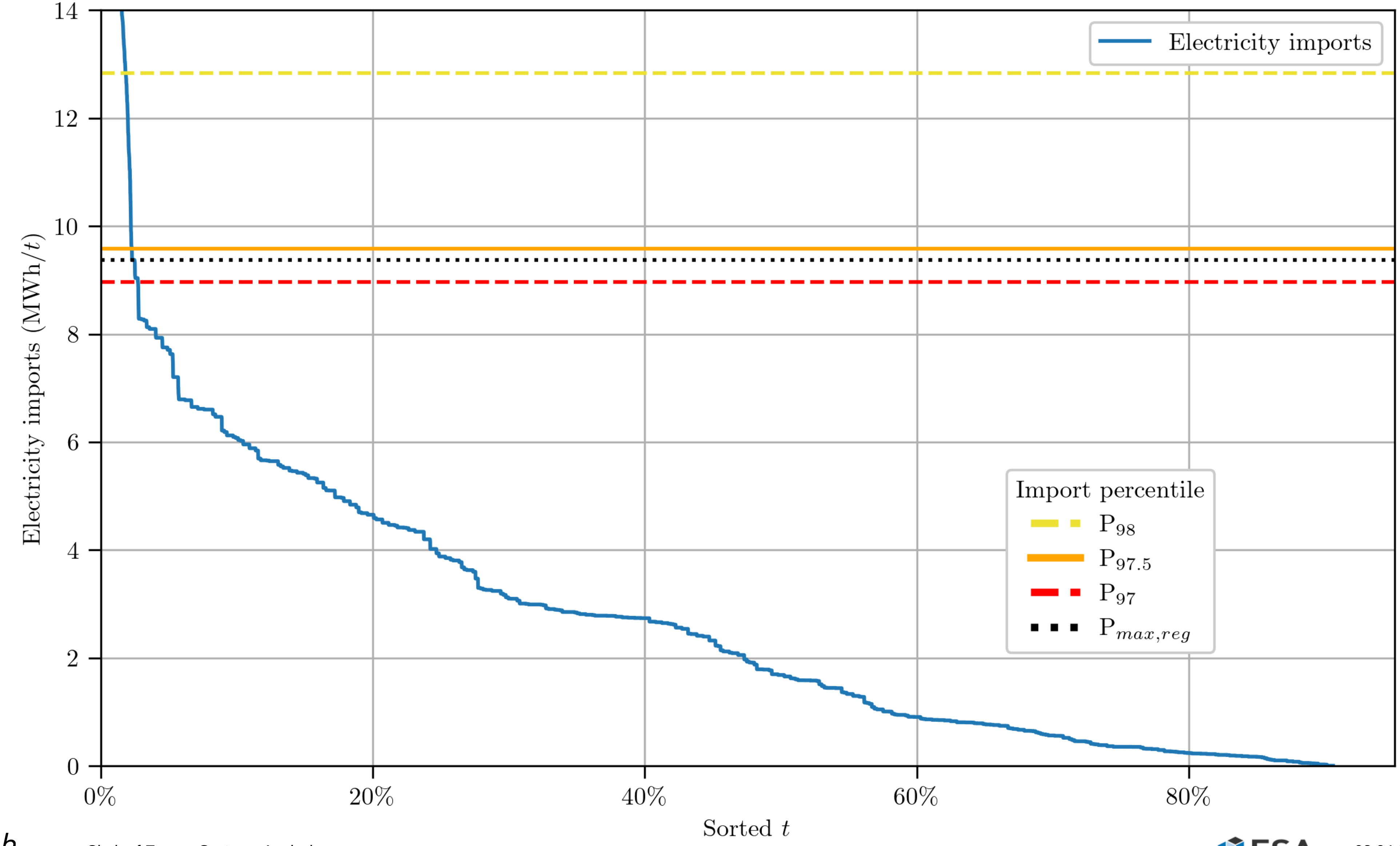
Source of cost savings pt. 2 – spatio-temporal differences



Impact of regional differences on cost and supply security



Deriving transmission constraints



Trade-off between system cost and security of supply

- Doubling LOLE reduces costs by 1% for regions with a lower VOLL
- Even at a VOLL of 0.55 €/kWh, load is only curtailed during power shortages (but during 70% of those)

→ Load curtailment during power shortages lowers cost, regional differences with minimal impact