ENSYS Digitaler Wandel in Energiesystemen

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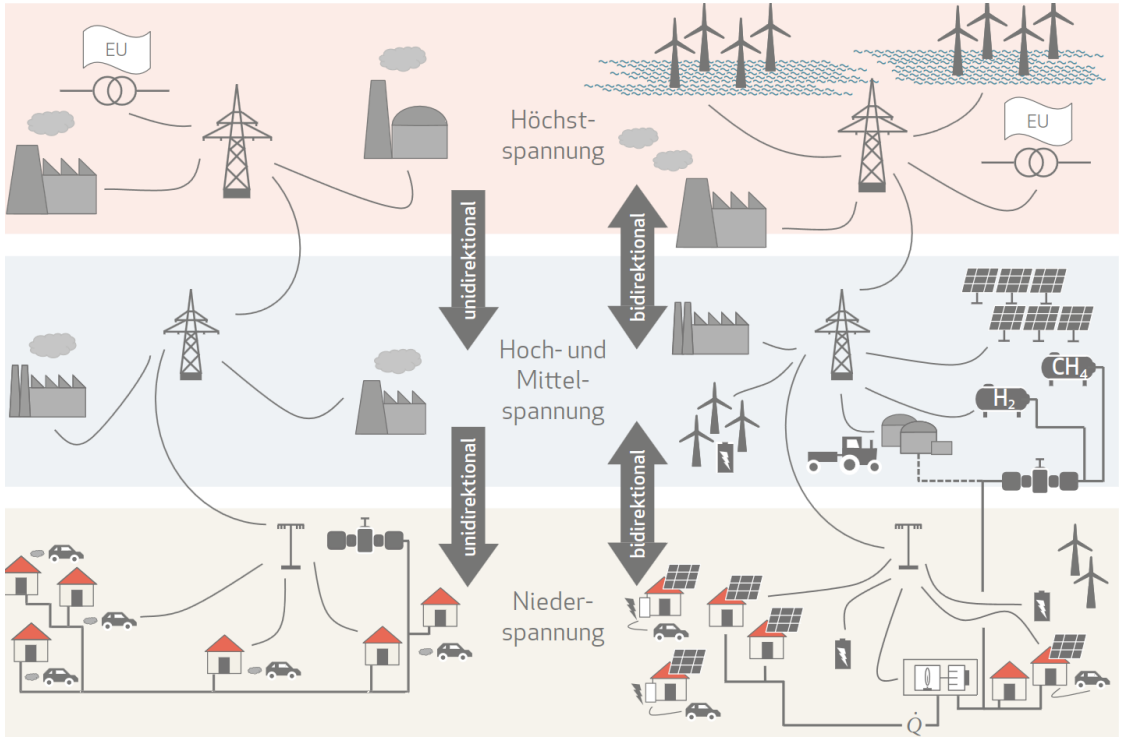
Evaluating the load-balancing potential for the energy system provided through distribution grid flexibilities

Julian Endres | Thesis Presentation | 26. April 2023

Outline

1. Motivation
2. Research Questions
3. Grid Topologies
4. Methodology
5. Results
6. Comparison
7. Conclusion

Sector coupling requires grid expansion



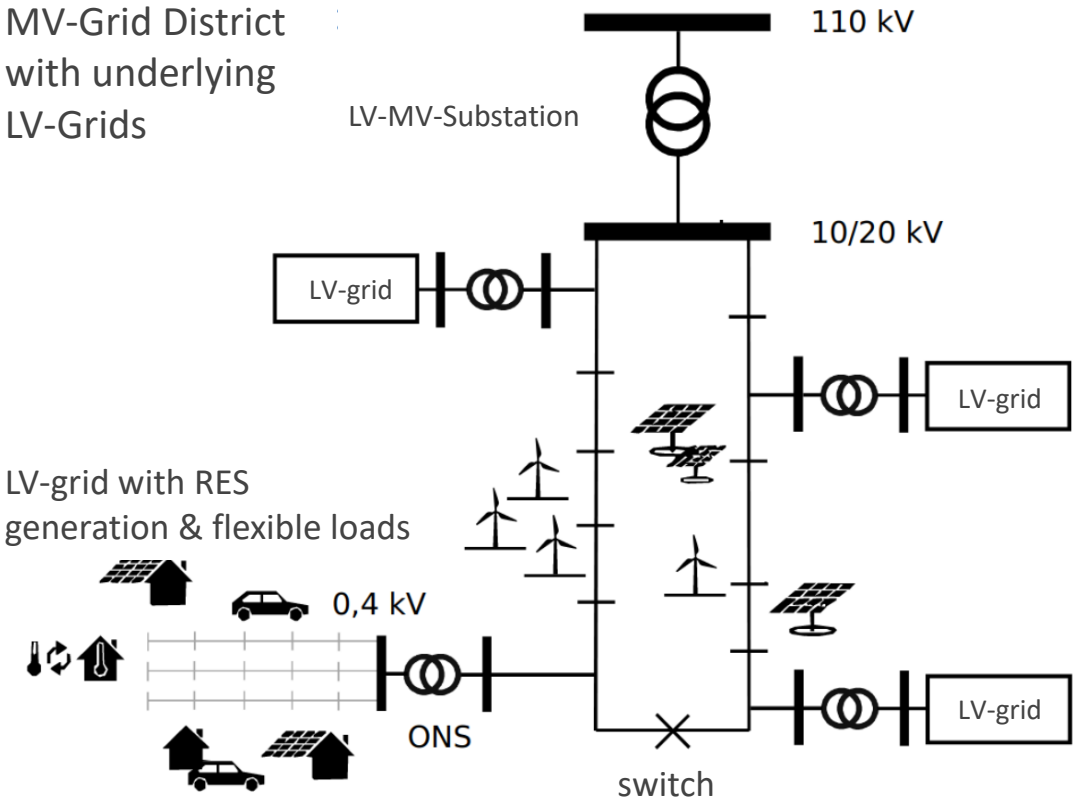
[BBH]

- Decarbonization through electrification of all sectors (sector coupling)
- Increased power demand by “new consumers”
- More renewable generation
- Reinforcement necessary in distribution grids
- Storage capacity makes battery electric vehicle (BEV) and heat pump (HP) operation more flexible

Can temporal flexibilities be used to reduce the demand of spatial flexibility?

The interplay of spatial and temporal flexibility

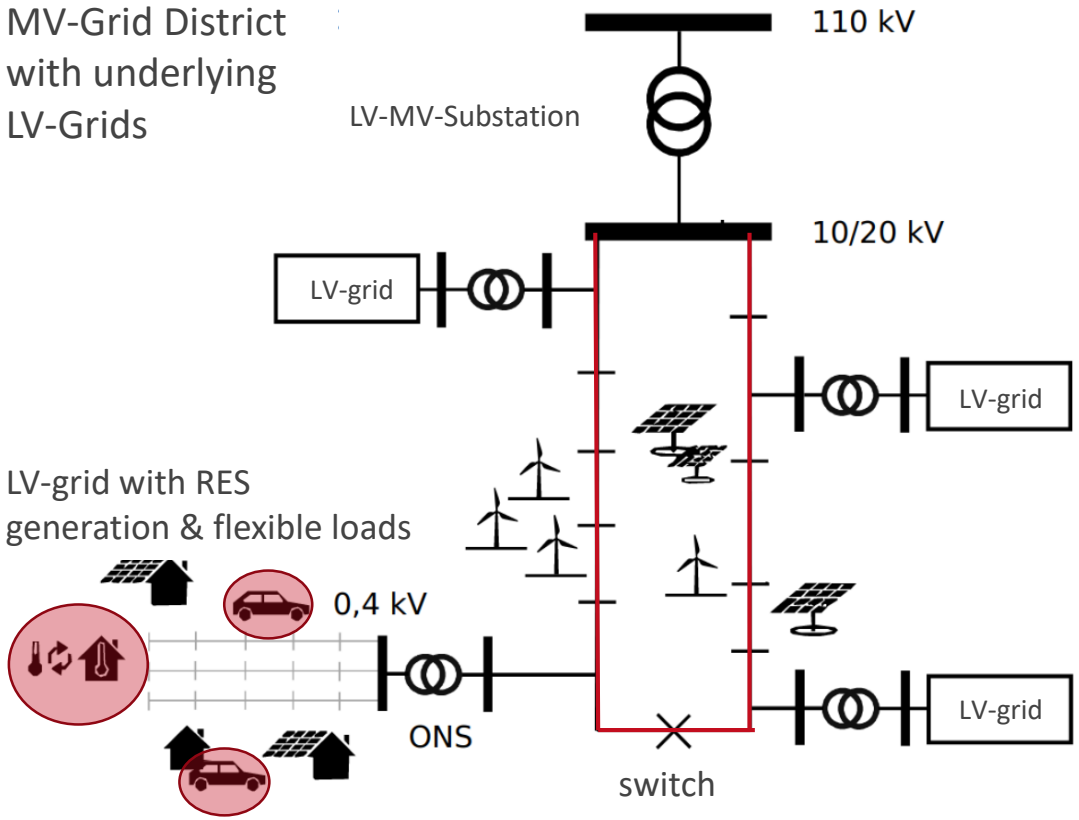
MV-Grid District with underlying LV-Grids



[BEA]

The interplay of spatial and temporal flexibility

MV-Grid District with underlying LV-Grids



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1. What is the minimum required reinforcement in distribution grids using flexible demand units?

The interplay of spatial and temporal flexibility

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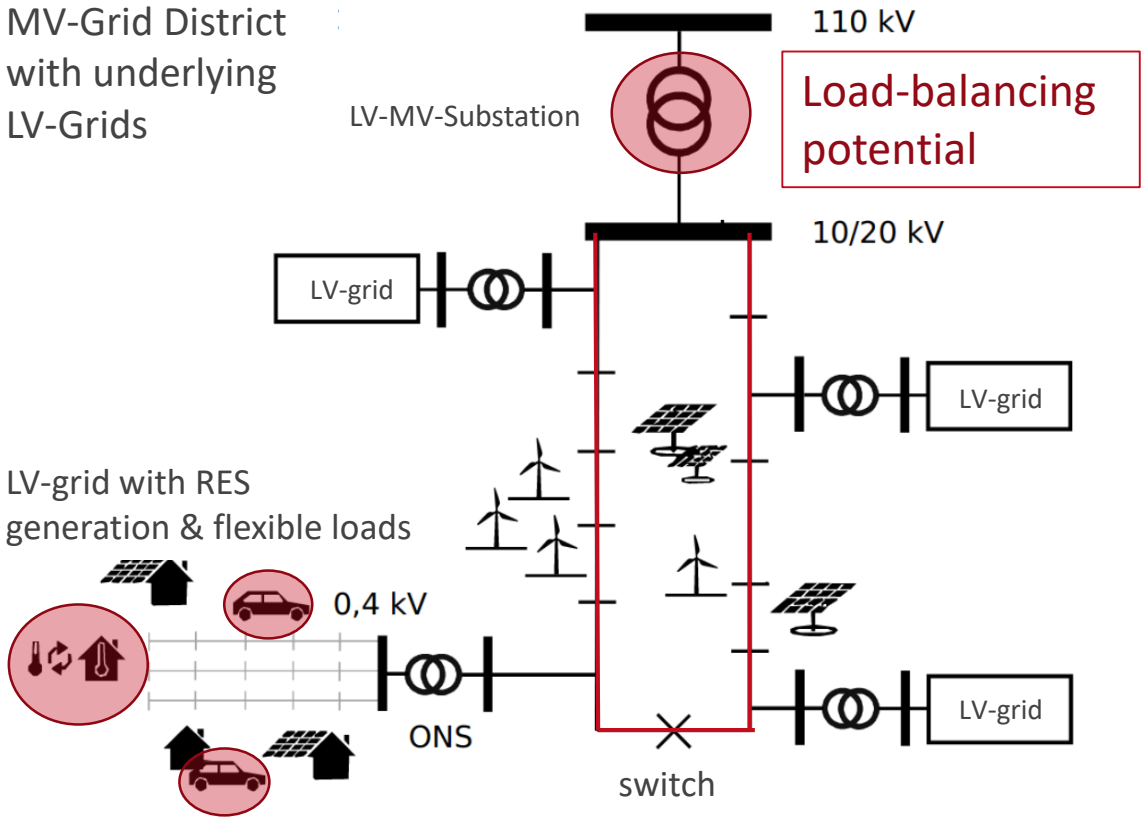

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1. What is the minimal required reinforcement in distribution grids using flexible demand units?

2. Which flexibility potential can be provided to the overlying grid levels?

The interplay of spatial and temporal flexibility

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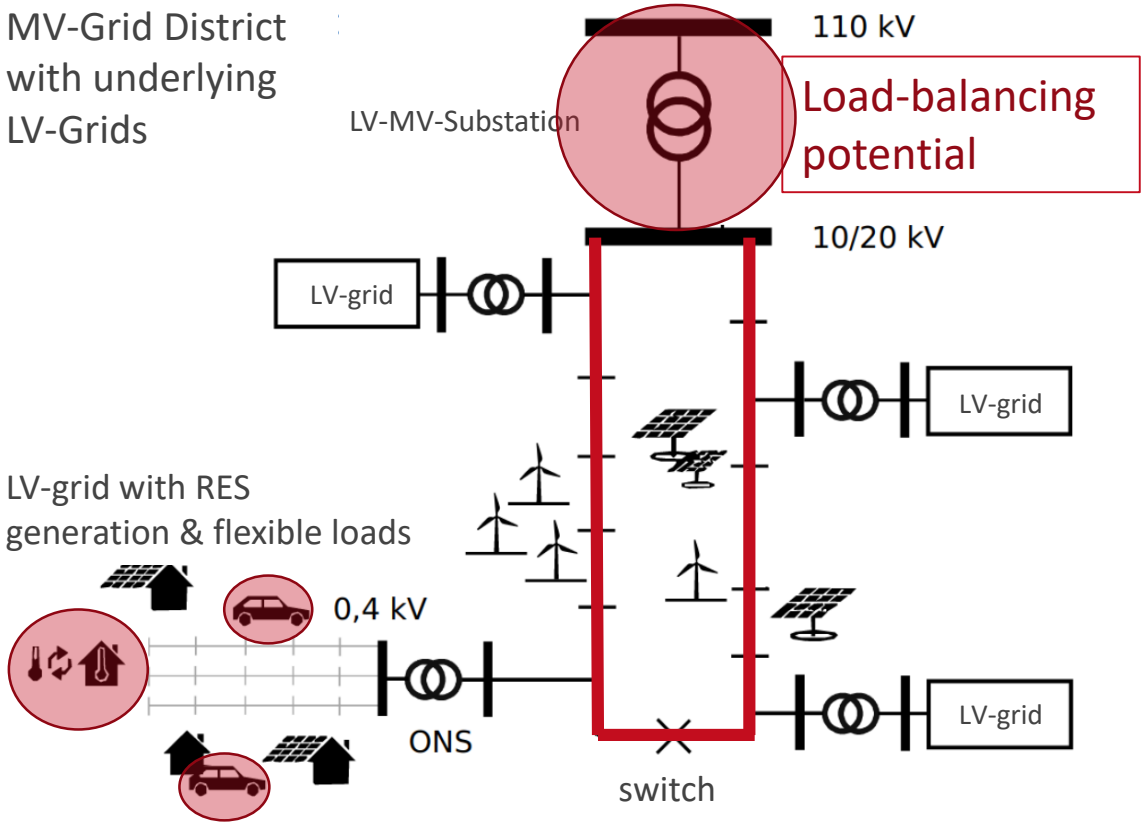

[BEA]

1. What is the minimum required reinforcement in distribution grids using flexible demand units?

2. Which flexibility potential can be provided to the overlying grid levels?

3. How does the provided flexibility potential increase with additional reinforcement?

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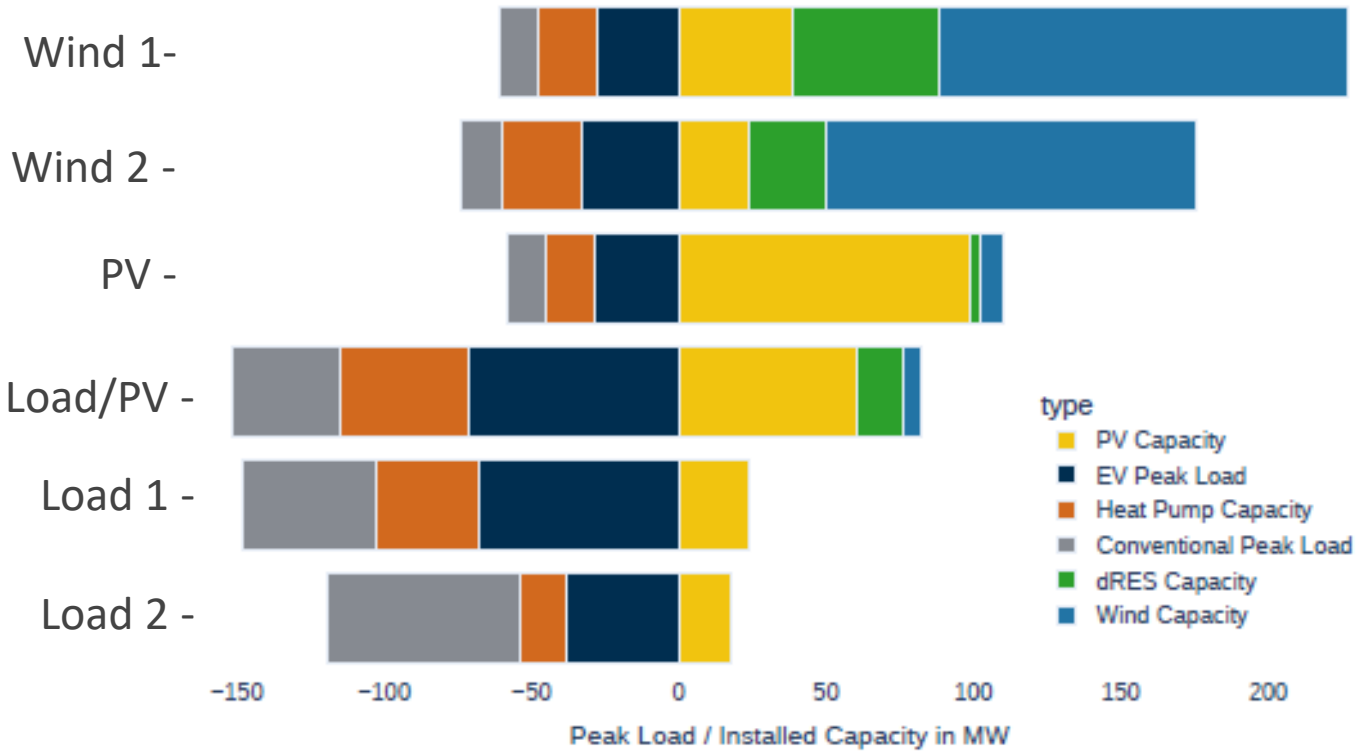
Grid Topologies

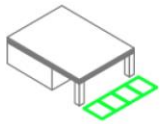
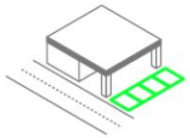
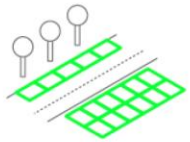
We analyzed heterogeneous grid topologies



- Synthetic distribution grids
- Selected by k-means clustering
- Representative for all rural and suburban Germany
- BEV/HP penetration follow NEP 2035 C

Source	Total	Unit
Wind Onshore	98.4	GW
Wind Offshore	27.8	GW
Photovoltaic	97.8	GW
Biomass	27.8	GW
Hydropower	3.2	GW

Home and work charging is assumed to be flexible

Installation location	Private space			Publicly accessible space			
Charging use case	Home		Work	Charging hub		Public	
Typical locations for charging infrastructure	 Garage or private parking space at home	 Parking spaces (e.g. in residential areas, multi-family houses, apartment blocks)	 Company parking on own site	 Charging station/ charging hub in town	 Charging station/ charging hub on road axes	 Customer parking spaces or multi-storey car parks (e.g. shopping malls)	 Road side, public parking spaces
Typical charging capacity (kW)	Up to 11	Up to 11	Up to 22	Up to 150	Up to 350	Up to 50	Up to 22
Average standing time	Overnight	Overnight	7 hours	10 - 20 minutes	15 - 30 minutes	30 - 90 minutes	15 minutes up to 14 hours
Destination	Home		Work	Fast charging event		Business, School, Shopping, Private/Ridesharing, Leisure	

Characteristics of different charging use cases [BEV]

Home and work charging is assumed to be flexible

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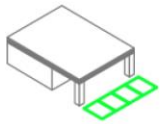
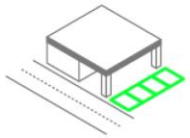
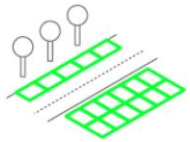
Typical locations for charging infrastructure	 Garage or private parking space at home	 Parking spaces (e.g. in residential areas, multi-family houses, apartment blocks)	 Company parking on own site	 Charging station/ charging hub in town	 Charging station/ charging hub on road axes	 Customer parking spaces or multi-storey car parks (e.g. shopping malls)	 Road side, public parking spaces
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Methodology

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Observation periods

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Observation periods

- Reinforcement
- Flexibility potential

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Observation periods

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- Flexibility potential

Minimal reinforcement

Methodology

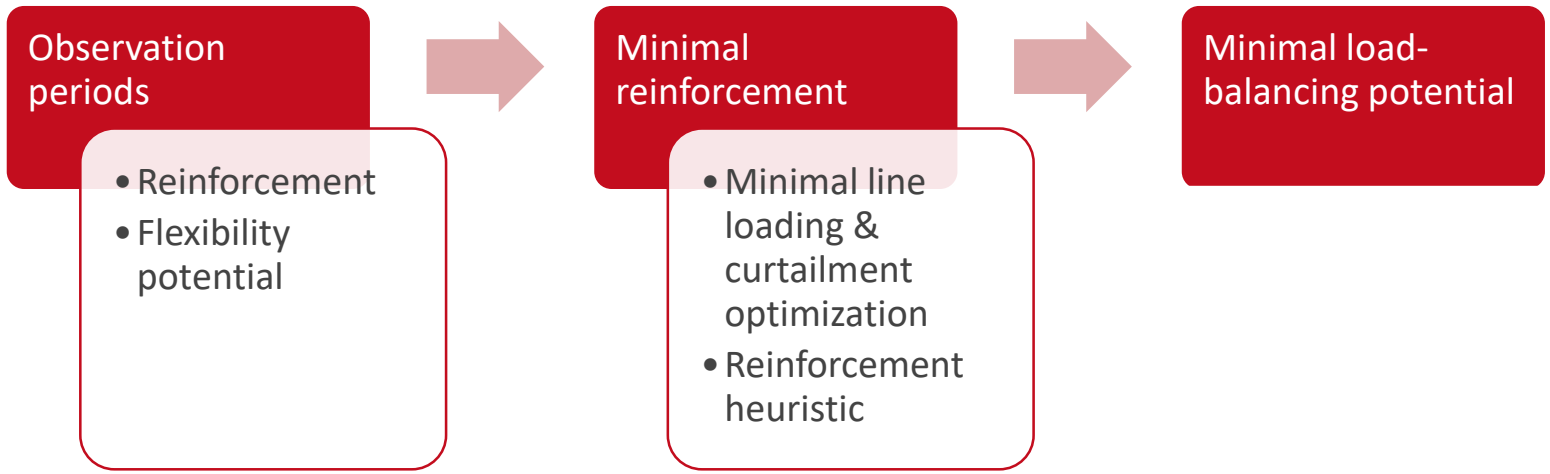
Observation periods

- Reinforcement
- Flexibility potential

Minimal reinforcement

- Minimal line loading & curtailment optimization
- Reinforcement heuristic

Methodology



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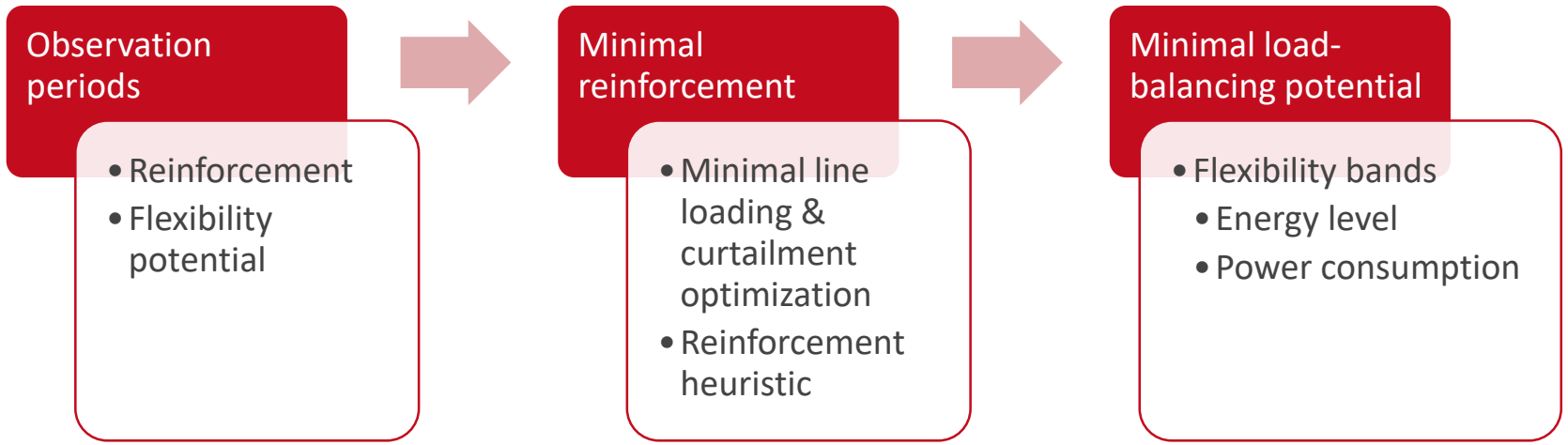

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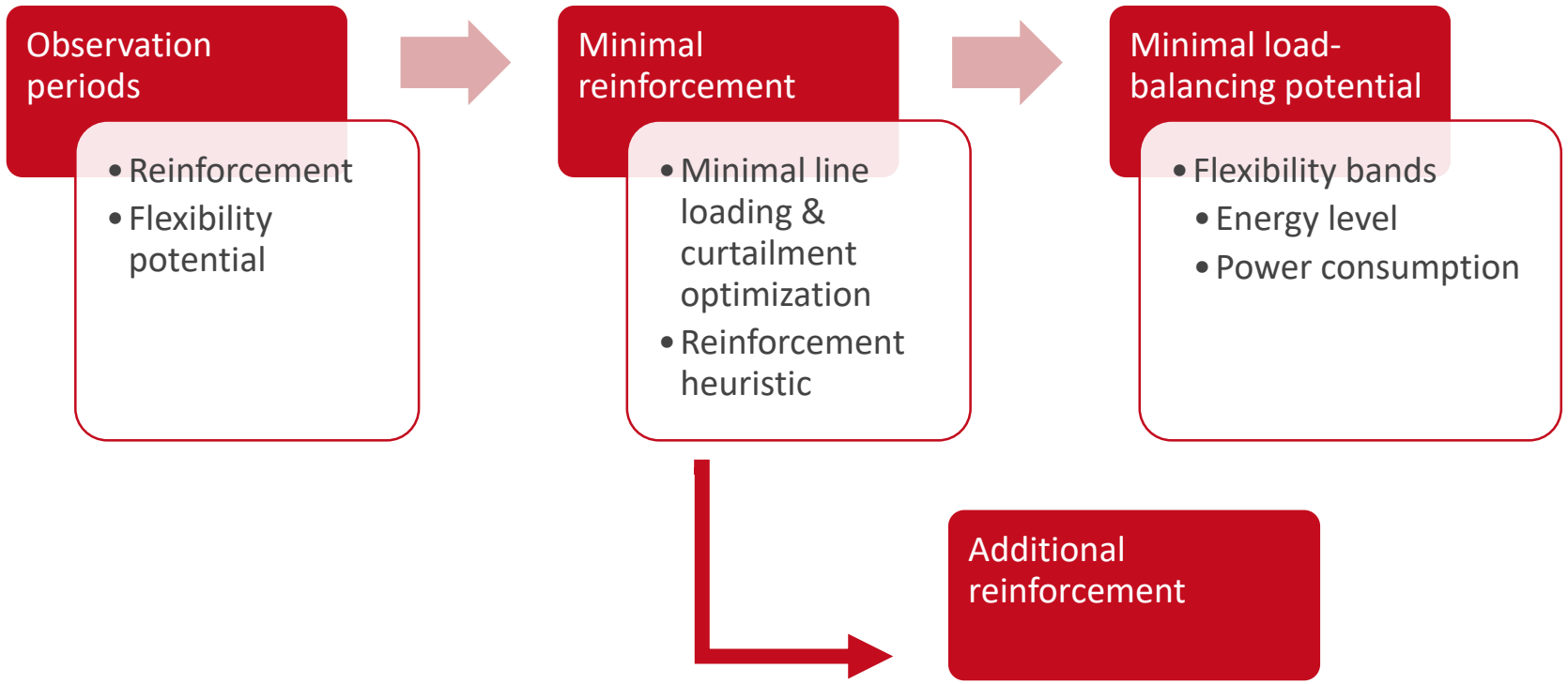

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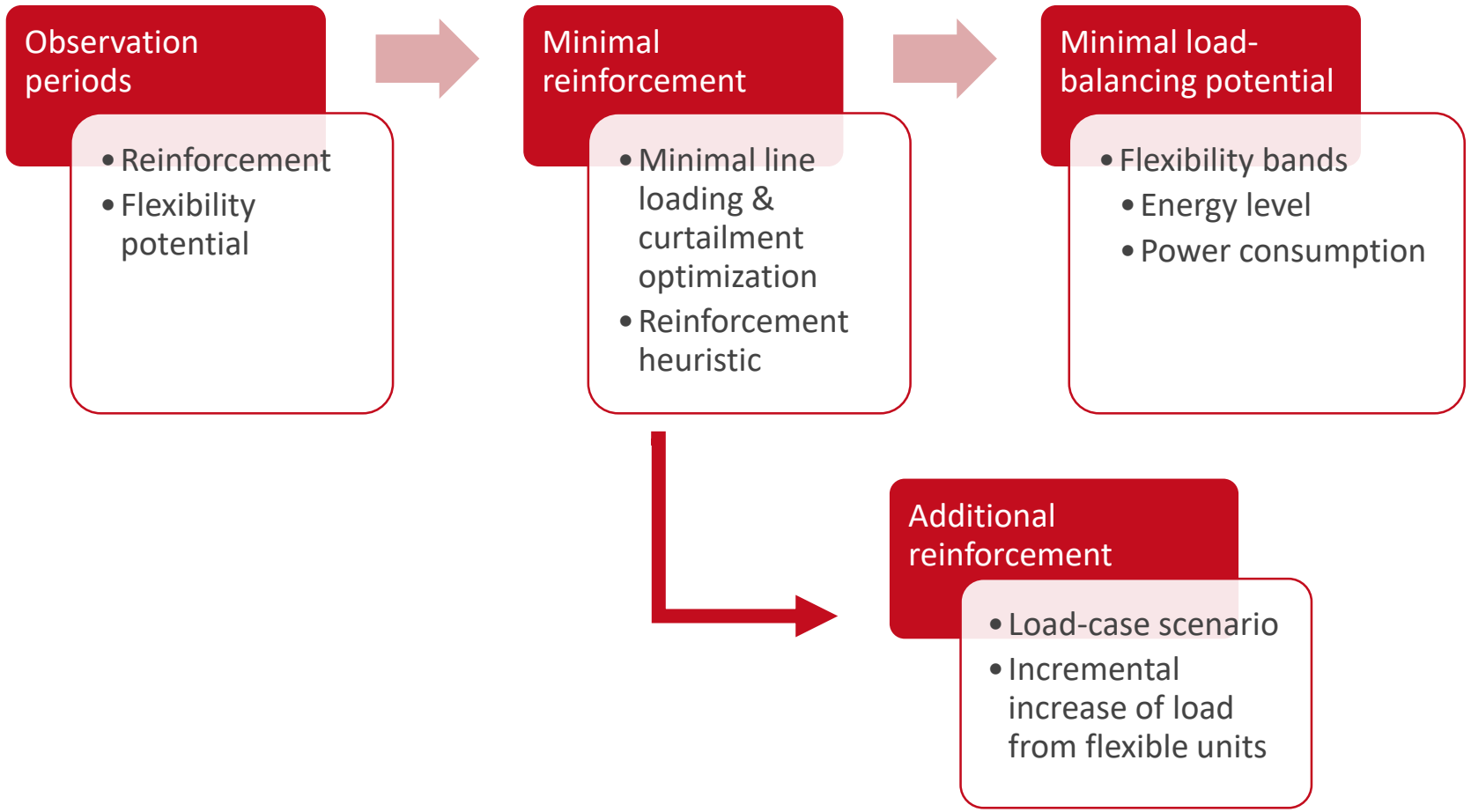

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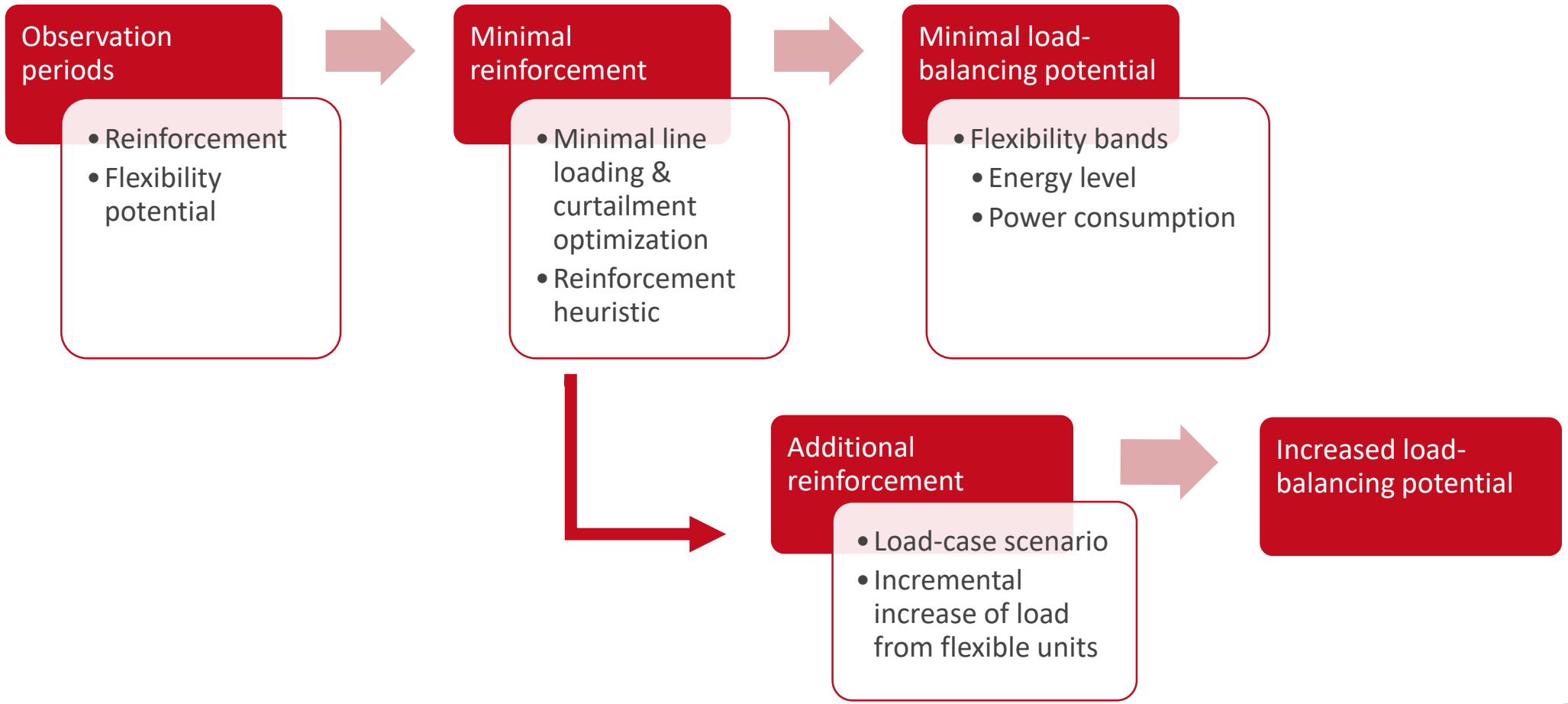

Scenarios build on each other

Name	Based on
Reference	no flexible charging
Minimal reinforcement	optimized dispatch
20 % flex load	1h load case
40 % flex load	1h load case
60 % flex load	1h load case
80 % flex load	1h load case
100 % flex load	1h load case

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Scenarios build on each other

Name	Based on
Reference	no battery/thermal storage
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20 % flex load	1h load case
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Results

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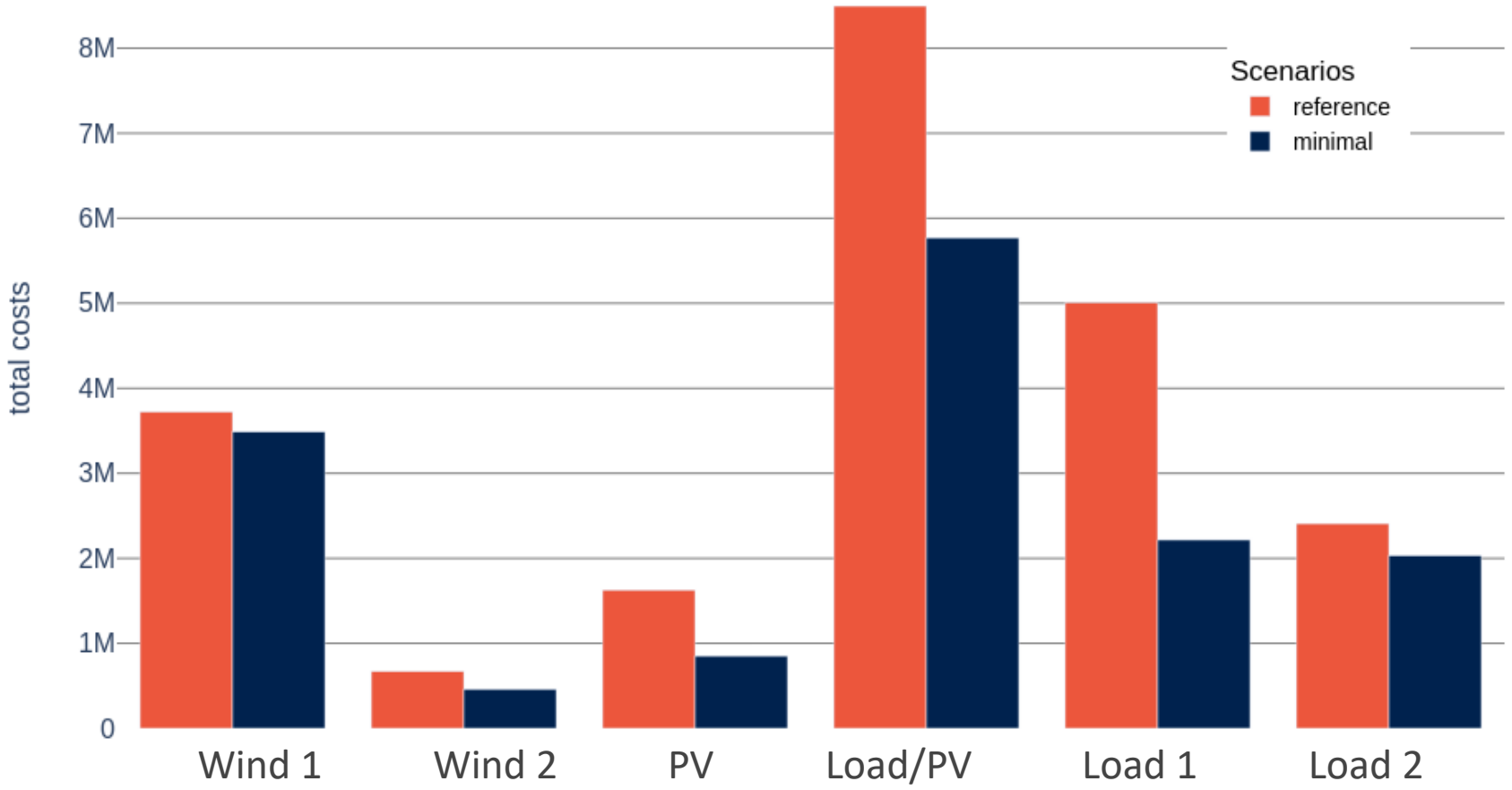
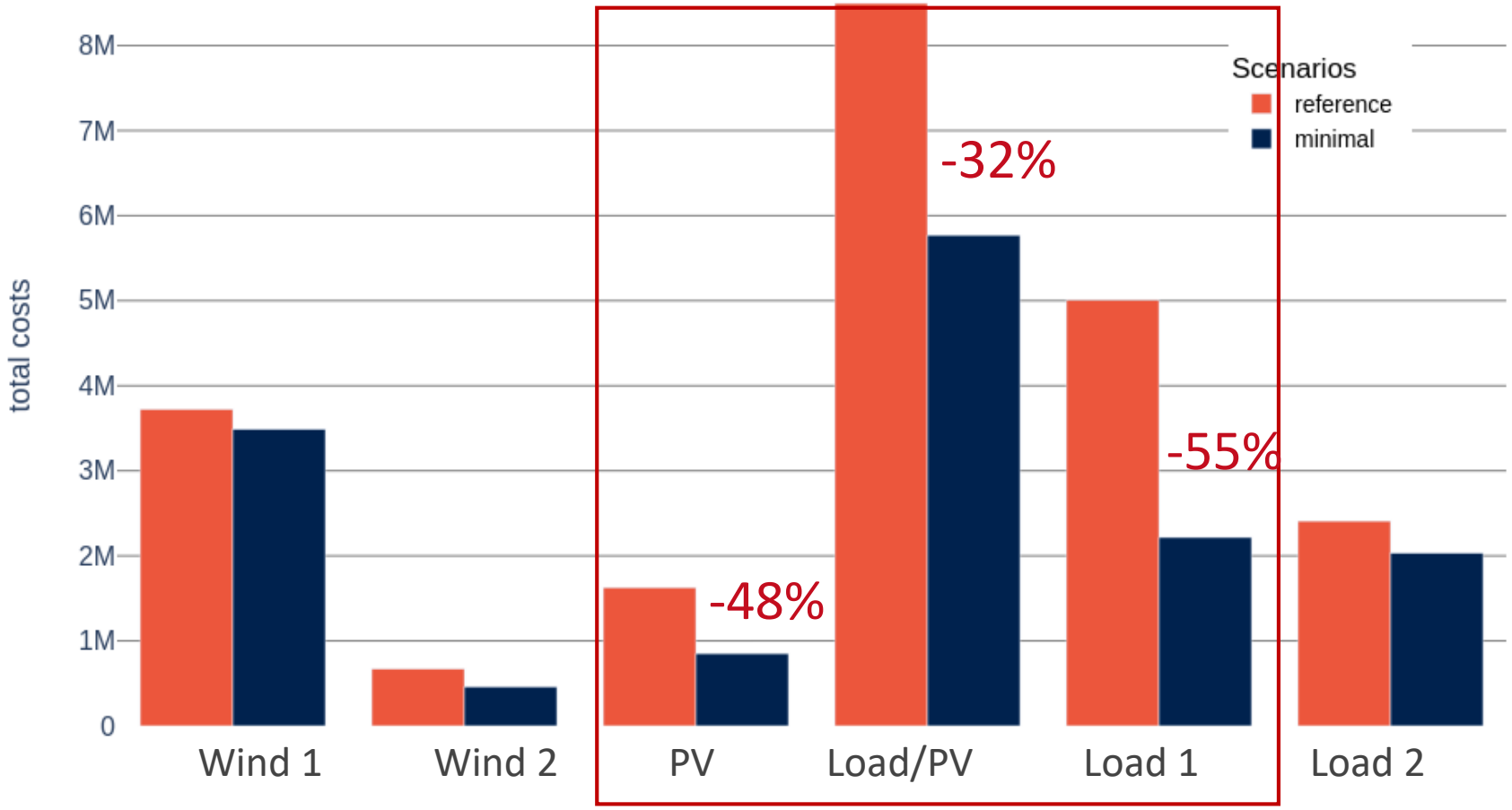
Research Question 1:

What is the minimal required reinforcement?

Flexible operation strategies reduce reinforcement demand



Flexible operation strategies reduce reinforcement demand



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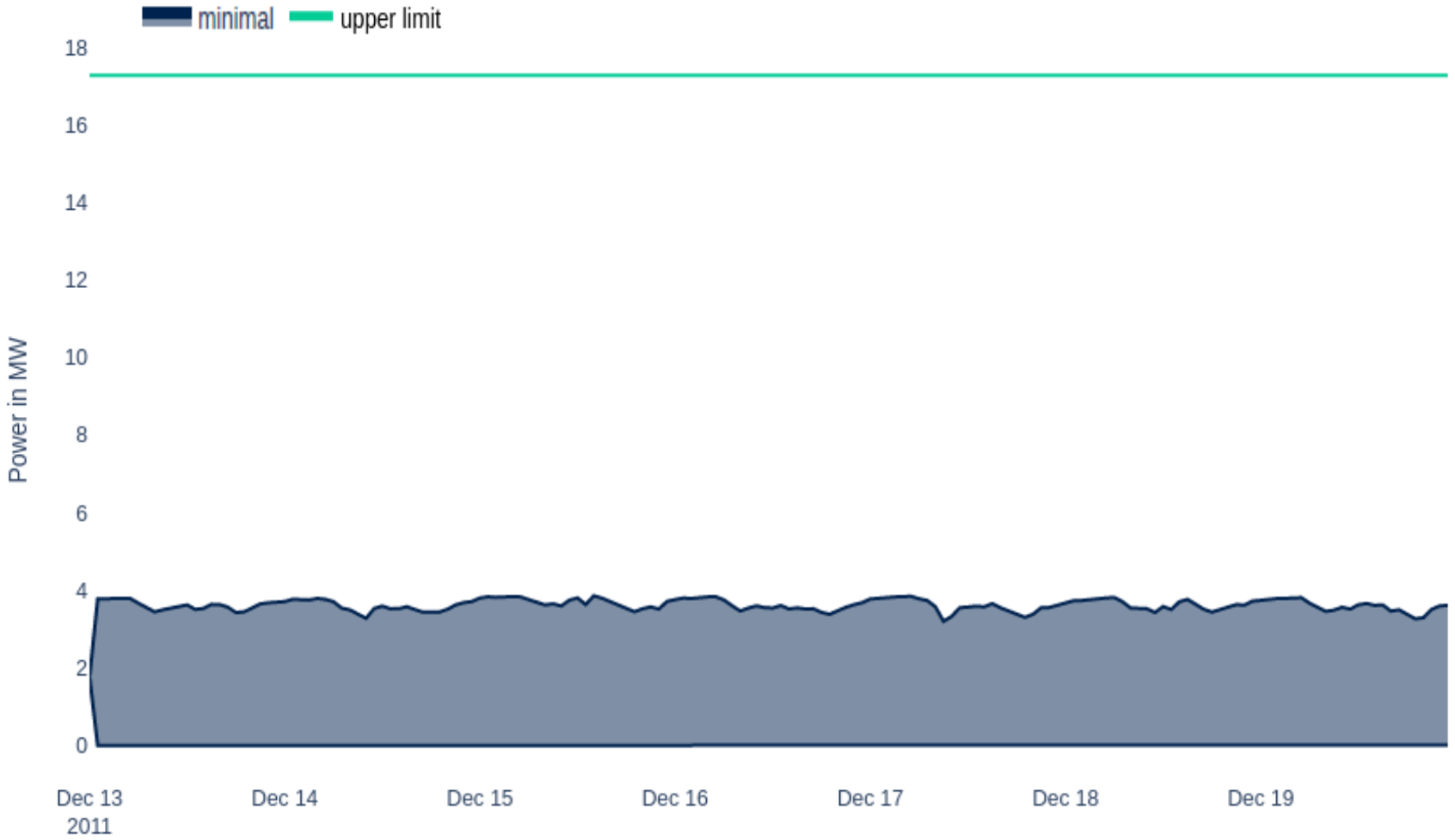
Research Question 2:

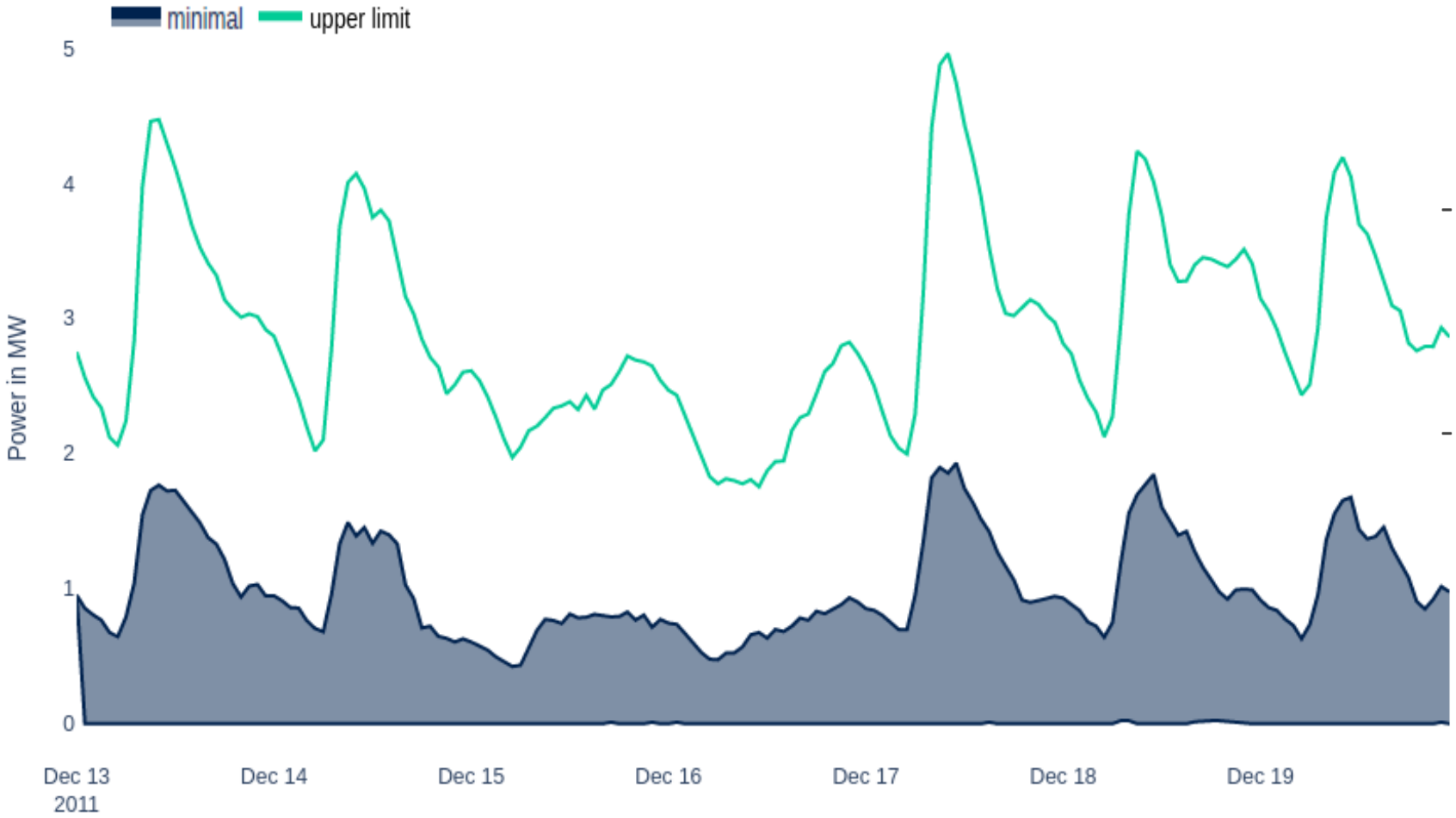
Which flexibility potential can be provided to the overlying grid levels?

A limited load balancing potential is available for HPs



- Flexibility band defines operational space of HP’s
- Only about ¼ of the installed capacity can be used due to grid constraints

Minimal Power Potential BEV



- Flexibility band defines operational space of BEV's
- About 1/2 of the available capacity can be used

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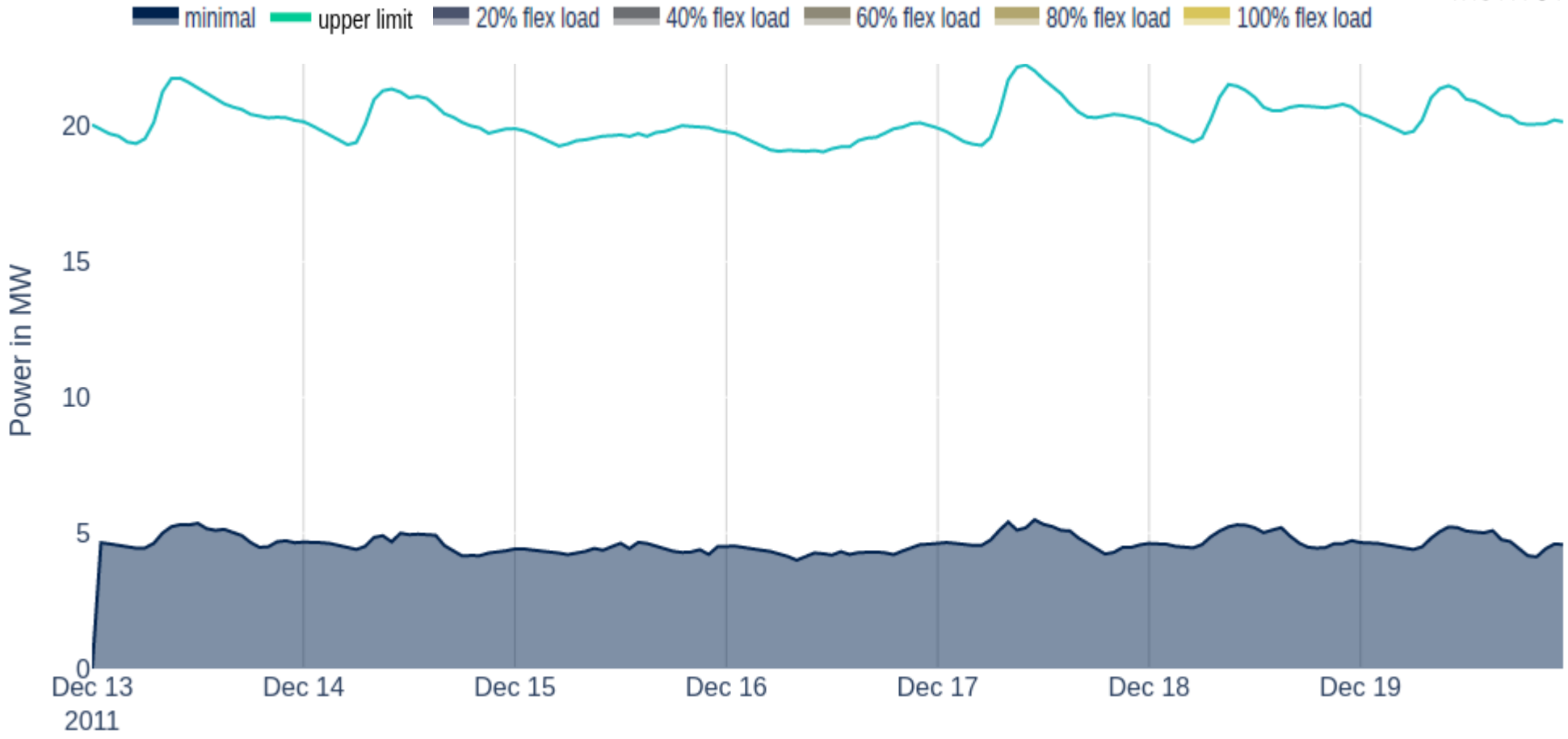
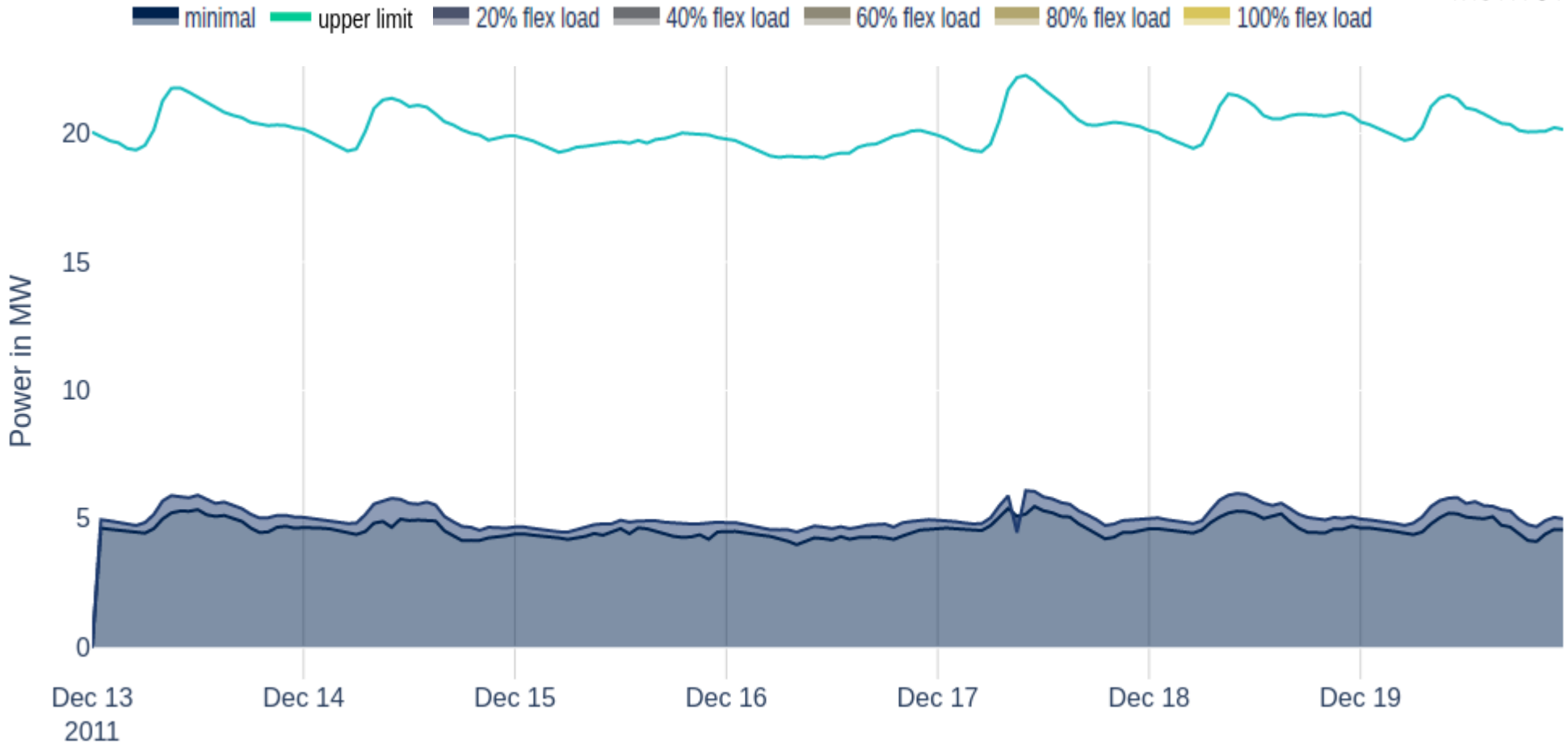
Research Question 3:

How does the provided flexibility potential increase with additional reinforcement?

Load Balancing Potential increases with reinforcement



Load Balancing Potential increases with reinforcement



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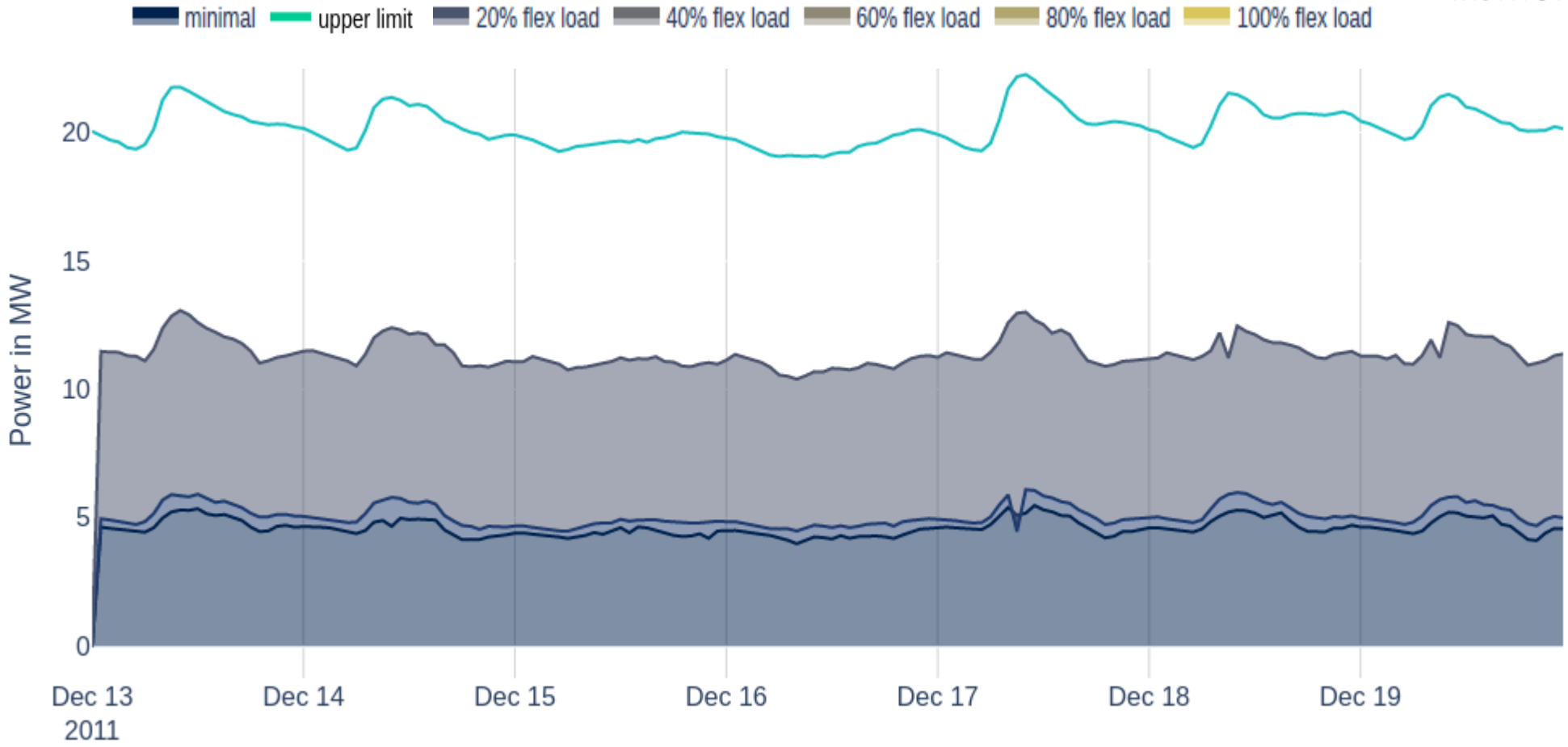

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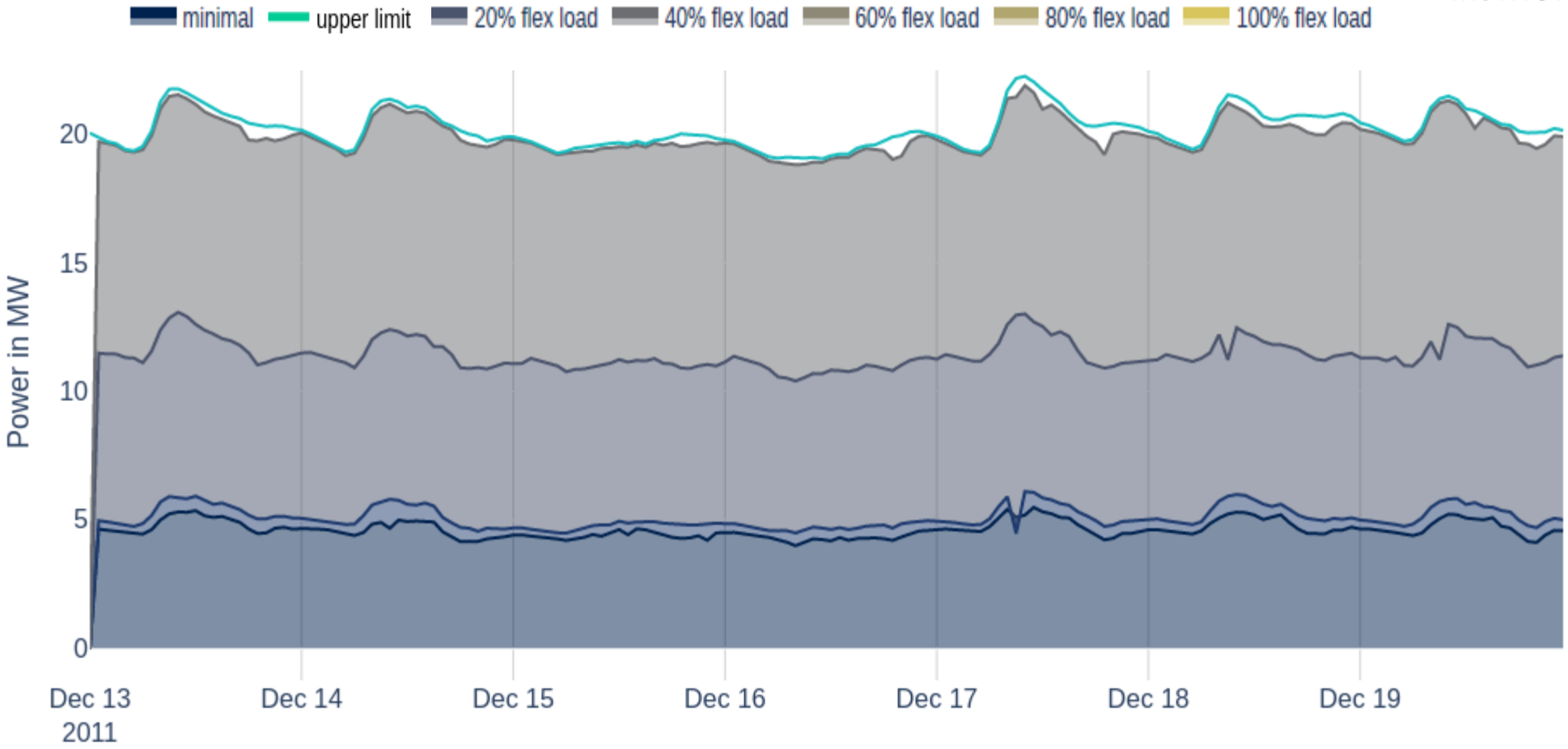

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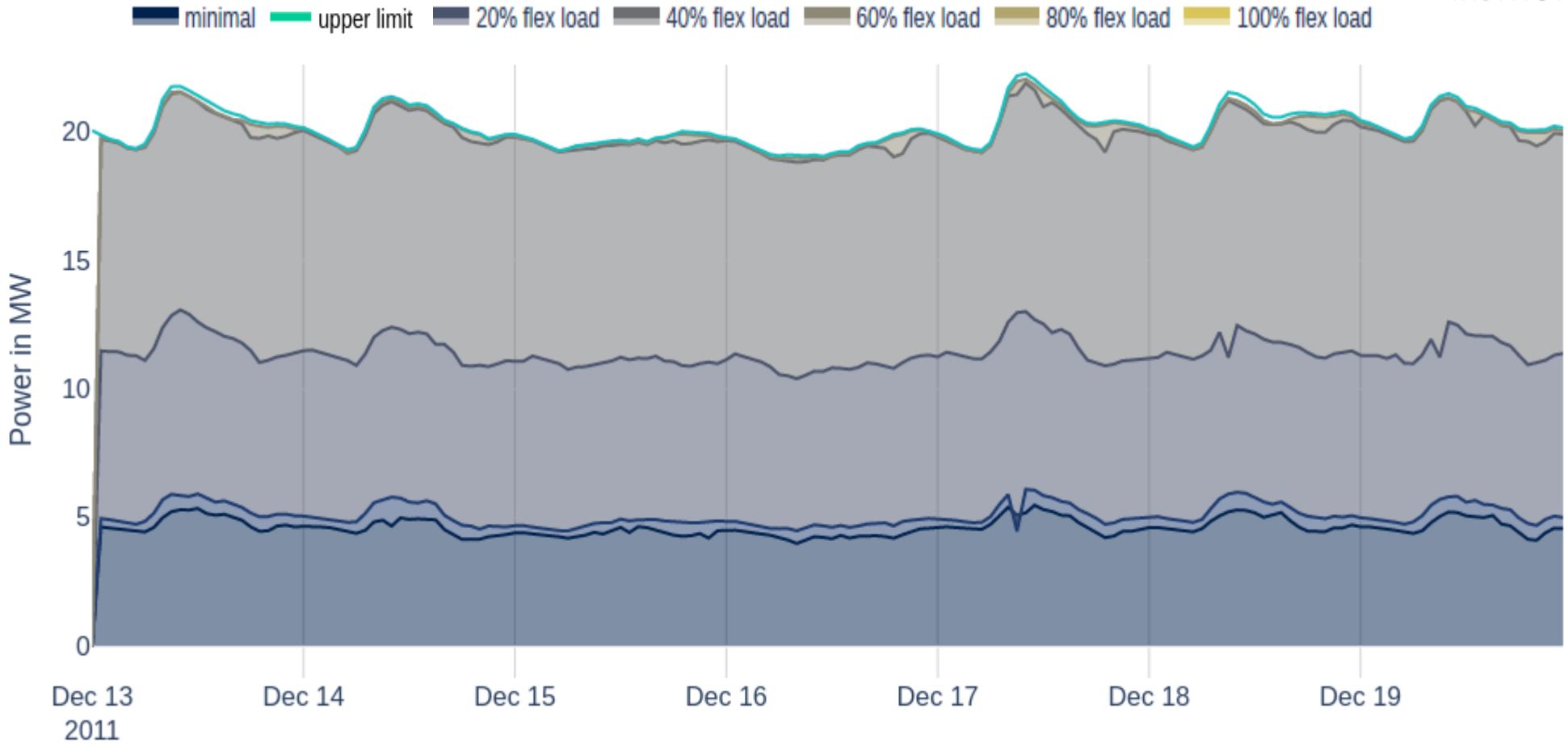
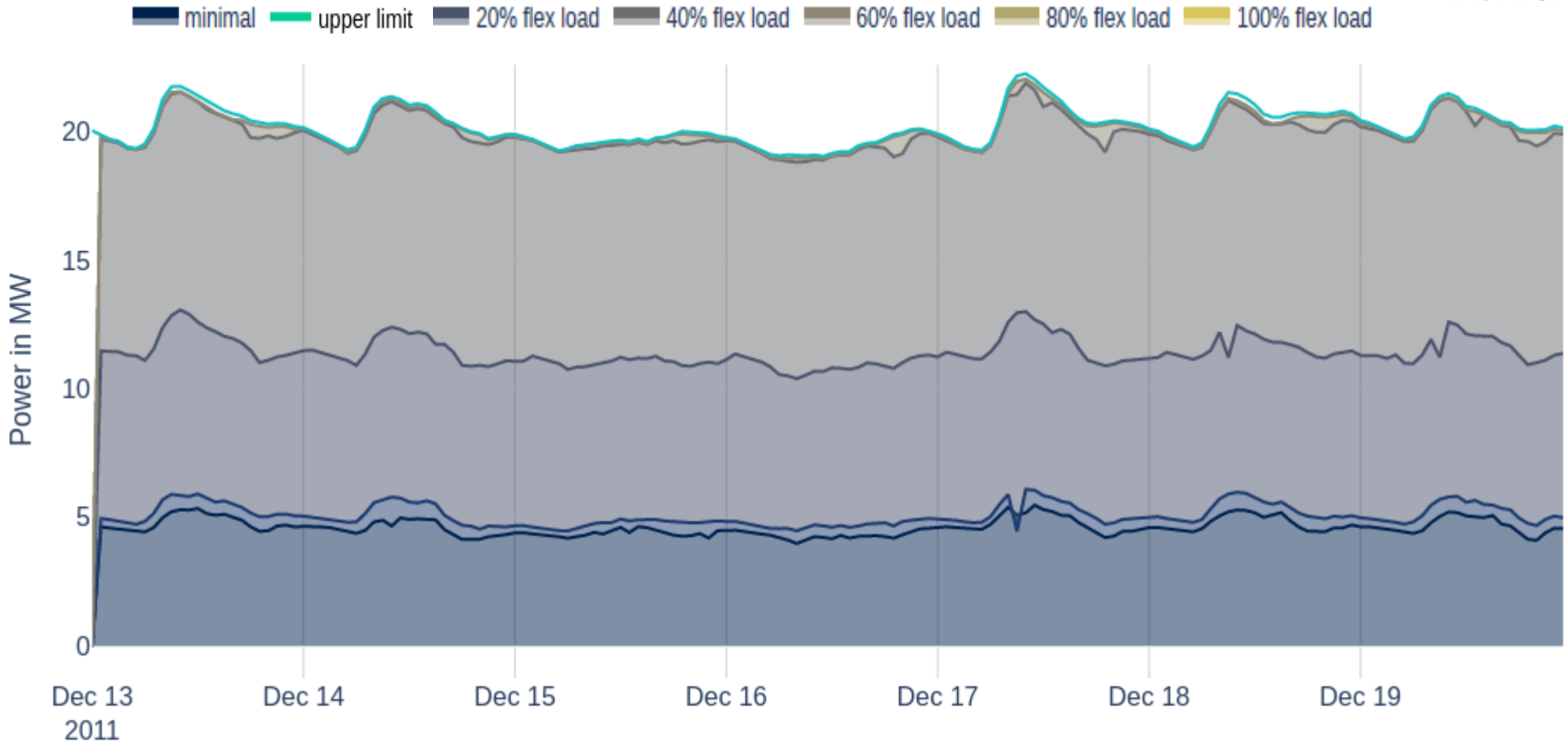


Load Balancing Potential increases with reinforcement



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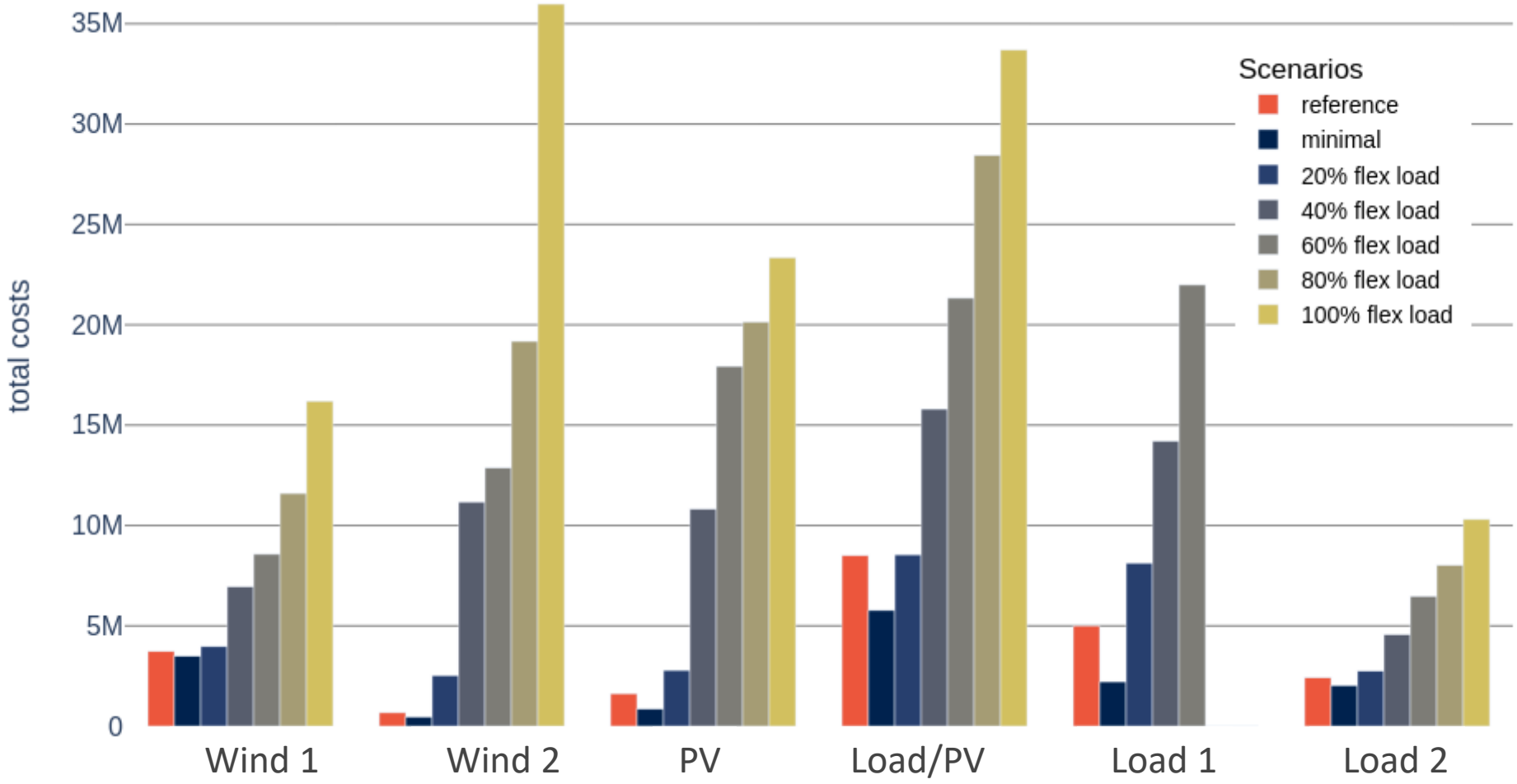
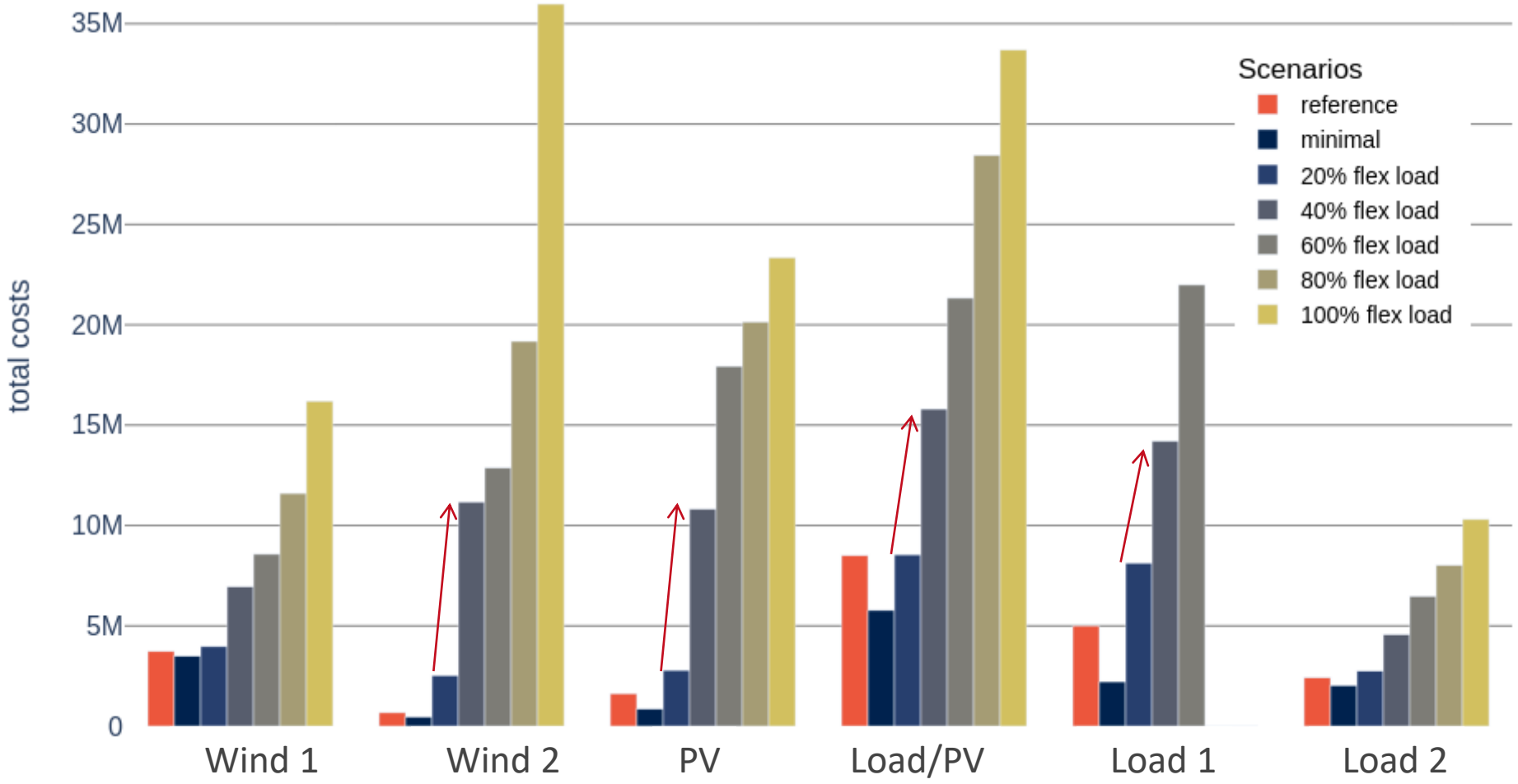
Grid Comparison

Strong cost increase with additional reinforcement



Strong cost increase with additional reinforcement



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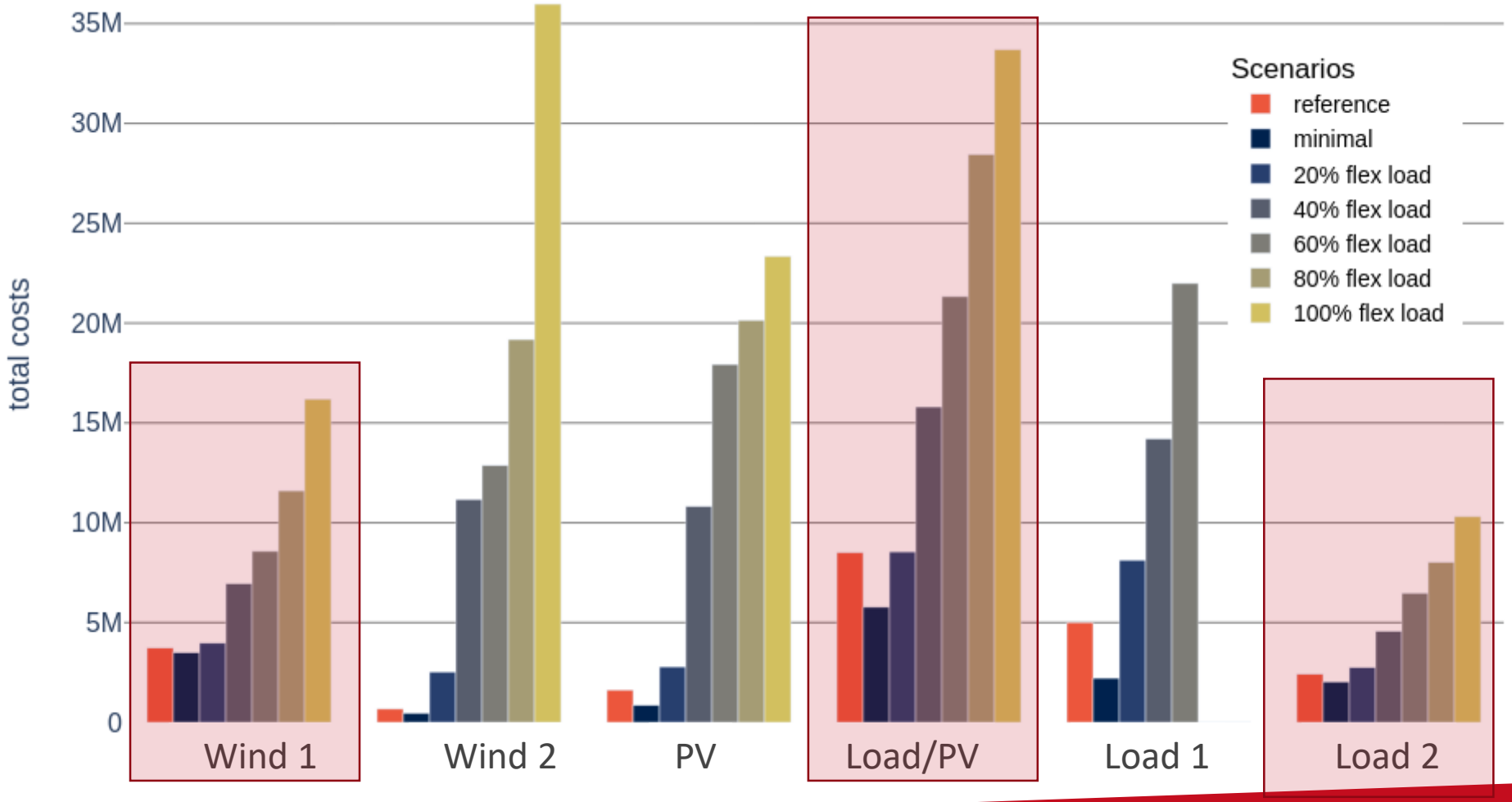
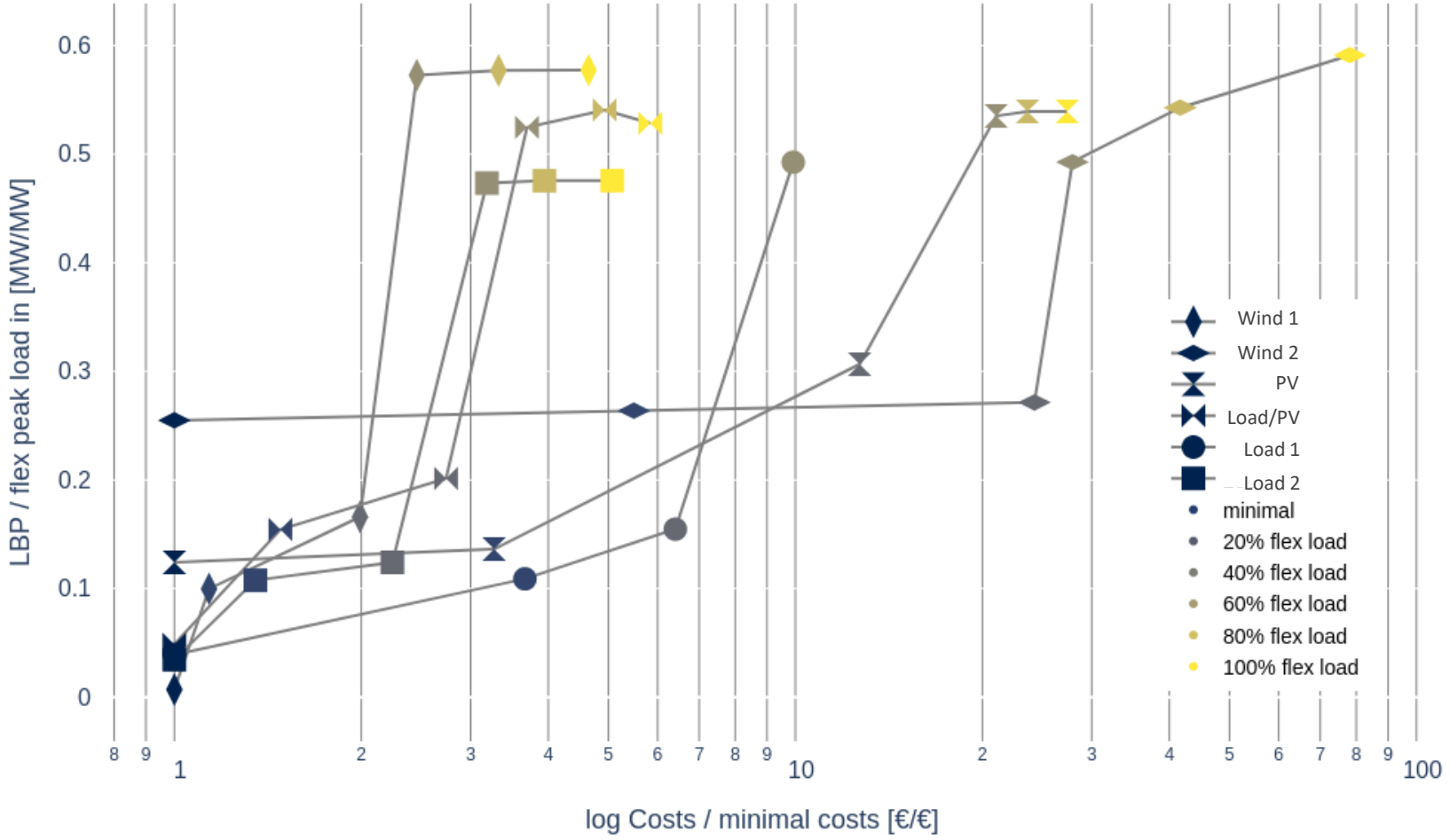
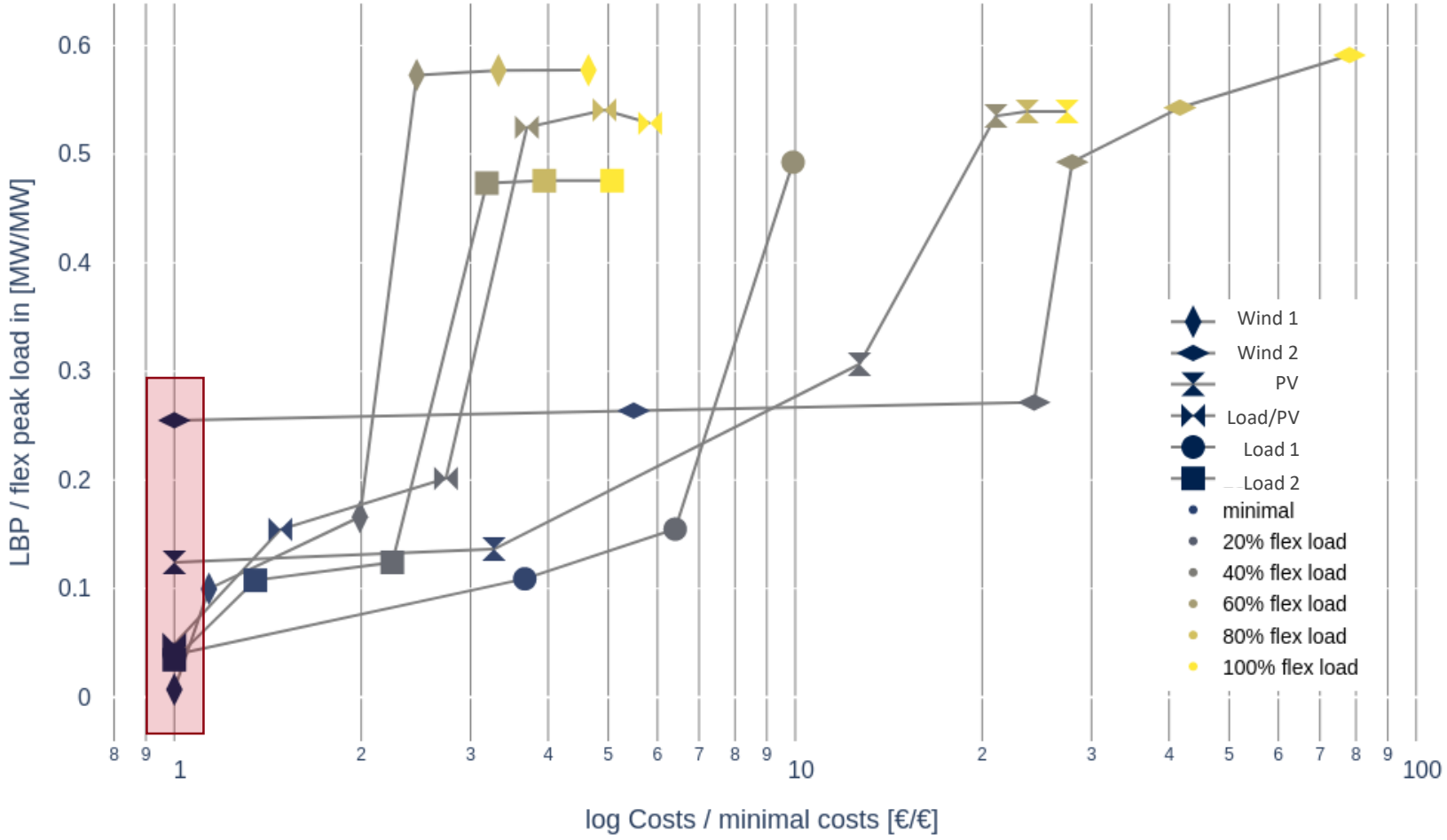


For half of the networks, the cost increase is within reasonable limits



For half of the networks, the cost increase is within reasonable limits



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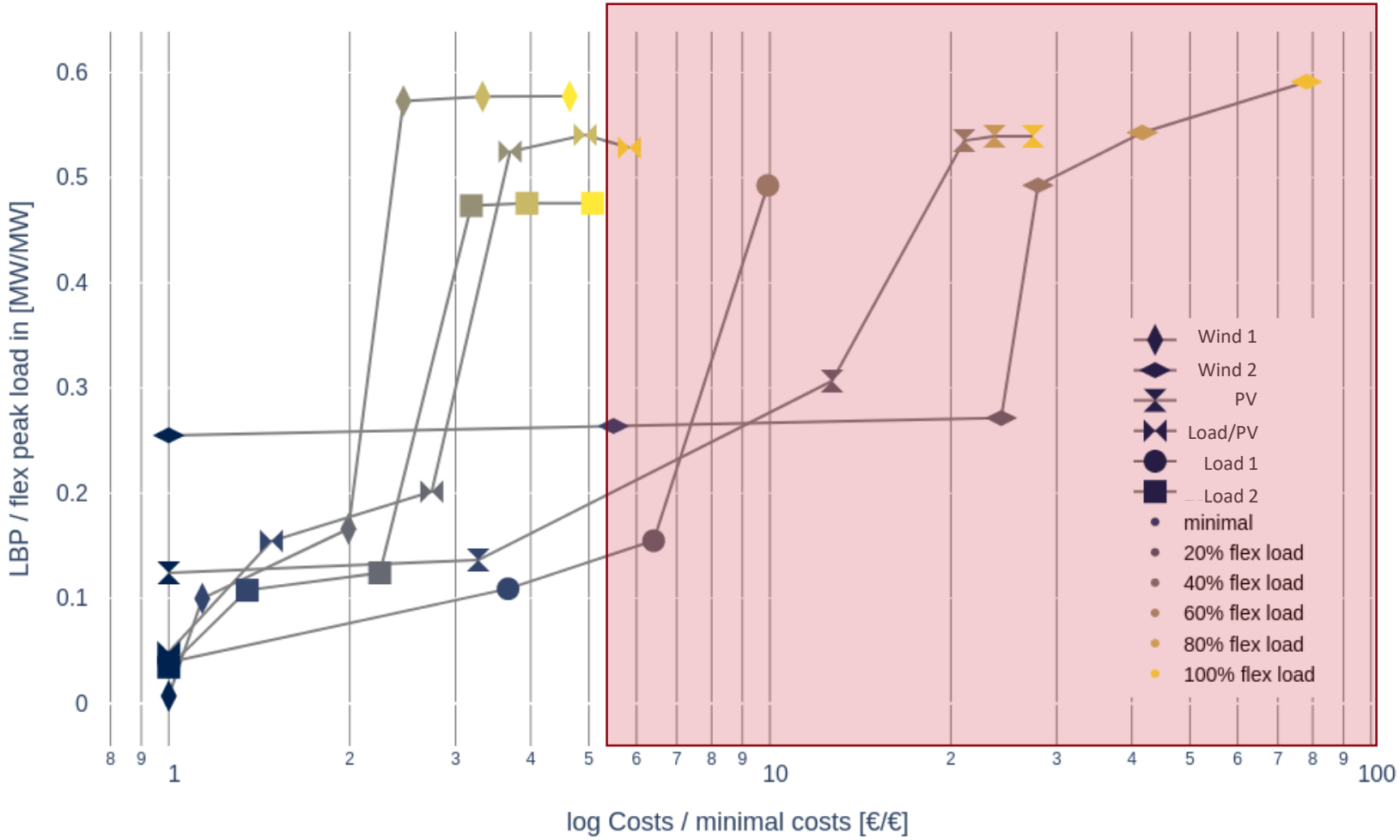

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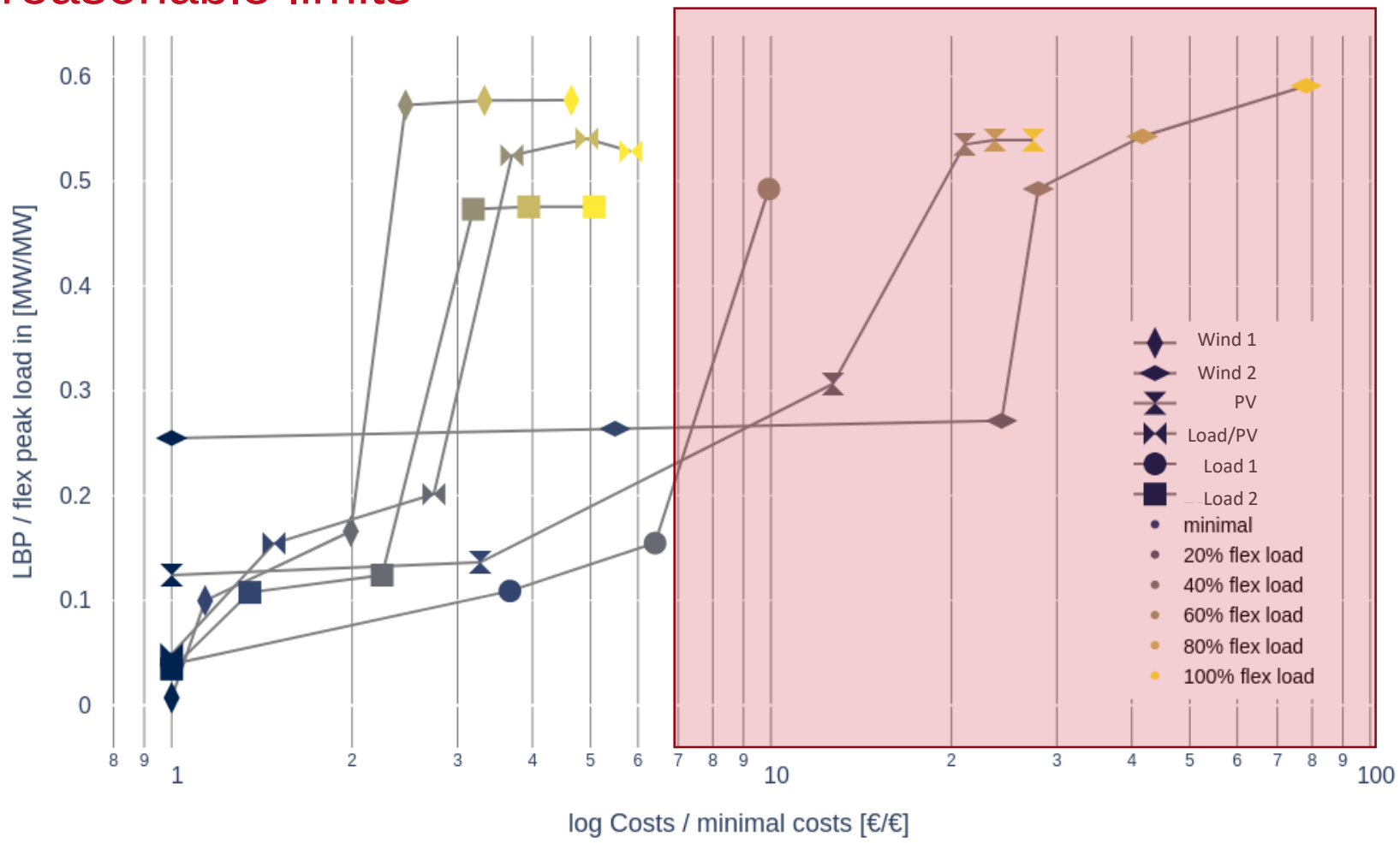

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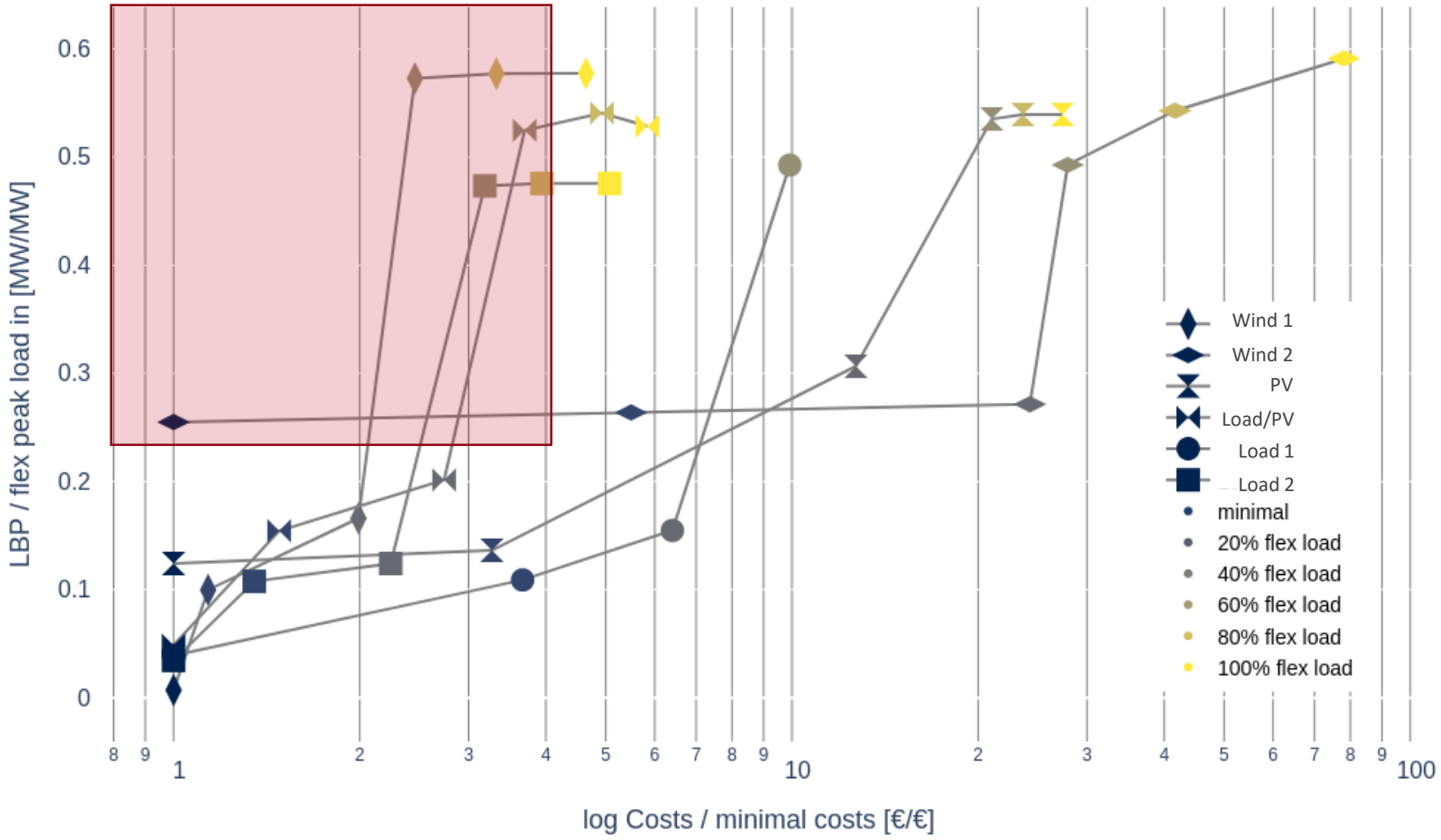

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Conclusion

Conclusion

- Reinforcement costs can be reduced with flexible operation strategies by up to 55%
- In this state, a limited load balancing potential can be provided to the transmission grid
- Additional reinforcement is expensive but necessary to provide substantial load balancing potential
- For half the grids, the costs are in a range which could be economically reasonable
- Further research is needed to determine:
    - economic benefit
    - transmission grid and storage expansion savings

Sources

[BEV] Gemassmer, J.; Daam, C.; Reibsch, R. Challenges in Grid Integration of Electric Vehicles in Urban and Rural Areas. *World Electr. Veh. J.* **2021**, *12*, 206.

[BEA] Kucevic, D., Tepe, B., Schachler, B., Röpcke, T., Helfenbein, K., Dotzauer, P., Hesse, H. C., & Jossen, A. (2022). *Open Battery Models for Electrical Grid Applications : Abschlussbericht open_BEA*. Technische Universität München.

[EGO] U. P. Mueller, B. Schachler, M. Scharf, *et al.*, “Integrated Techno-Economic Power System Planning of Transmission and Distribution Grids,” *Energies*, vol. 12, no. 11, p. 2091, 11 Jan. 2019

[BBH] Becker Buettner Held, “Verteilnetzbetreiber 2030”, May 2018

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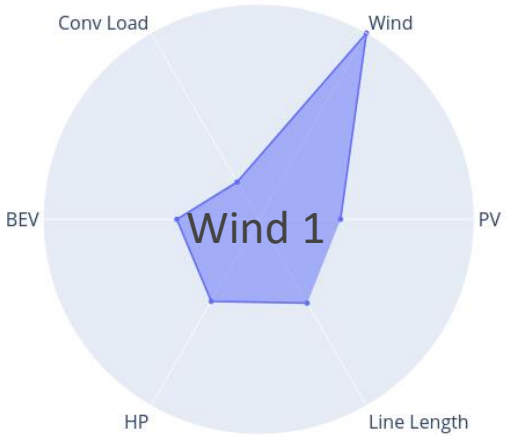
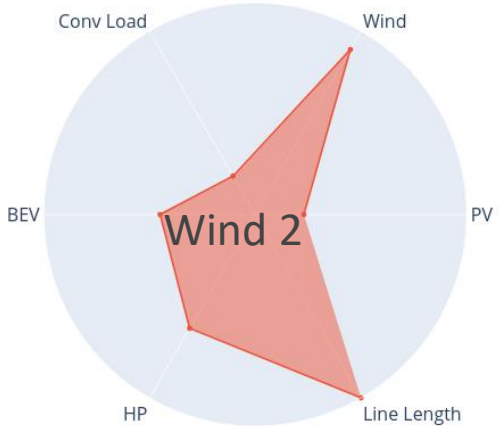
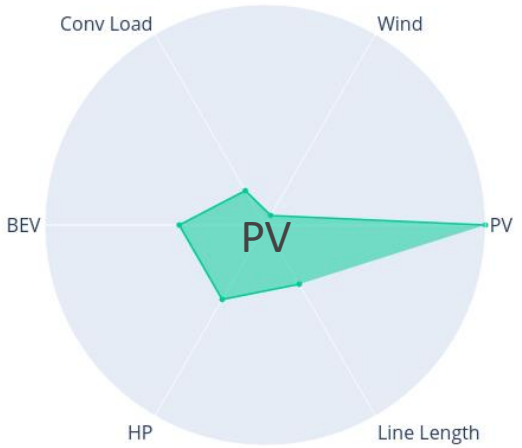
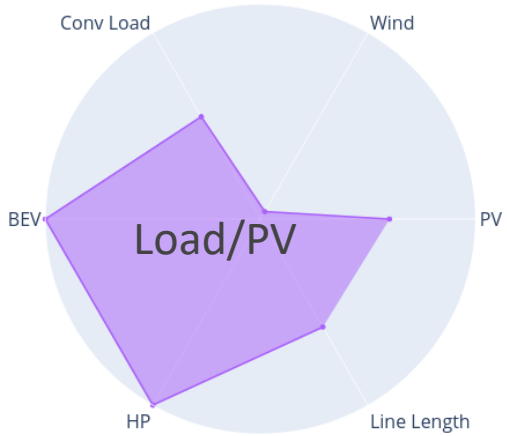
Thank you for the attention

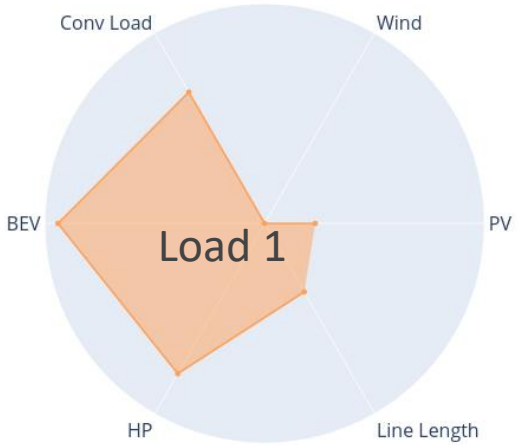
We used heterogeneous topologies

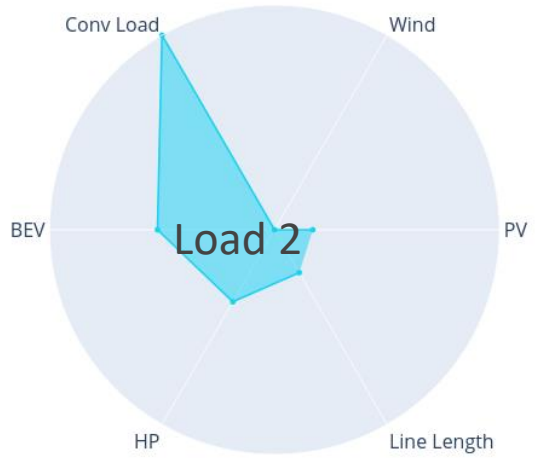




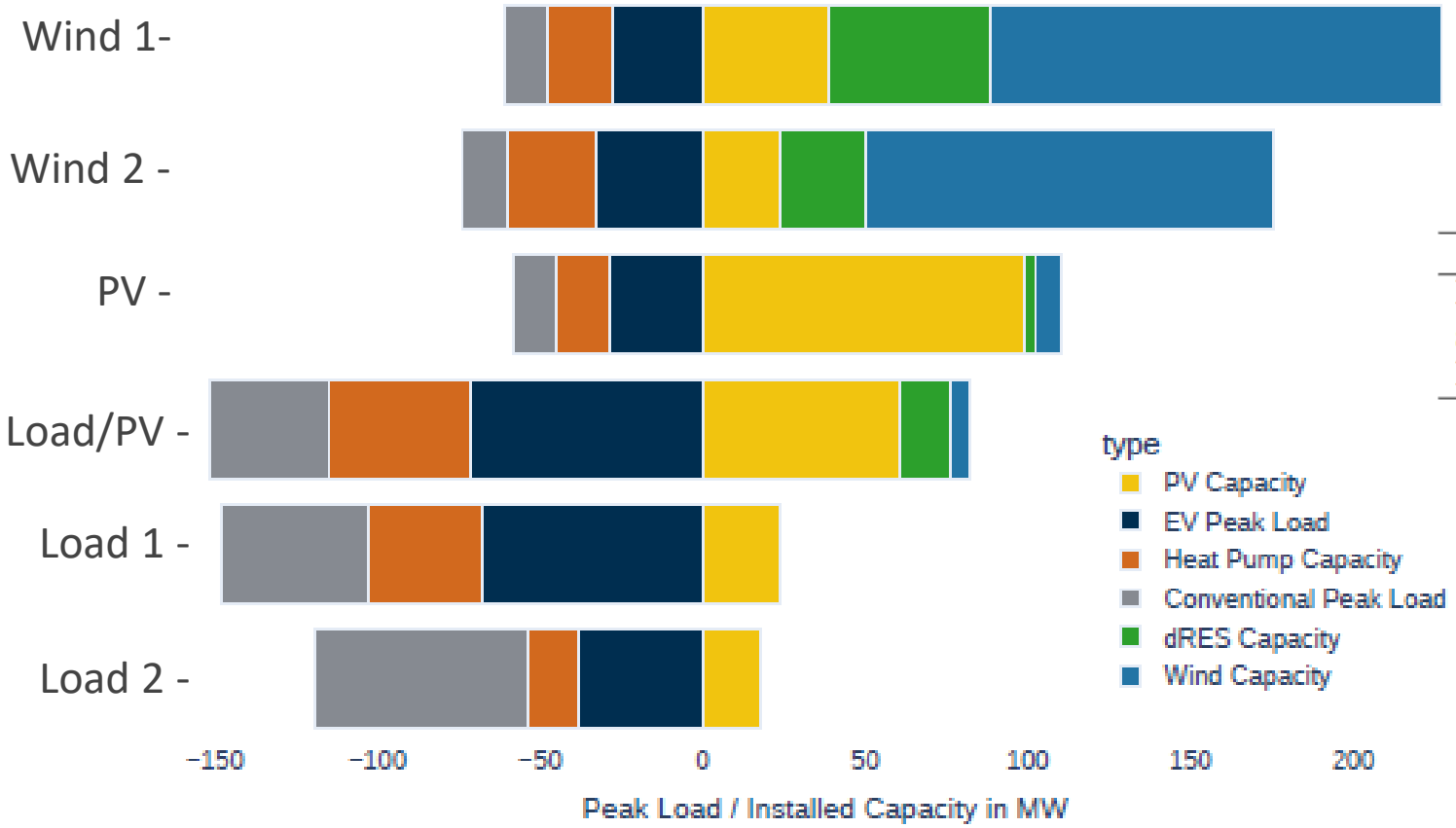






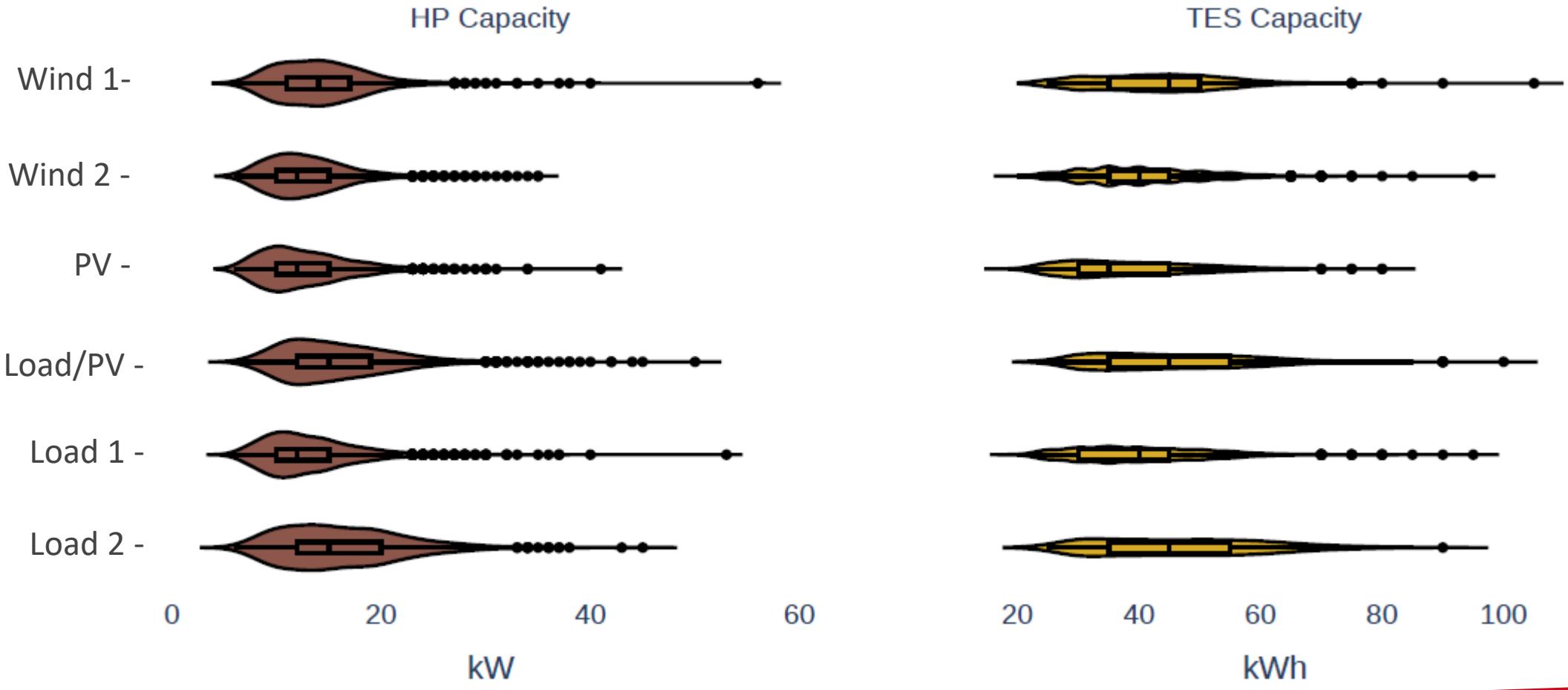


Grid topologies

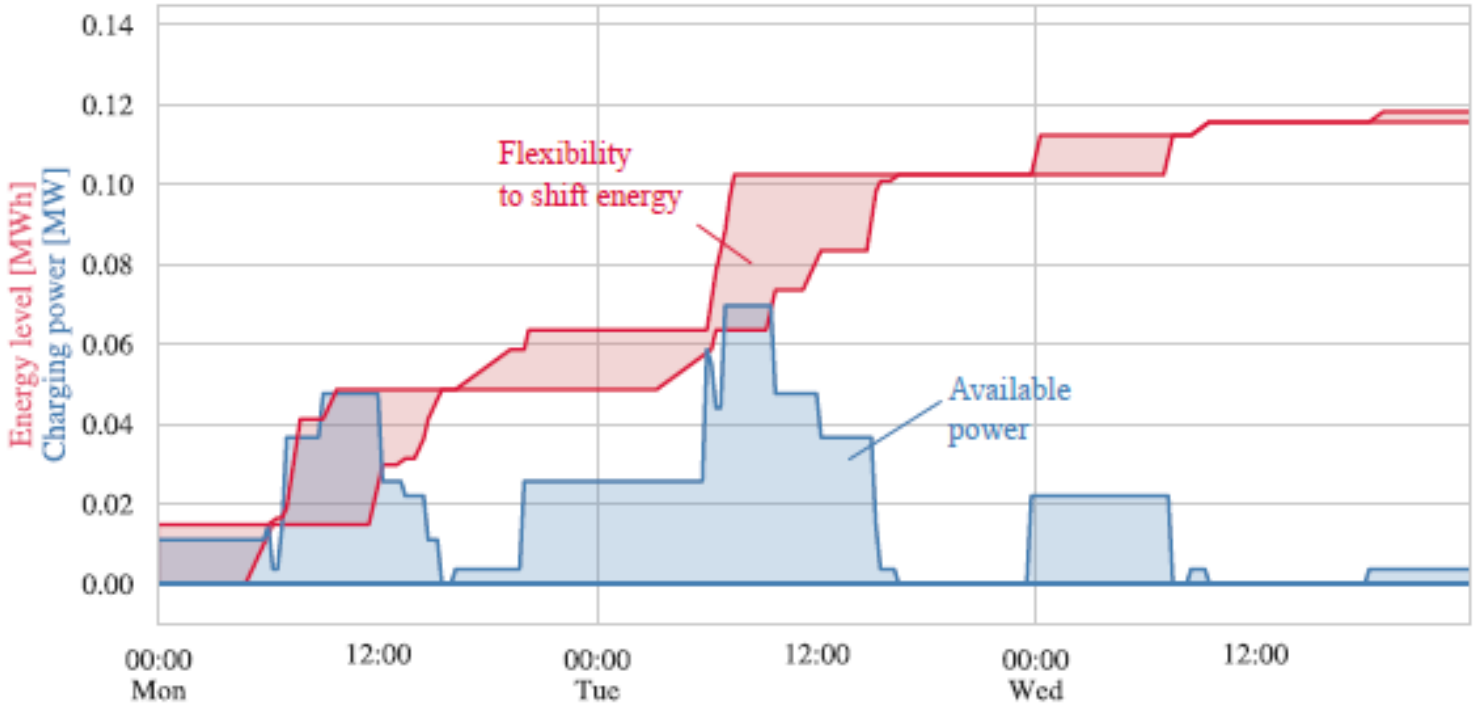


	1690	1811	1056	176	177	2534	unit
lv-grids	179	381	130	196	110	56	-
surface area	529	1665	445	308	145	62	km^2
line length	689	1515	474	881	556	341	km

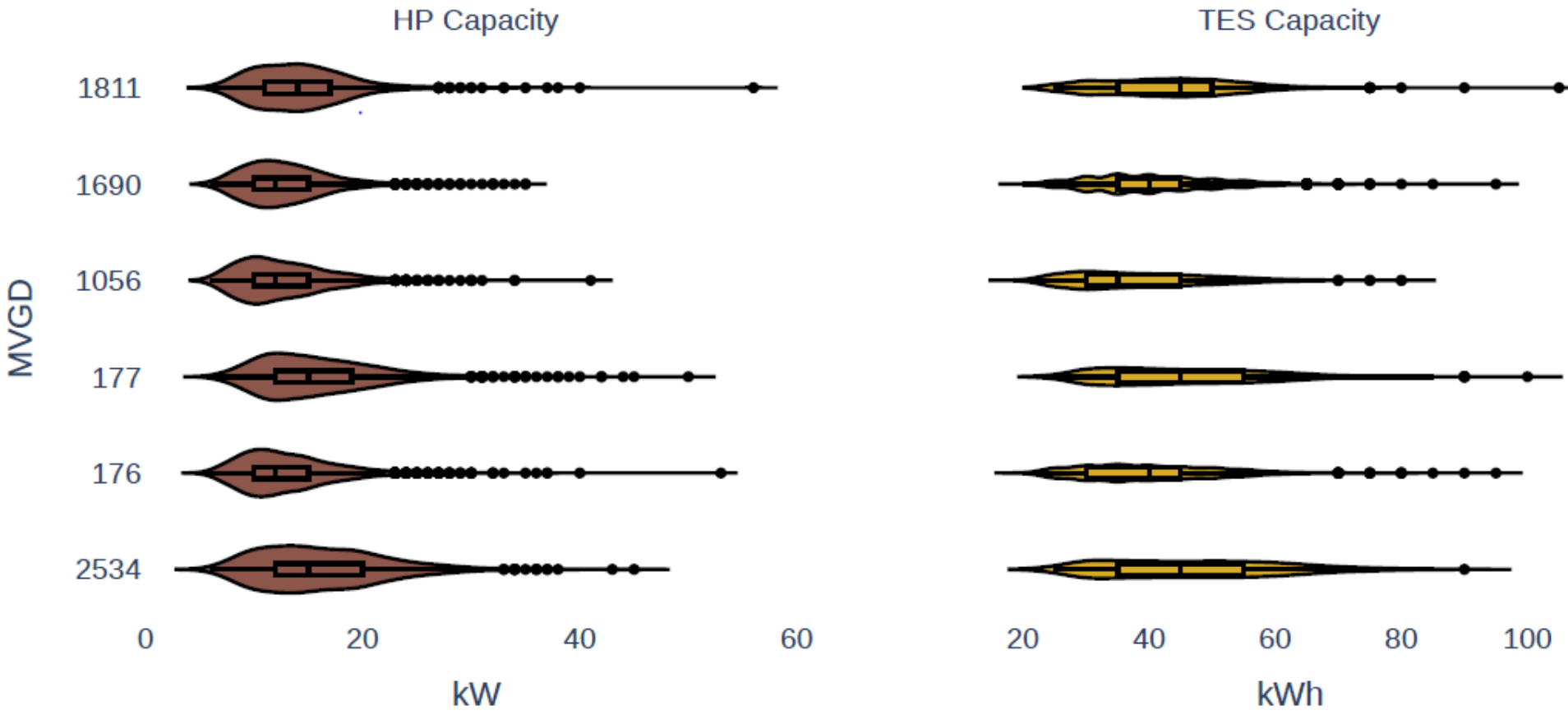
HP Charging and Storage Capacity



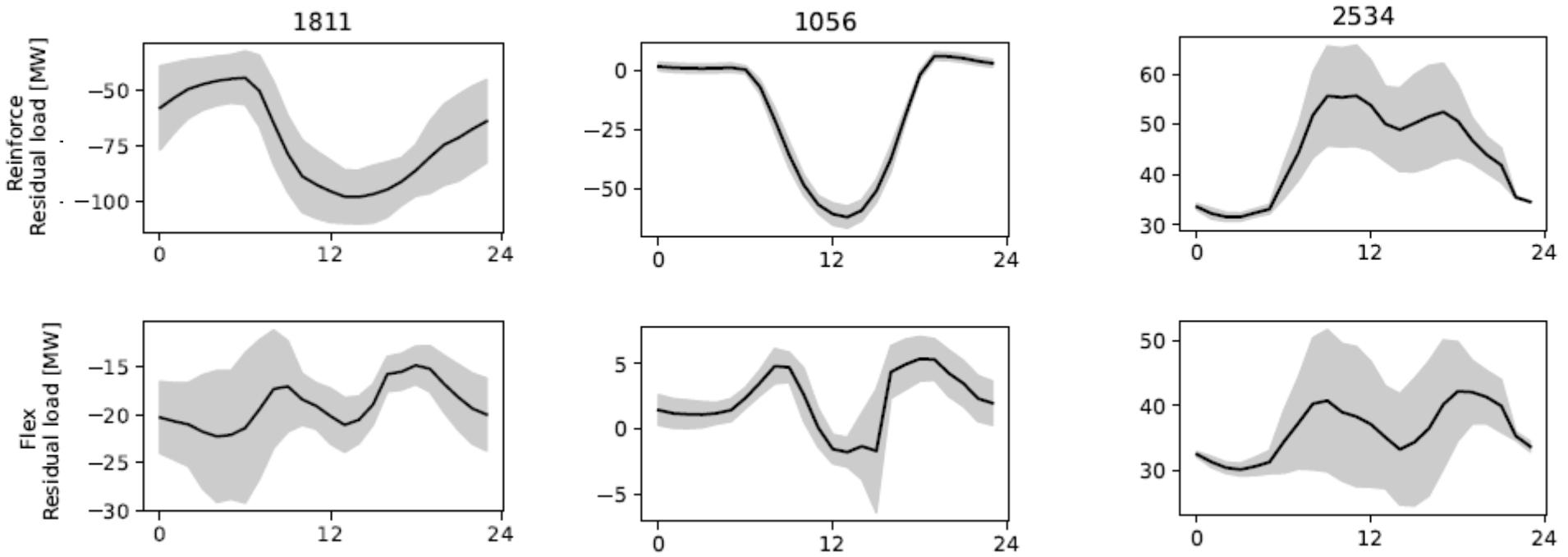
Flexibility Bands for BEV



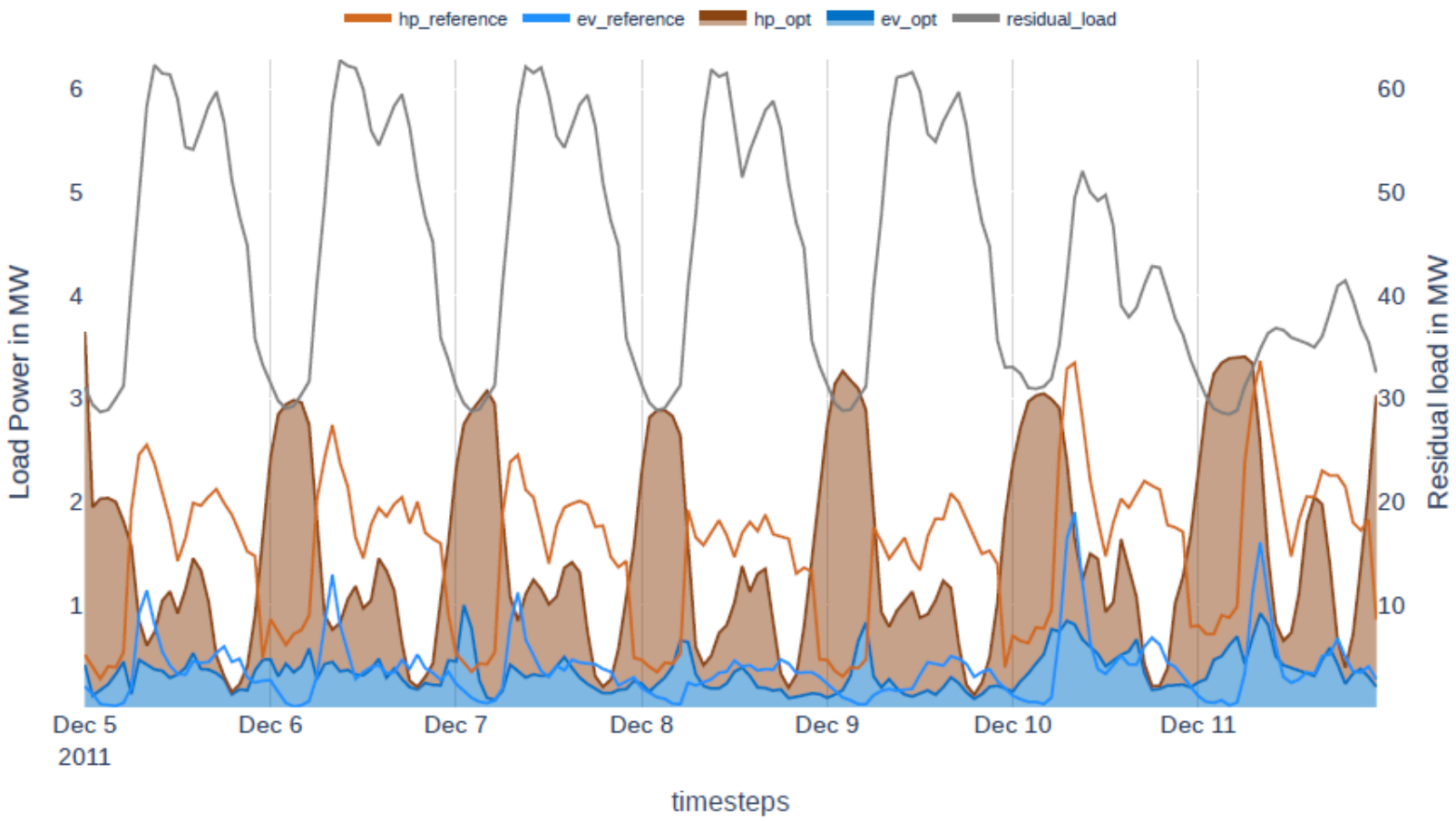
HP and TES Capacity



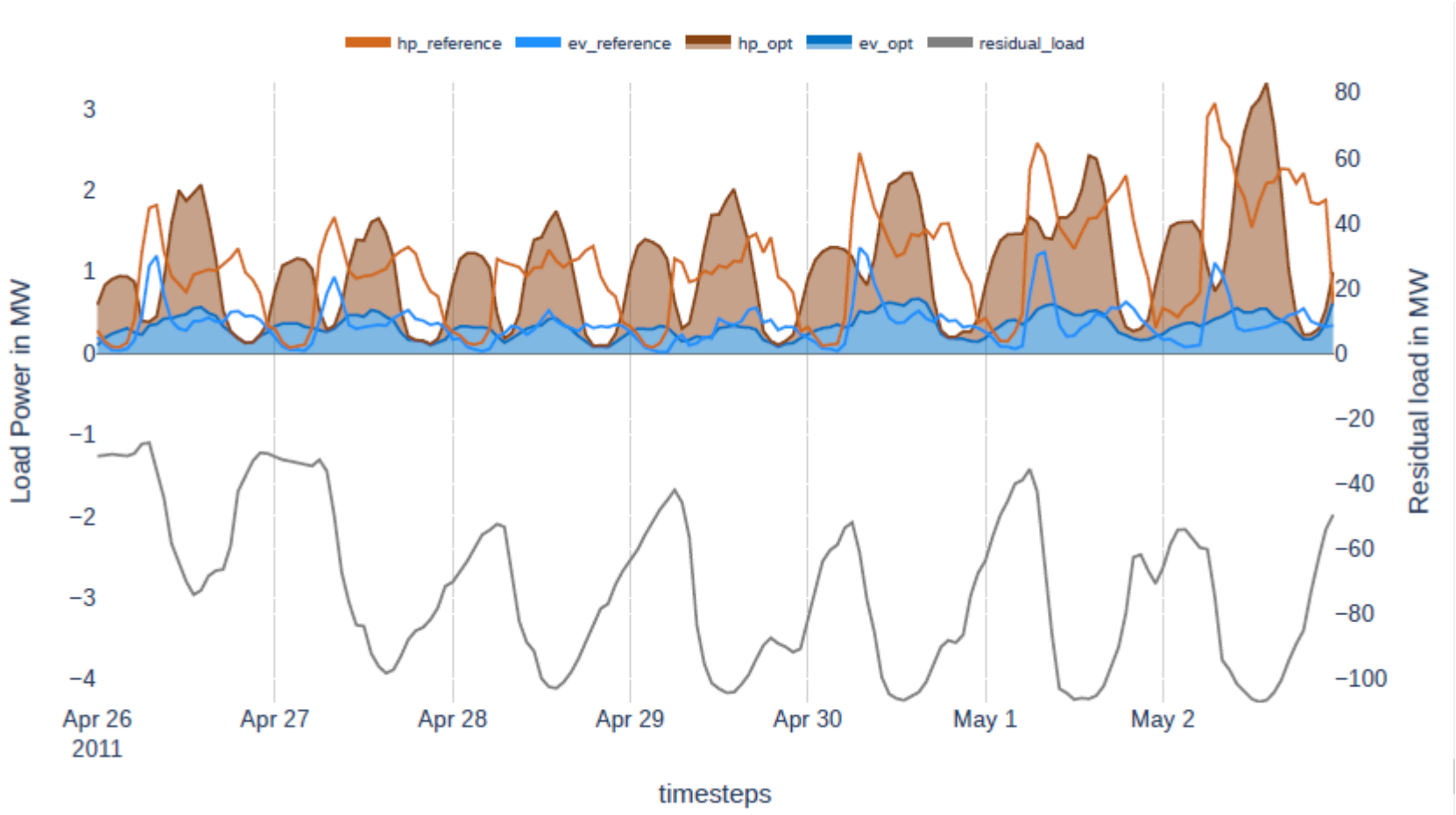
Selected observation periods



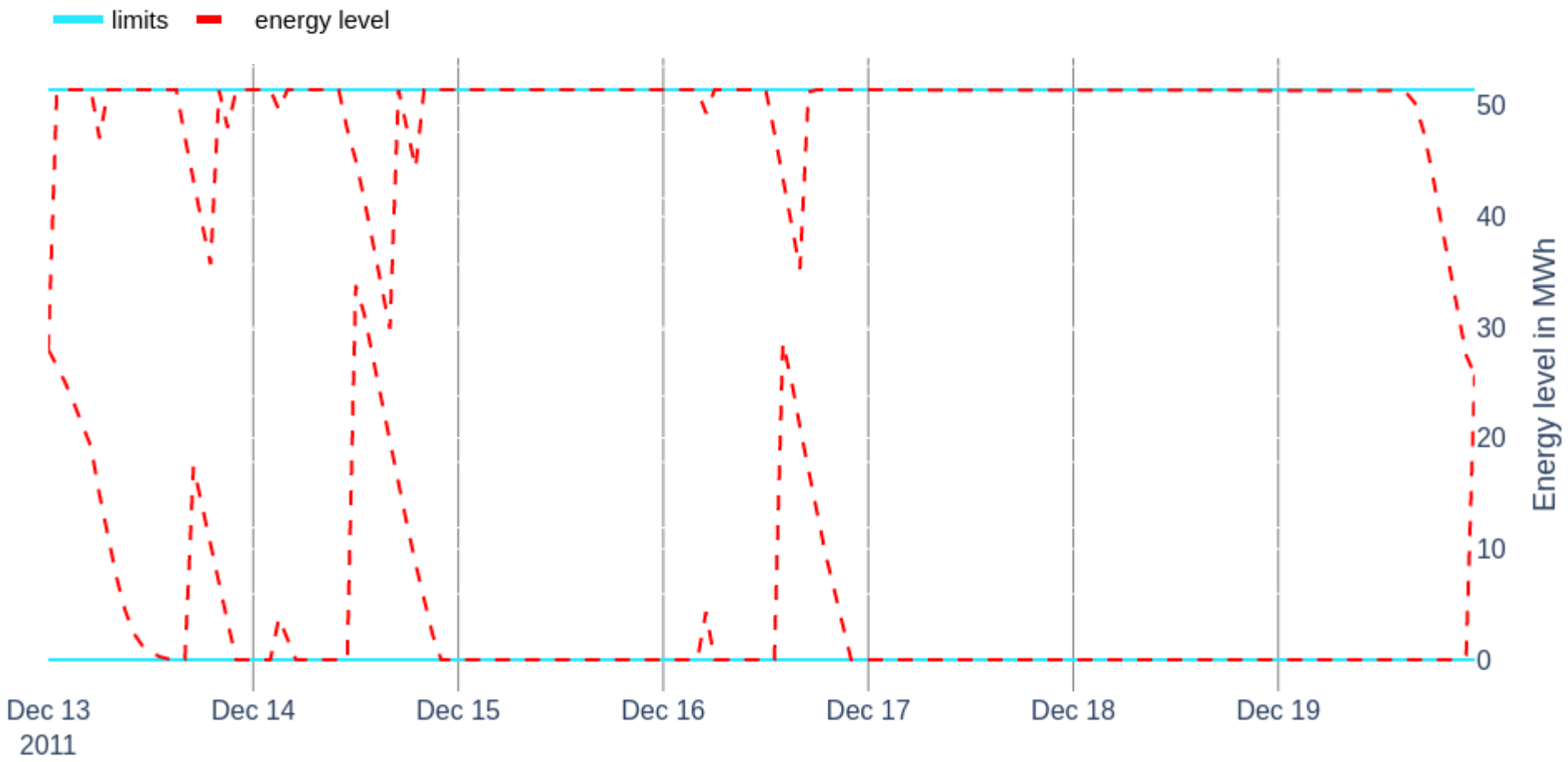
Minimal line loading optimization



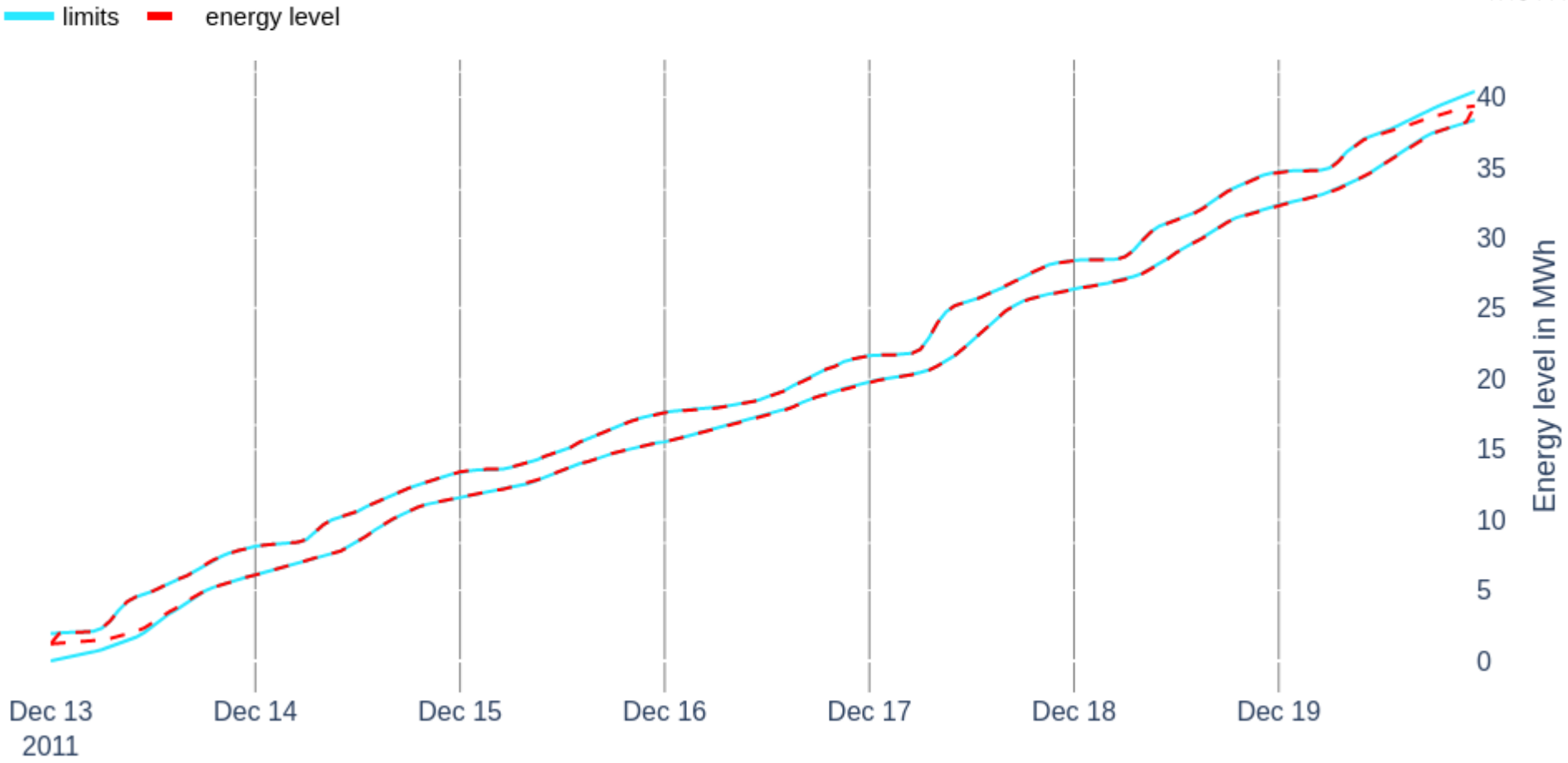
Minimal line loading optimization



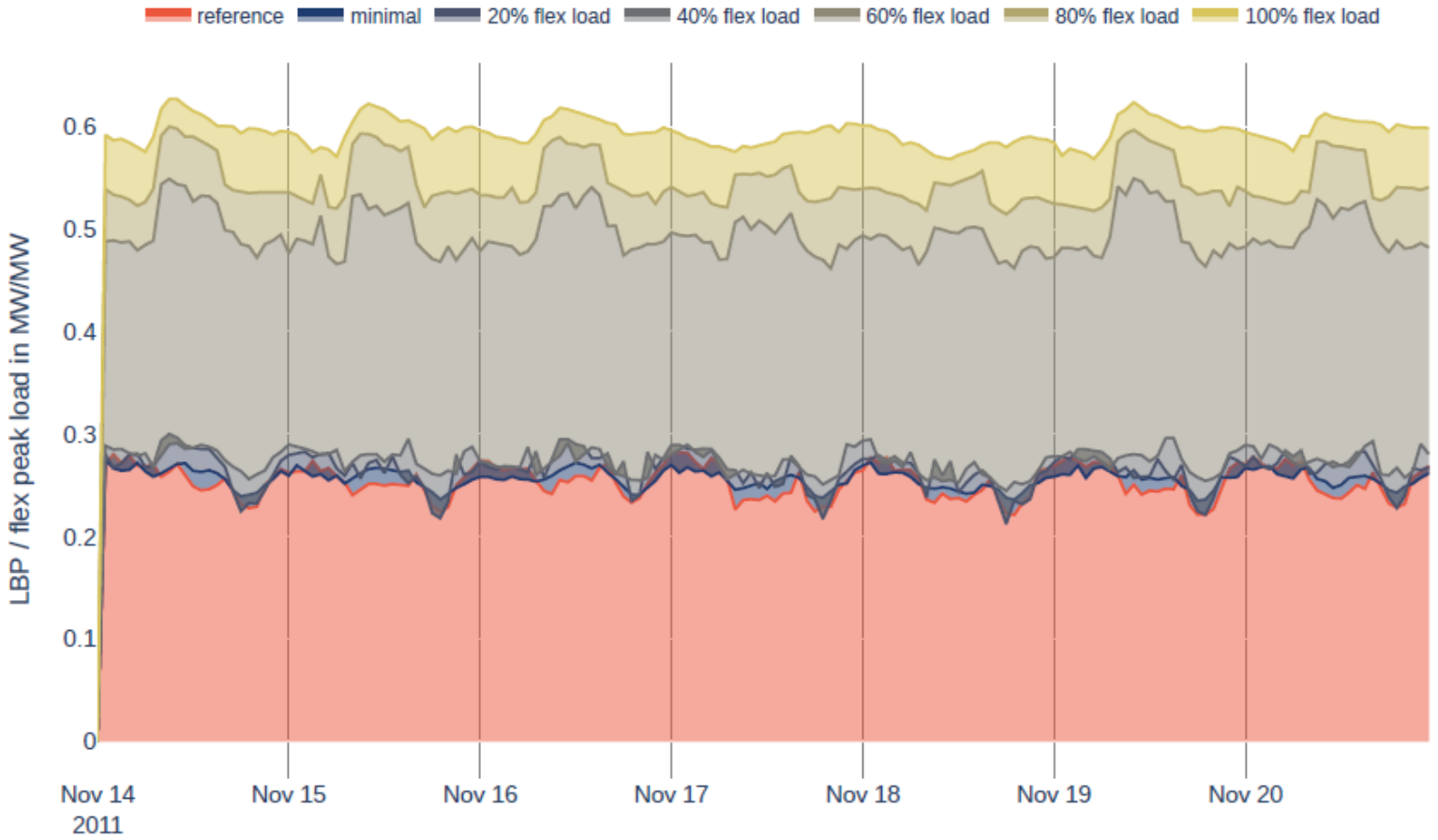
Minimal Energy Level Potential HP



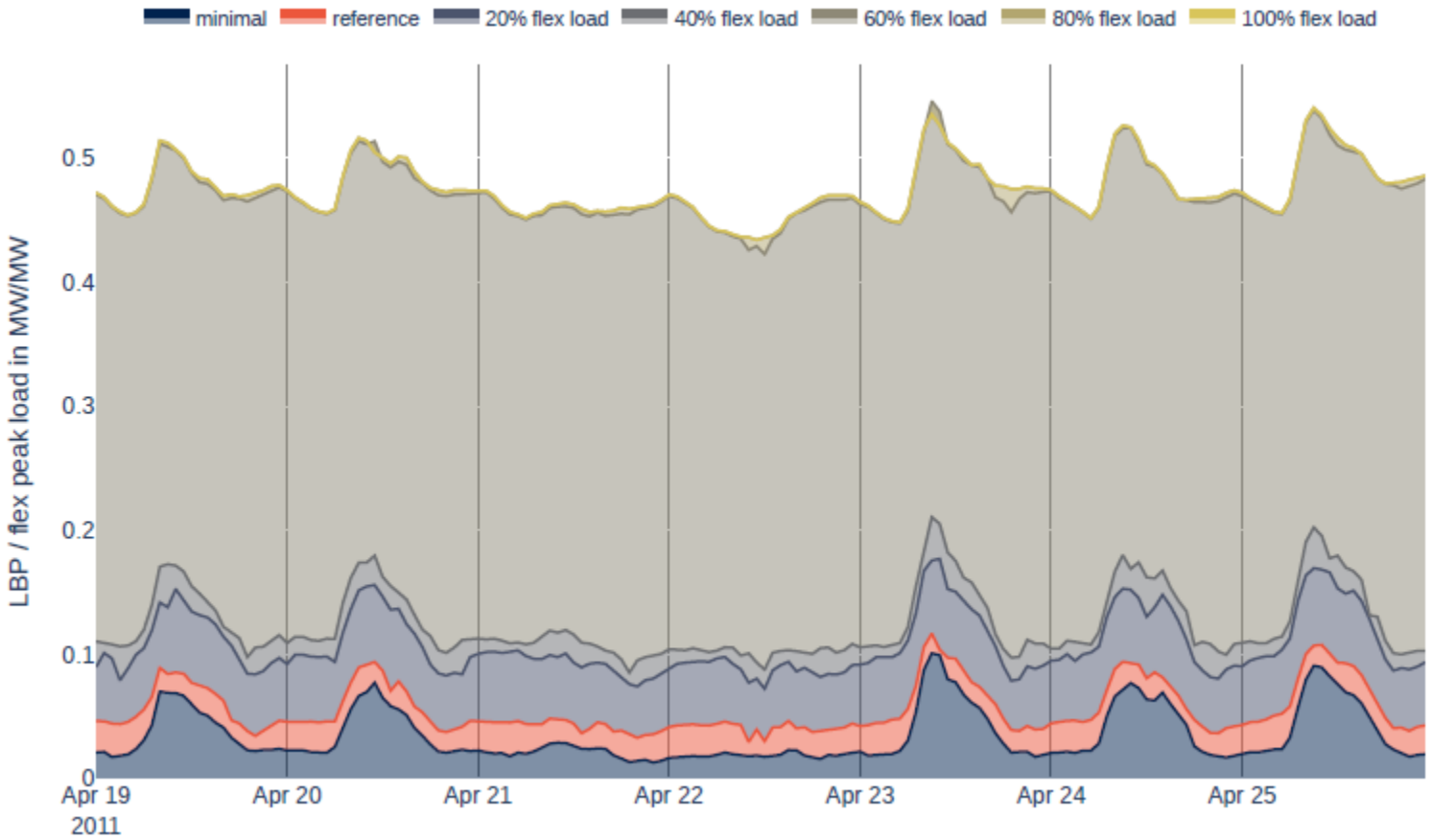
Minimal Energy Level Potential BEV



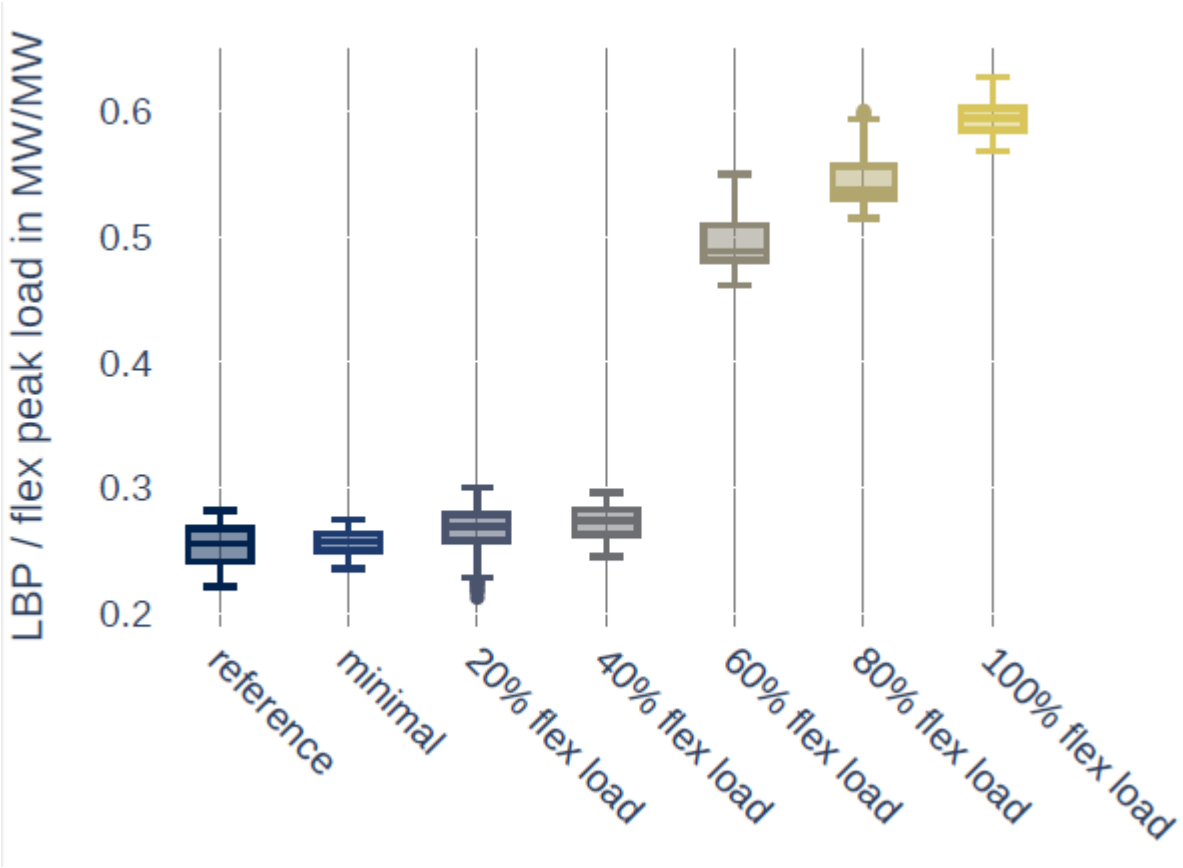
Results: Increased Potential through Reinforcement



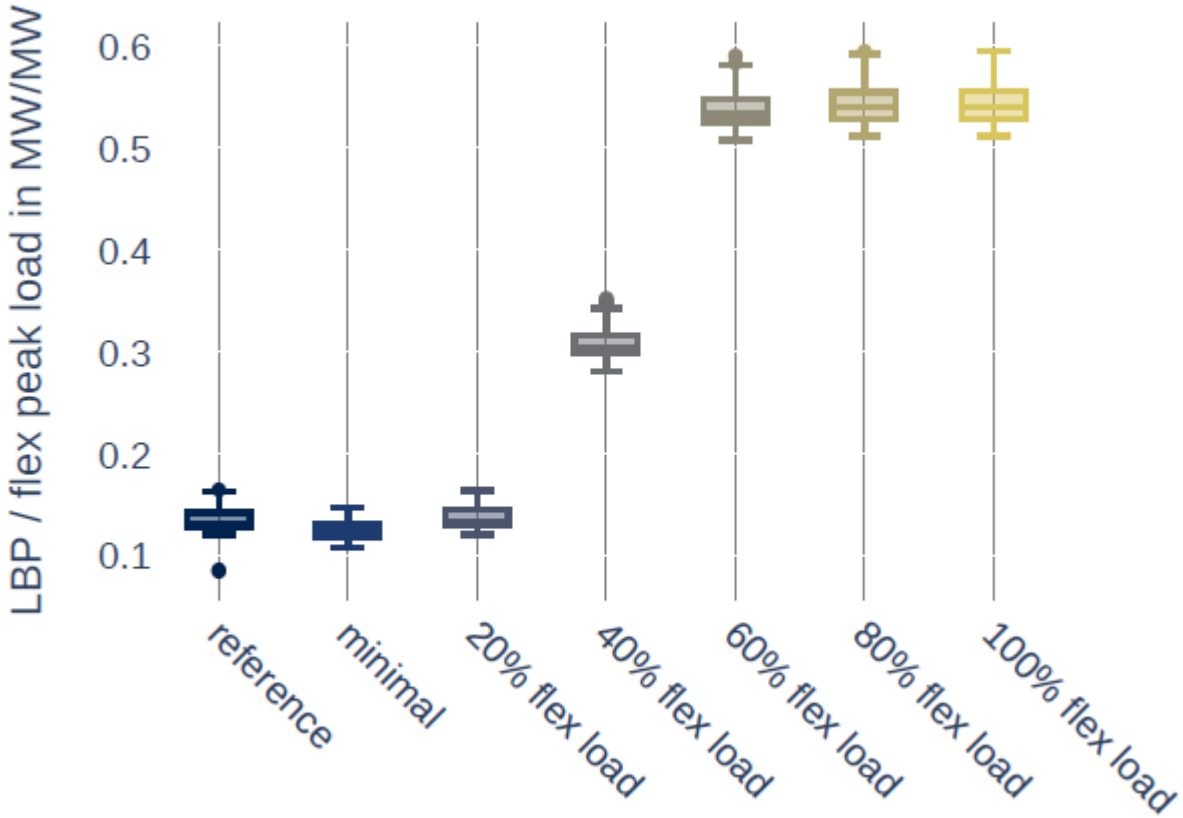
Results: Increased Potential through Reinforcement



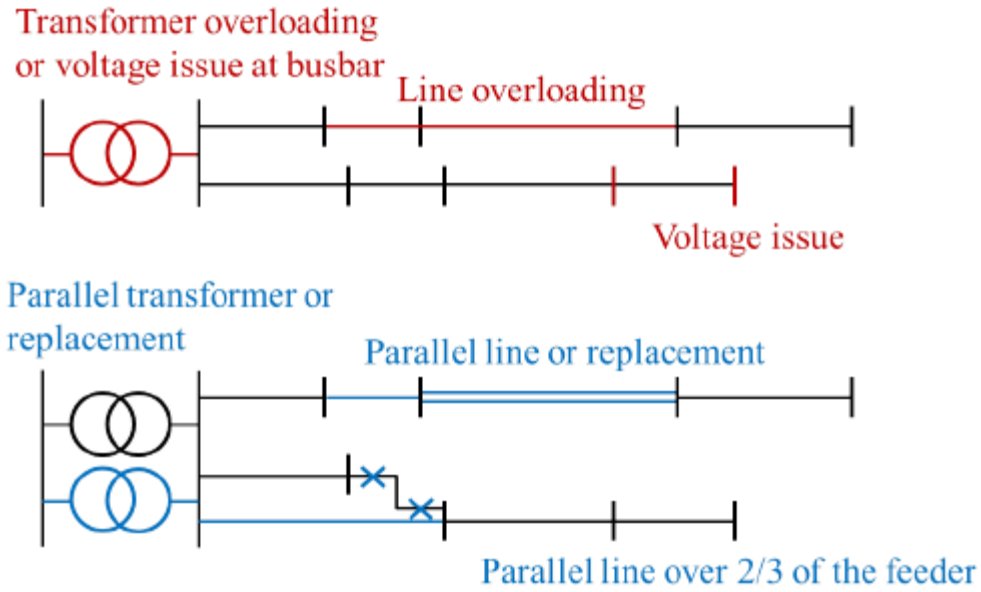
Results: Increased Potential through Reinforcement



Results: Increased Potential through Reinforcement

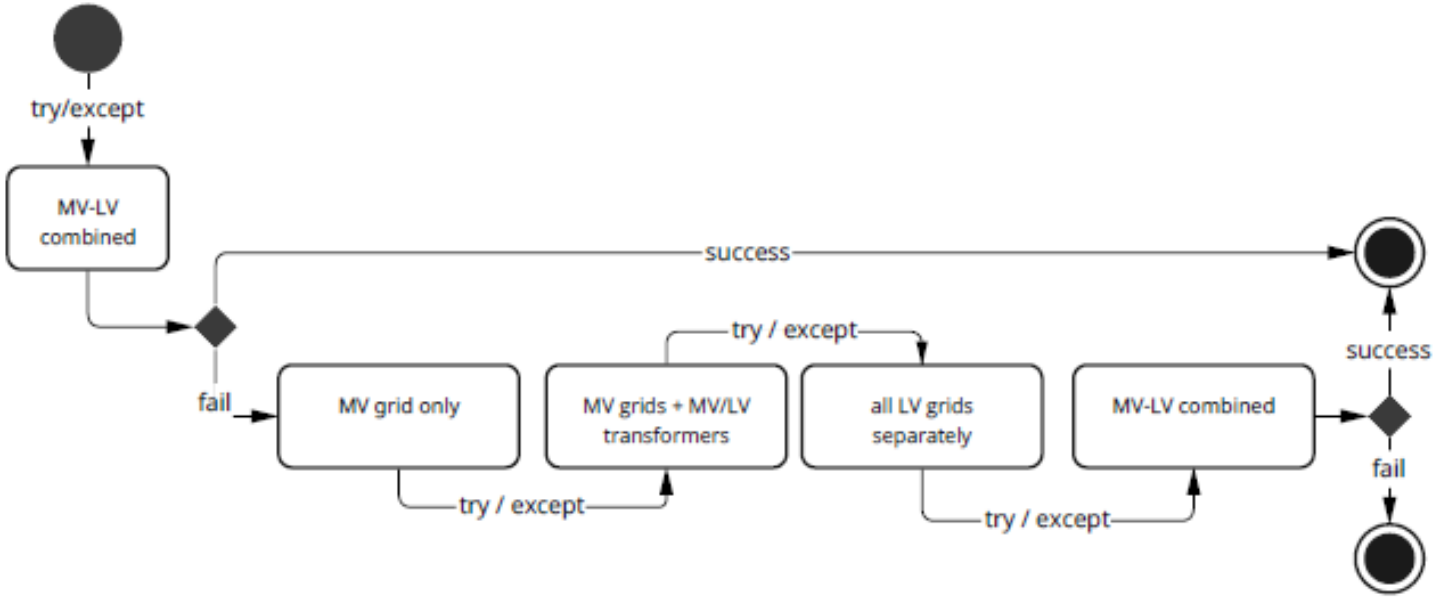


Reinforcement Measures



Reinforcement Measures in eDisGo[EGO]

Reinforcement Measures



Grid Model: Power

$$p_{b,t} = \sum_{n \in down(b)} \left(P_{n,t}^{fix} + p_{c(n),t}^{EV} + p_{c(n),t}^{HP} - p_{n,t}^{curt,l/BEV/HP} + p_{n,t}^{curt,f} \right), \tag{4.6}$$

$$q_{b,t} = \sum_{n \in down(b)} \left(Q_{n,t}^{fix} - q_{n,t}^{curt,l} + q_{n,t}^{curt,f} \right) \qquad \forall t \in T, \;\; b \in B. \tag{4.7}$$

$$-P_{b,t} \leq p_{b,t} \leq P_{b,t}, \tag{4.8}$$

$$P_{b,t} = \sqrt{\left(S_b^{nom}\right)^2 - \left(Q_{b,t}^{fix}\right)^2} \qquad \forall t \in T, \;\; b \in B. \tag{4.9}$$

Grid Model: Voltage

$$v_{slack,t} = V_{nom}^2 \qquad \forall t \in T, \tag{4.10}$$

$$v_{m,t} = v_{n,t} + 2 \cdot (p_{b,t} \cdot R_b + q_{b,t} \cdot X_b) \qquad \forall t \in T, \;\; b \in B, \tag{4.11}$$

$$V_{min,l}^2 \leq v_{n,l} \leq V_{max,l}^2 \qquad \forall n \in N, \;\; l \in \{lv, mv\}. \tag{4.12}$$

Minimal Line Loading

$$\min_{p,q,\dot{q},e,soe,v} \delta_{curt} \sum_{t\in T}\sum_{n\in N} p_{n,t}^{curt} + \delta_{load} \sum_{t\in T}\sum_{b\in B} l_{b,t}^2 \qquad \text{with} \qquad l_b = \frac{p_{b,t}}{P_{b,t}}, \tag{4.3}$$

$$\delta_{curt} = 10^{-2} \qquad >> \qquad \delta_{load} = 10^{-5}. \tag{4.4}$$

$$p_{n,t}^{curt} = \delta_{curt,l}\, p_{n,t}^{curt,l} + \delta_{curt,EV}\, p_{n,t}^{curt,EV} + \delta_{curt,HP}\, p_{n,t}^{curt,HP} + \delta_{curt,f}\, p_{n,t}^{curt,f}. \tag{4.5}$$

Flexibility Potential: Energy Level

$$\min_{p,q,\dot{q},e,soe,v} \sum_{t \in T} e_t^{cum} \qquad \forall t \in T, \tag{4.26}$$

$$\max_{p,q,\dot{q},e,soe,v} \sum_{t \in T} e_t^{cum} \qquad \forall t \in T, \tag{4.27}$$

$$e_t^{cum} = e_{t-1}^{cum} + \left(\sum_{c \in CP} p_{c,t}^{EV} + \sum_{h \in HP} p_{h,t}^{HP} \right) \cdot \Delta t \qquad \forall t \in T \setminus \{0\},\ c \in CP,\ h \in HP, \tag{4.28}$$

(4.29)

Flexibility Potential: Power

$$\min_{p,q,\dot{q},e,v} \quad \delta_{curt} \sum_{t \in T} \sum_{n \in N} p_{n,t}^{curt} + \delta_{power} \left(\sum_{c \in CP} p_{c,t}^{EV} + \sum_{h \in HP} p_{hp,t}^{HP} \right), \tag{4.30}$$

$$\max_{p,q,\dot{q},e,v} \quad -\delta_{curt} \sum_{t \in T} \sum_{n \in N} p_{n,t}^{curt} + \delta_{power} \left(\sum_{c \in CP} p_{c,t}^{EV} + \sum_{h \in HP} p_{hp,t}^{HP} \right), \tag{4.31}$$

$$\delta_{curt} = 10^{-2} \quad >> \quad \delta_{power} = 10^{-5}. \tag{4.32}$$

Heat Pump Model

$$p_{h,t}^{HP} \cdot COP_{h,t} = \dot{Q}_t^D + \dot{q}_{h,t}^{TES} \qquad \forall t \in T, \quad h \in HP, \qquad (4.19)$$

$$soe_{h,t}^{TES} = \eta_{th} \cdot soe_{h,t-1}^{TES} + \dot{q}_{h,t}^{TES} \cdot \Delta t \qquad \forall t \in T, \quad h \in HP \qquad (4.20)$$

$$0 \leq \quad p_{h,t}^{HP} \quad \leq P_h^{nom} \qquad \forall t \in T, \quad h \in HP, \qquad (4.21)$$

$$0 \leq soe_{h,t}^{TES} \leq C_h^{TES} \qquad \forall t \in T, \quad h \in HP, \qquad (4.22)$$

$$soe_{h,-1}^{TES} = \frac{1}{2} \cdot C_h^{TES} \qquad \forall h \in HP, \qquad (4.23)$$

$$soe_{h,t_{end}}^{TES} = \frac{1}{2} \cdot C_h^{TES} \qquad \forall h \in HP. \qquad (4.24)$$

EV Model

$$\underline{p}_{c,t}^{EV} \leq p_{c,t}^{EV} \leq \overline{p}_{c,t}^{EV} \qquad \forall t \in T, \;\; c \in CP, \tag{4.15}$$

$$\underline{e}_{c,t} \leq e_{c,t} \leq \overline{e}_{c,t} \qquad \forall t \in T, \;\; c \in CP, \tag{4.16}$$

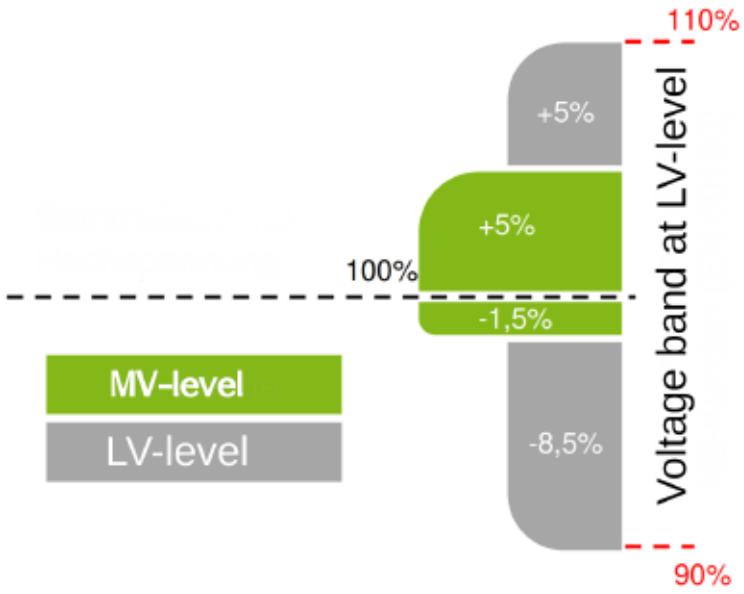
$$e_{c,t} = \frac{1}{2} \cdot \left(\underline{e}_{c,t} + \overline{e}_{c,t}\right) \qquad \forall t \in \{0, t_{end}\}, \;\; c \in CP, \tag{4.17}$$

$$e_{c,t} = e_{c,t-1} + \eta \cdot p_{c,t}^{EV} \cdot \Delta t \qquad \forall t \in T \setminus \{0\}, \;\; c \in CP. \tag{4.18}$$

Voltage Band Division

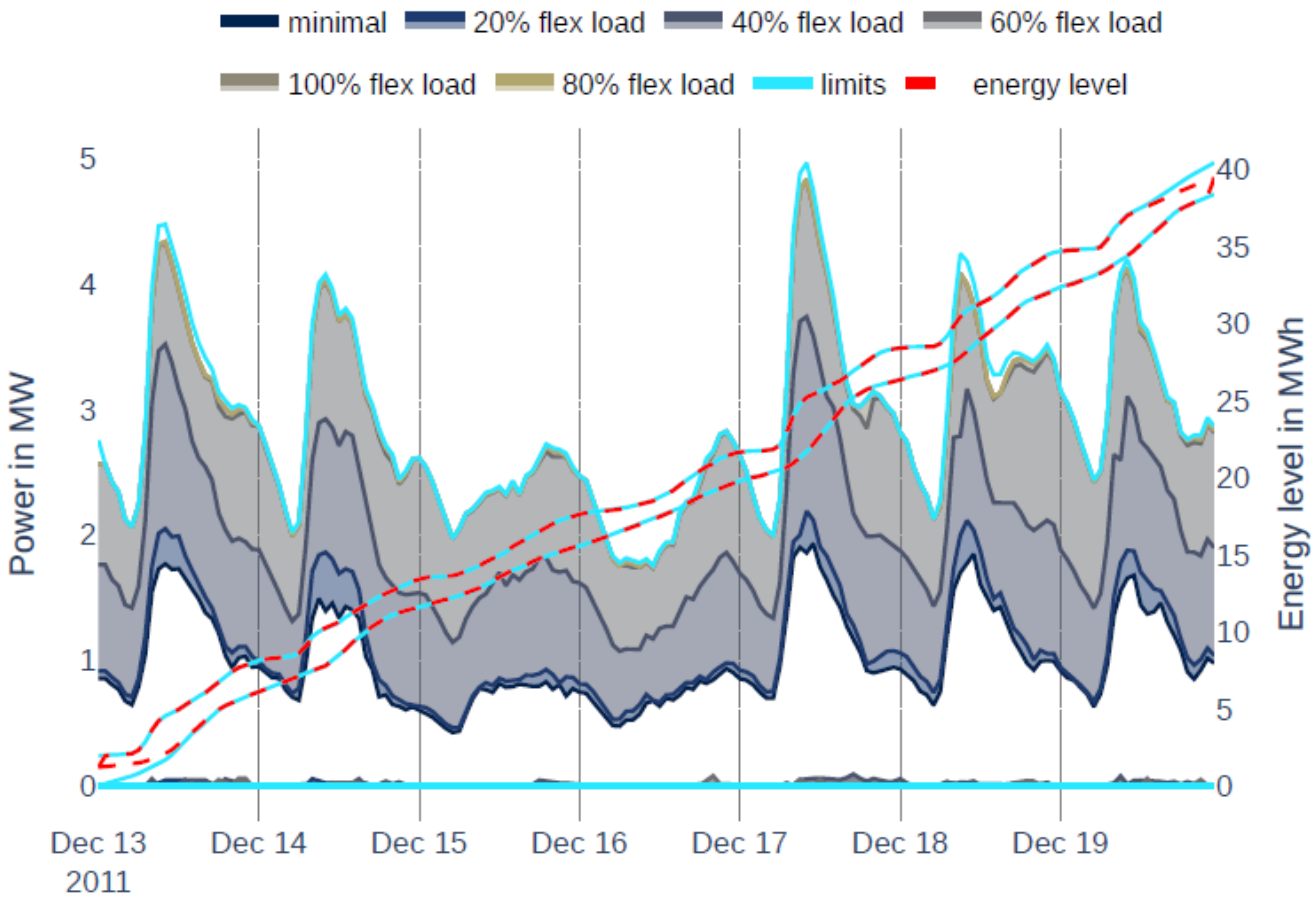
$$(0.9\ V_{nom})^2 \leq v_{n,lv} \leq (1.1\ V_{nom})^2, \qquad (4.13)$$

$$(0.985\ V_{nom})^2 \leq v_{n,mv} \leq (1.05\ V_{nom})^2. \qquad (4.14)$$

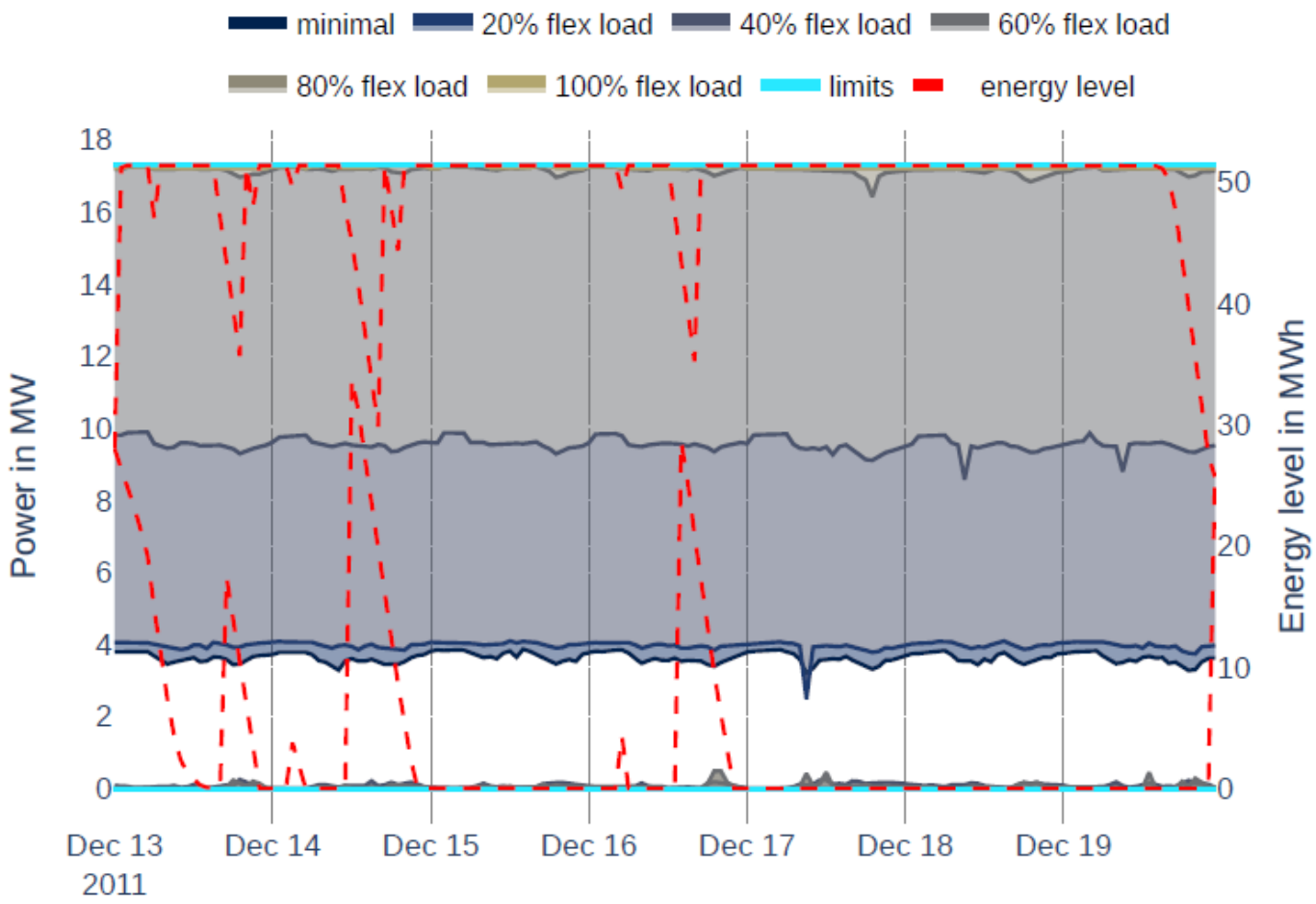


Voltage Band Division [REH]

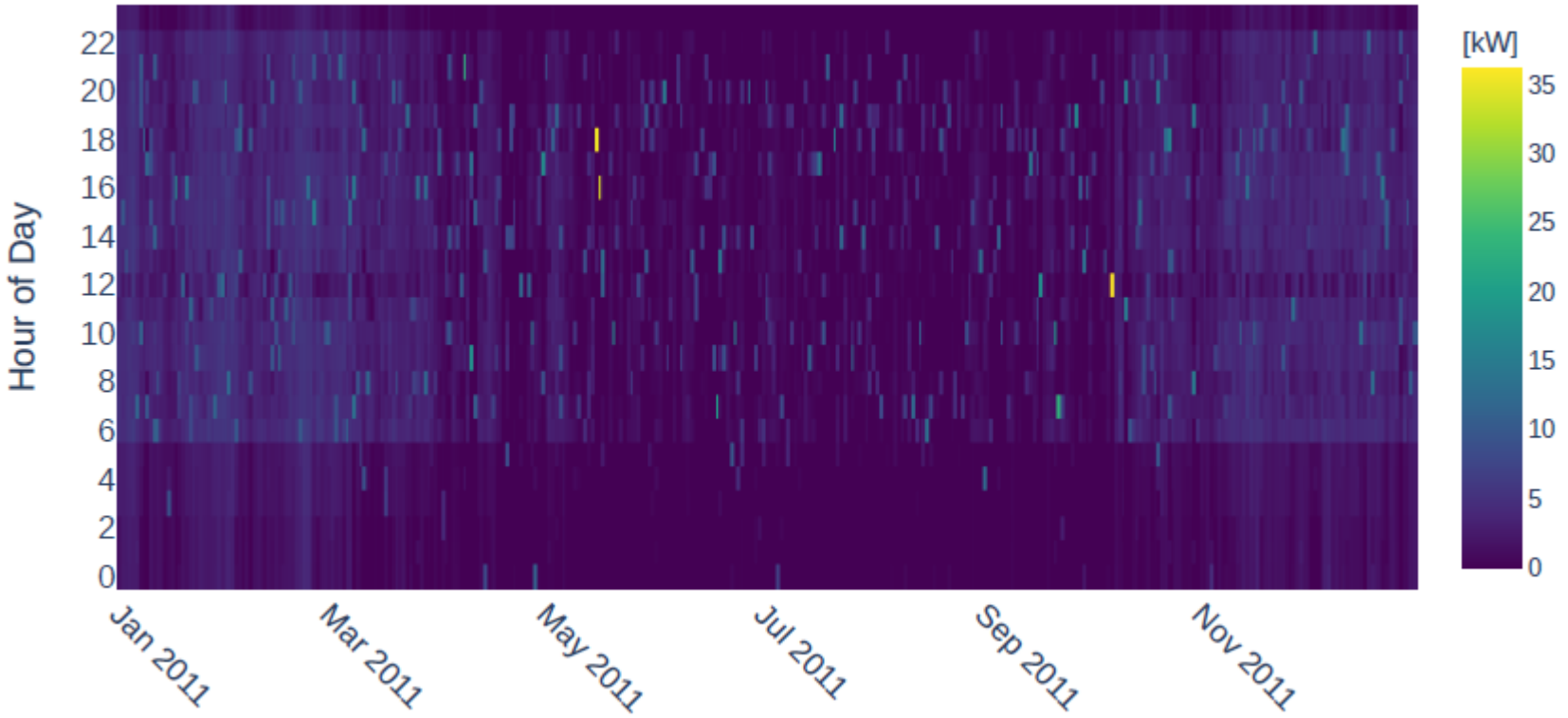
Power and Energy Potential: EV



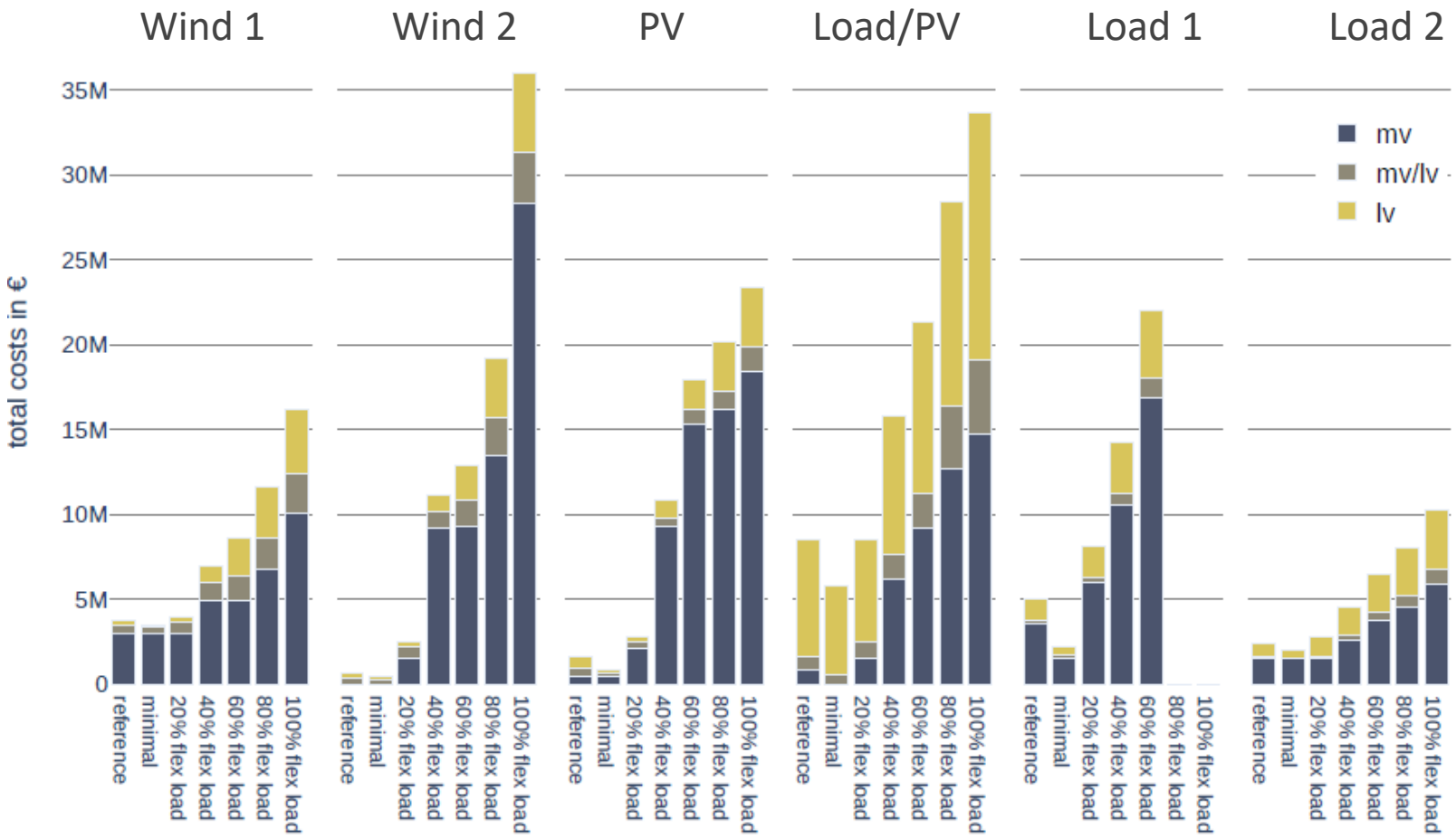
Power and Energy Potential: HP



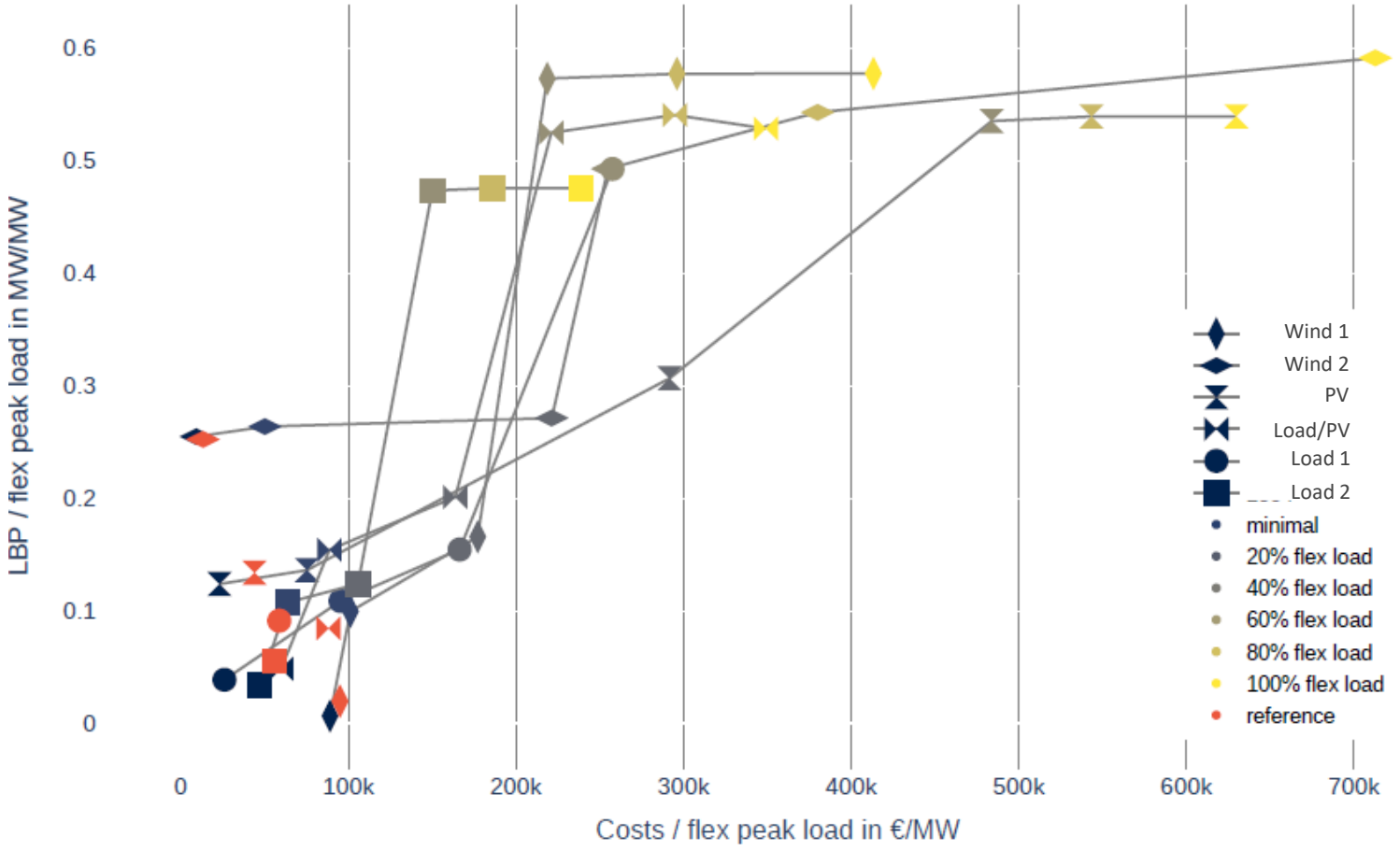
Residential Heat Demand Profile



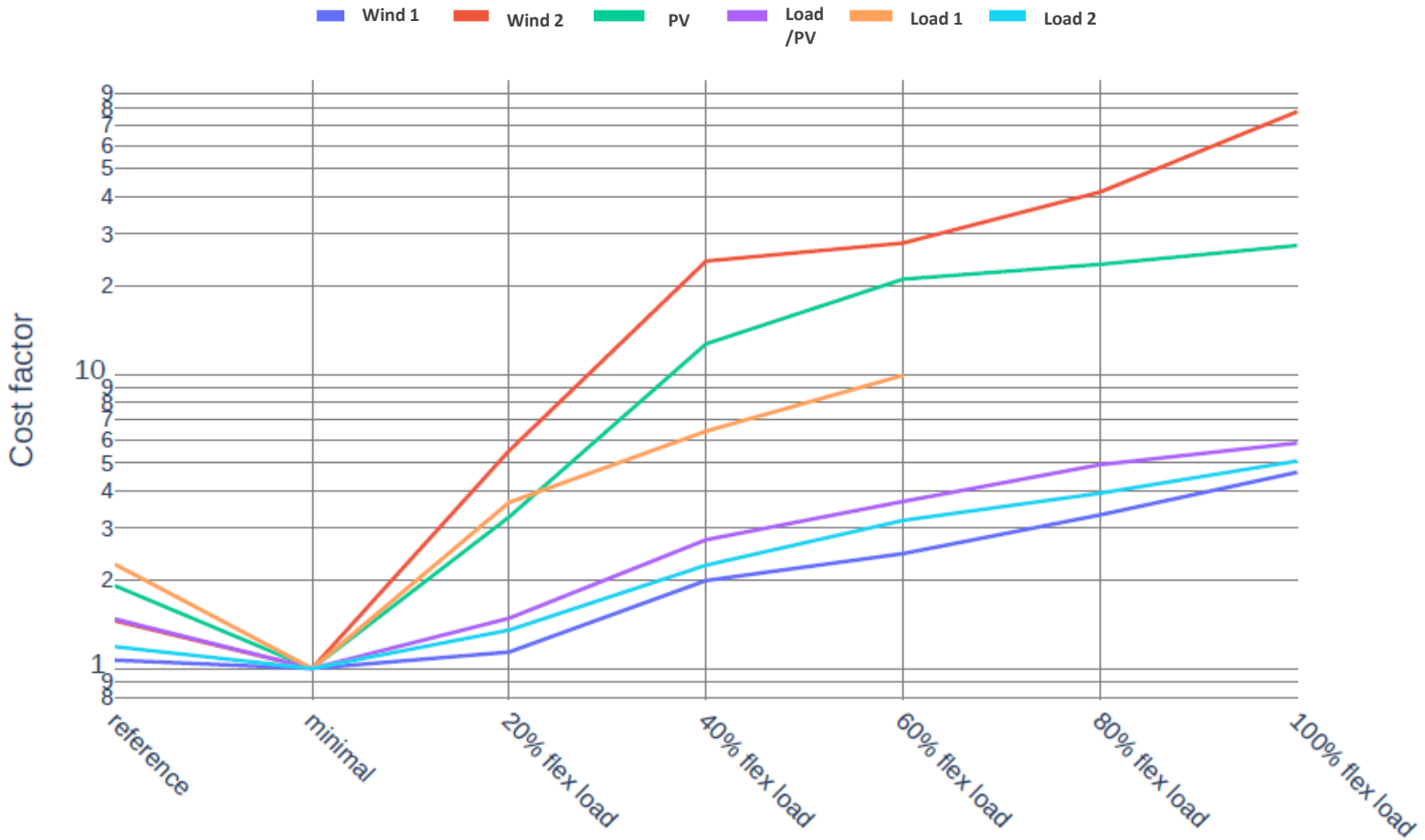
Reinforcement Costs



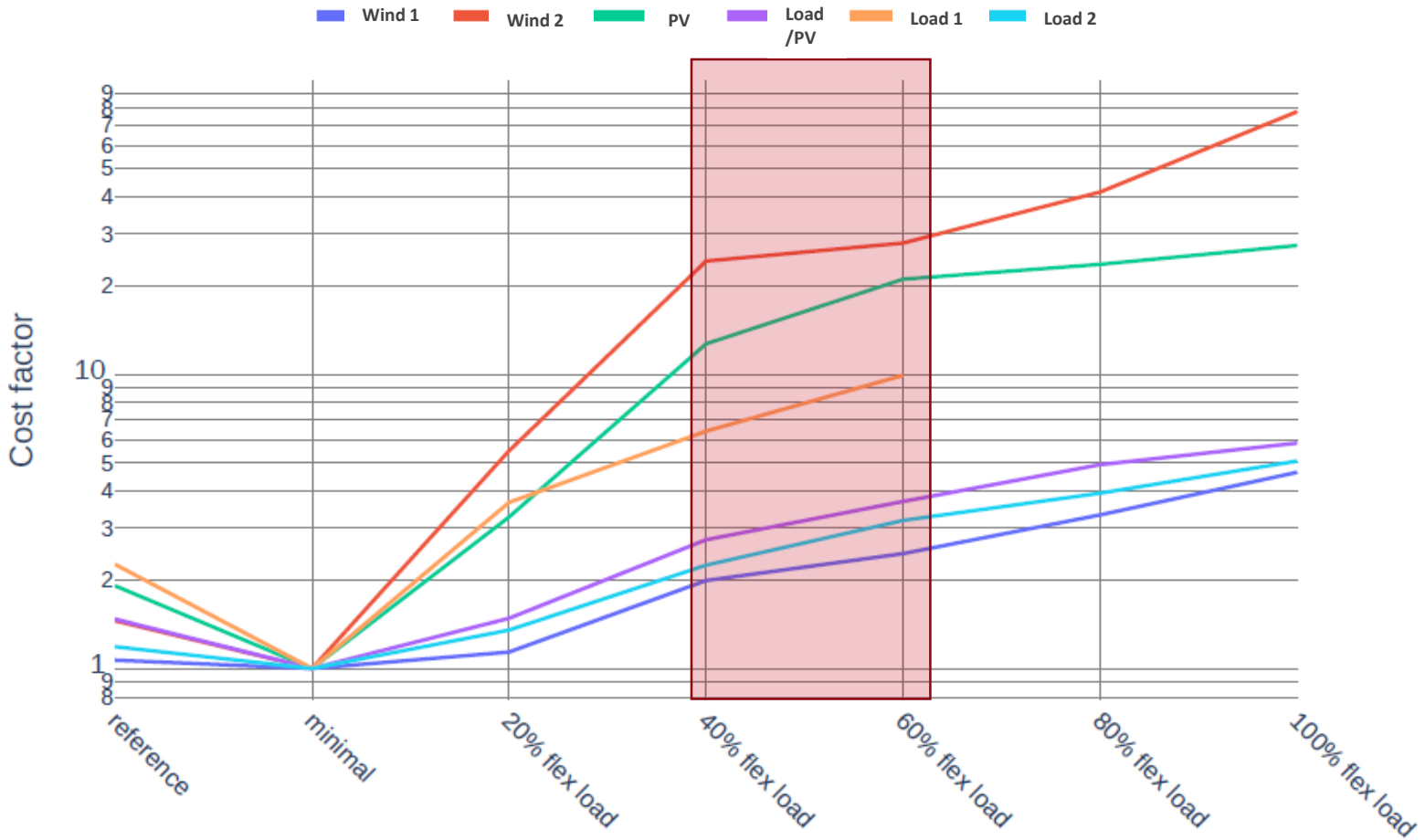
Cost Benefit for all grids



Additional Reinforcement Costs



Additional Reinforcement Costs



Methodology