Evaluating Demand Response Potentials in the climate-neutral German Power System

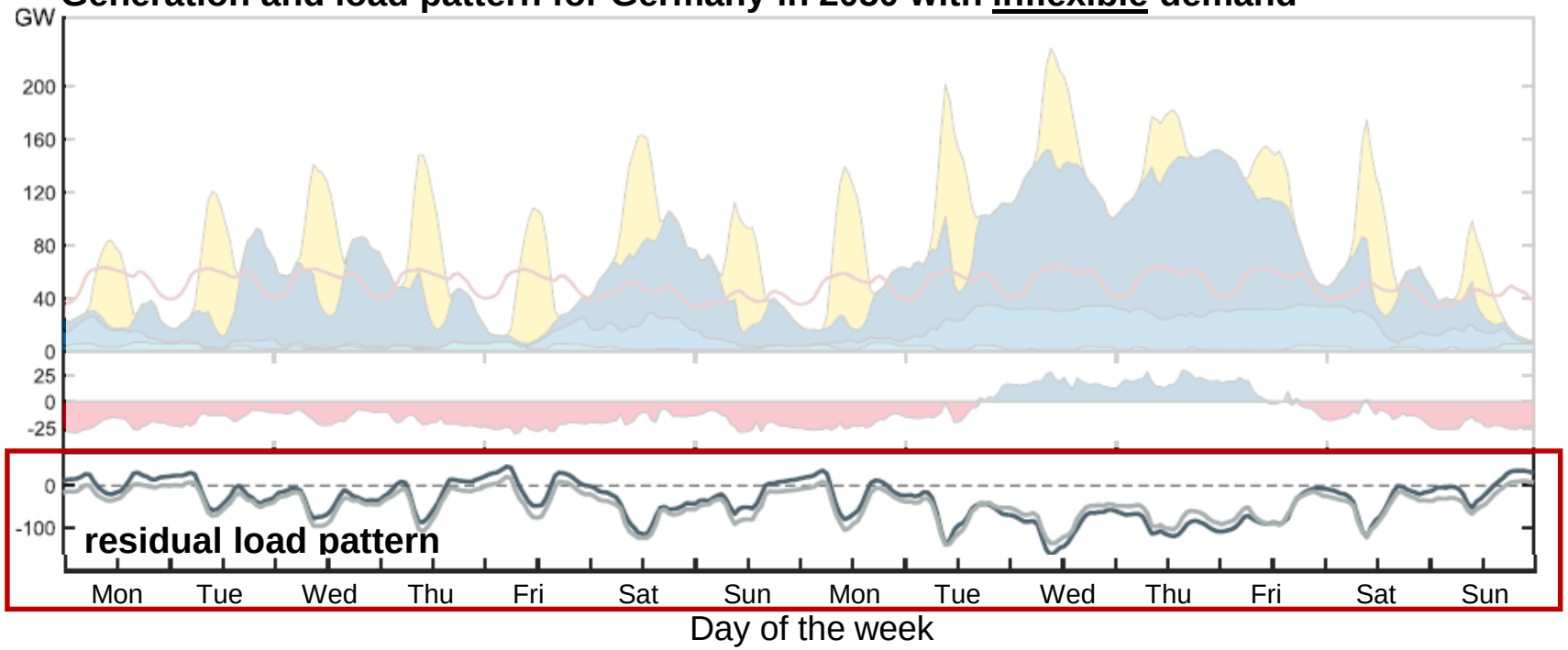
How power tariffs design can foster congruence among overall economic potentials and their micro-economic profitability

Johannes Kochems | DLR - Institute of Networked Energy Systems | ABM4Energy, Freiburg | 22.03.2024

Motivation

Using demand response to level out fluctuations from renewable generation

Generation and load pattern for Germany in 2050 with <u>inflexible</u> demand



load
photovoltaics
wind onshore
wind offshore
run of river
biomass

net exports
net imports

residual load
RL – Ex + Im

- Strong fluctuations of residual load
- situations with positive and negative residual loads

Demand Response, i.e. a flexible demand reaction, as <u>one</u> option to balance some fluctuations

source:[1], p. 31; modified

Motivation

Using demand response to level out fluctuations from renewable generation

Generation and load pattern for Germany in 2050 with inflexible demand

load
photovoltaics
wind onshore
wind offshore
run of river
biomass

net exports
net imports

residual load
RL – Ex + Im

– Strong fluctuations of residual load
– situations with positive and negative residual loads

Demand Response, i.e. a flexible demand reaction, as one option to balance some fluctuations

Overall system perspective

– Technical potential estimates [2-38]
– Overall economical potential estimates [8-9]; [18-19]; [21]; [28]

Micro-economic perspective

– Assessment of individual processes / appliances [39-48]
– Analyses of power tariffs design [49-74]

Research gap

Lack of joint assessment of both perspectives

How to bridge between them?

source:[1], p. 31; modified

Method & Research Questions

Fundamental model for potential assessment & agent-based model for profitability analysis

Parameterization

Meta-analysis on **technical** demand response (DR) **potentials** [75]

POMMES | AMIRIS

1 Overall power system

*How high are the **economic potentials** for demand response in the power sector?*

→ power sector development pathways from 2020 to 2045 for different scenarios

discrepancies

2 Microeconomic assessment

*Are investments in demand response **economically viable** for given power tariffs designs?*

→ studied for different **power tariff** designs

3 Contrasting & bridging perspectives

*How to design power tariffs in such a way that economic potentials are micro-economically viable, but neither over- nor underincentivized („**congruence**“)?*

Scenario design

Considering one scenario without and three scenarios with demand response

	no DR (DR none)	DR pessimistic (DR 5)	DR neutral (DR 50)	DR optimistic (DR 95)
Demand response (DR) prevalent?	✗	✓	✓	✓
Costs of DR	✗	↑	○	↓
Technical potential of DR	✗	↓	○	↑
Costs of other flexibility options	○	↓	○	↑

DR: Demand Response

Assessing microeconomic profitability

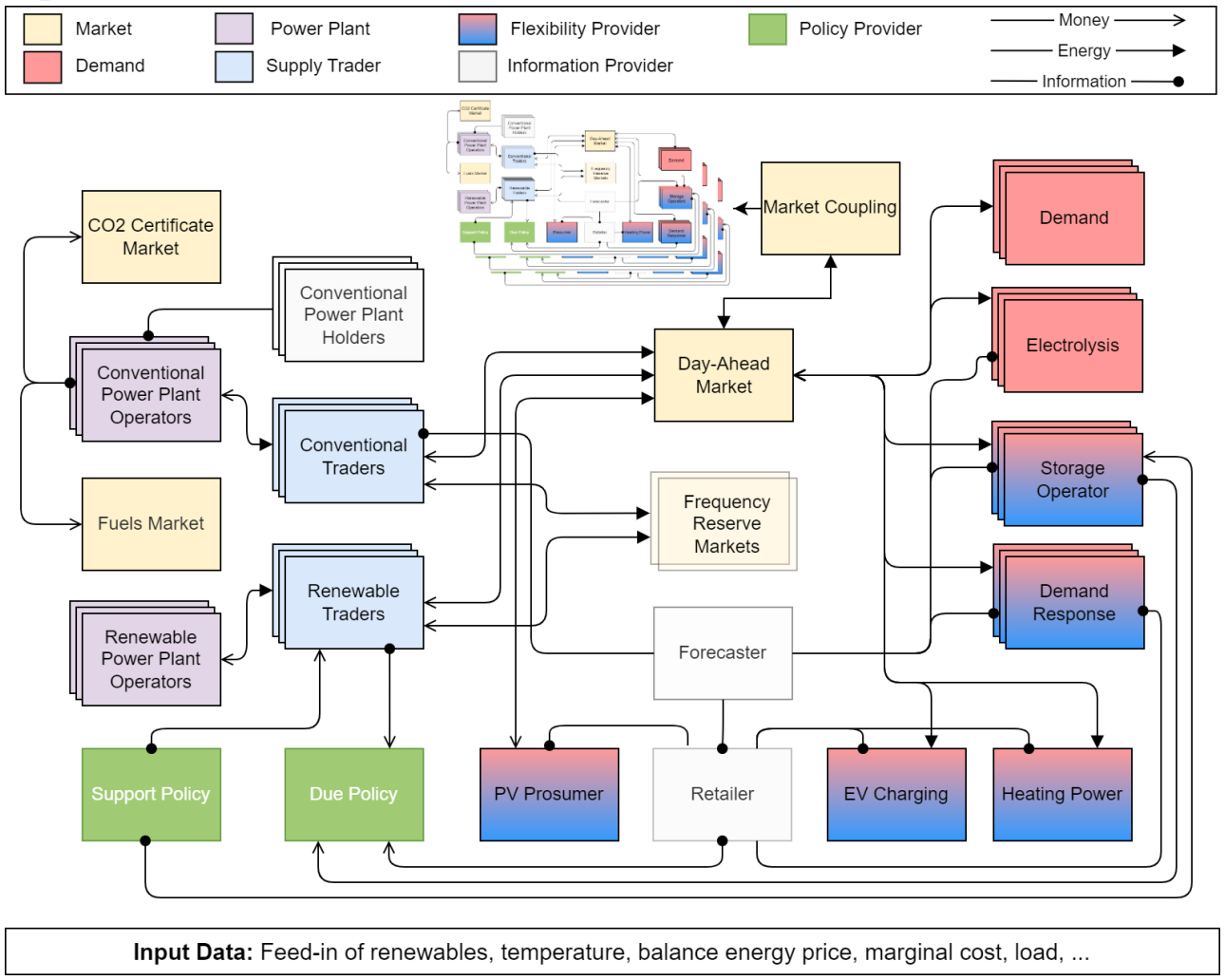
Utilizing the agent-based power market model AMIRIS

Capacity mix from POMMES

Power tariff design

- starting point: current payment obligation for a given load shifting **focus cluster**
- variation of
  - share of the **dynamic** energy tariff
  - **split** between **energy** and **capacity** tariff

AMIRIS



Input Data: Feed-in of renewables, temperature, balance energy price, marginal cost, load, ...

https://gitlab.com/dlr-ve/esy/amiris/amiris

Assessing microeconomic profitability

Utilizing the agent-based power market model AMIRIS

Capacity mix from POMMES

Power tariff design

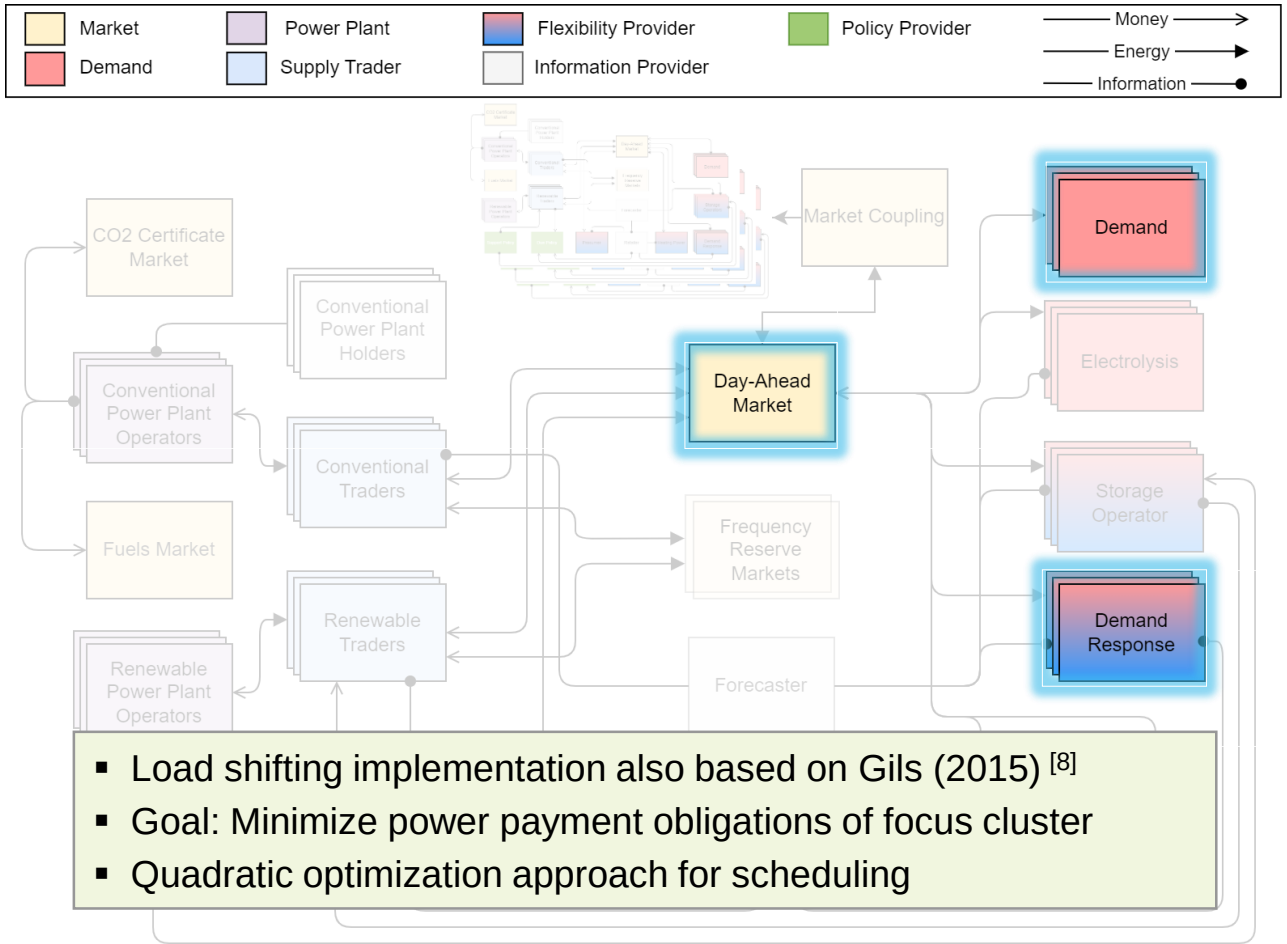
- starting point: current payment obligation for a given load shifting **focus cluster**
- variation of
  - share of the **dynamic** energy tariff
  - **split** between **energy** and **capacity** tariff

Assessment of profitability using net present values (NPV)

Overall goal: NPV ≈ 0

Interpretation:
system optimal investment choices are economically viable

AMIRIS



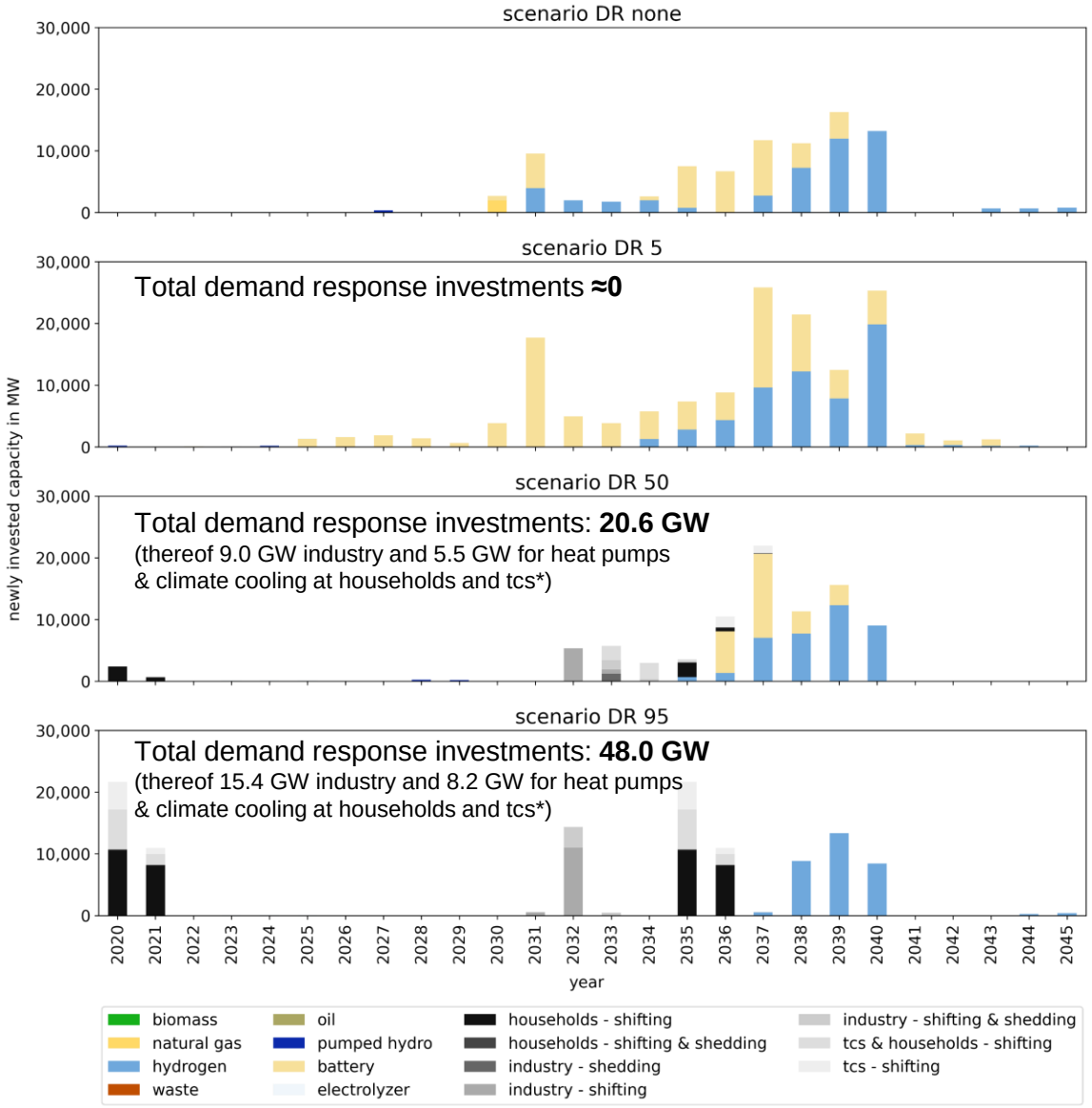
- Load shifting implementation also based on Gils (2015) [8]
- Goal: Minimize power payment obligations of focus cluster
- Quadratic optimization approach for scheduling

Input Data: Feed-in of renewables, temperature, balance energy price, marginal cost, load, ...

https://gitlab.com/dlr-ve/esy/amiris/amiris

Results: Overall economic potentials

Investments in backup capacity: demand response compete with batteries & H_2



Increased investments in demand response

Increased investments in batteries & H_2

Notes

- Brownfield Approach
- Backup only; RES expansion exogenous

Key findings

- 38 to 65 GW of **hydrogen-based** backup generation capacity until 2045
- **Effects** of demand-side flexibility on **H_2**
  → Capacity decreased up to 16 GW
  → Generation decreased up to 32 TWh
- Substitutional **competition** with **batteries** (E2P Ratio 2)
  → DR 5: 85 GW batteries
  → DR95: ≈0

*tcs: trade, commerce and services (commercial sector)

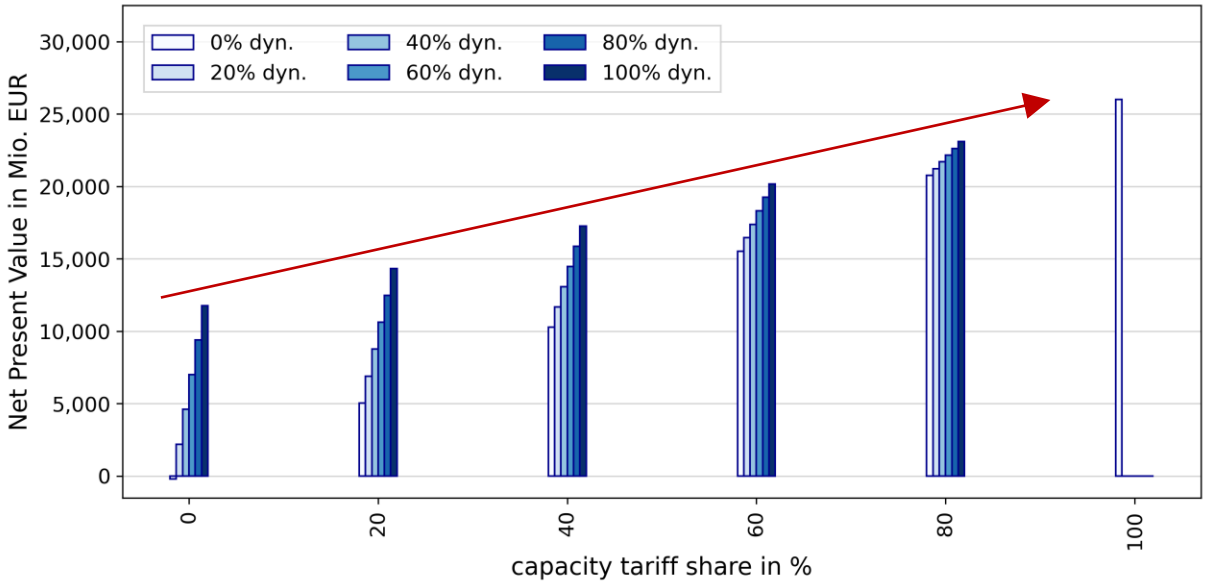
Results: Micro-economic assessments

NPVs for investments into demand response

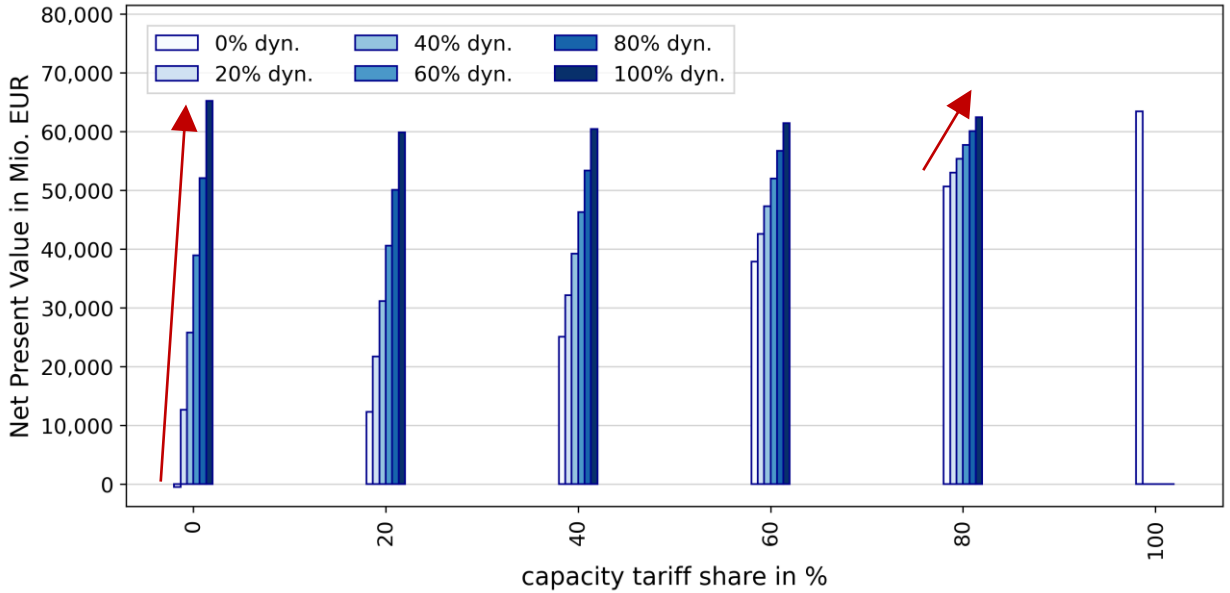
Cluster: Households, shifting only

Note the differently scaled axes!

DR 50



DR 95

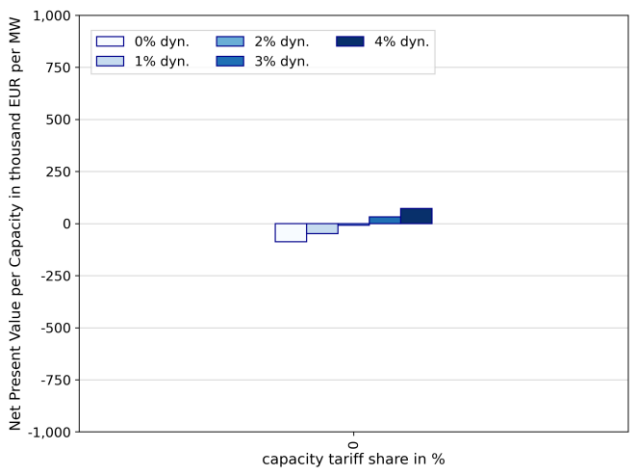
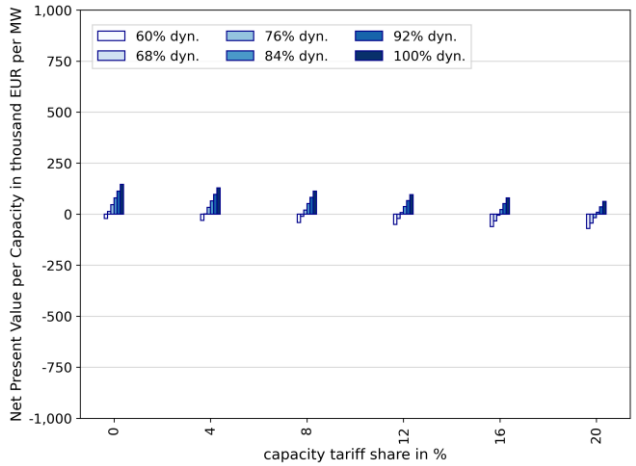
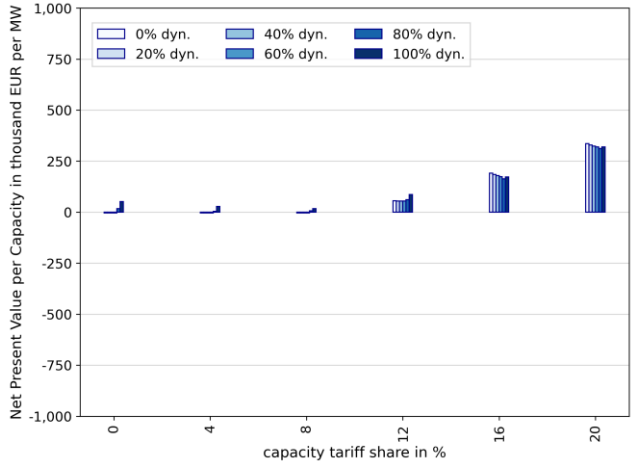
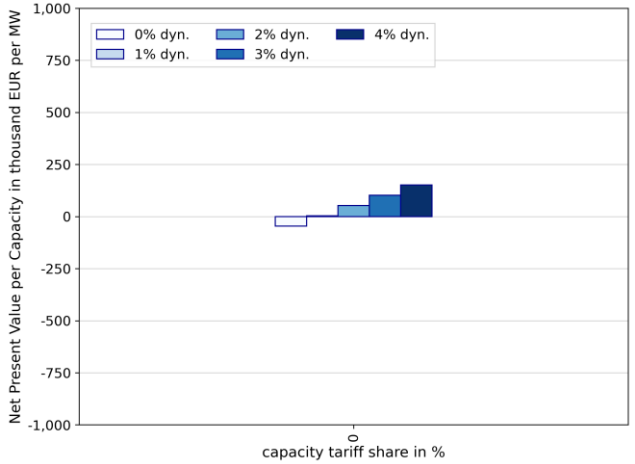
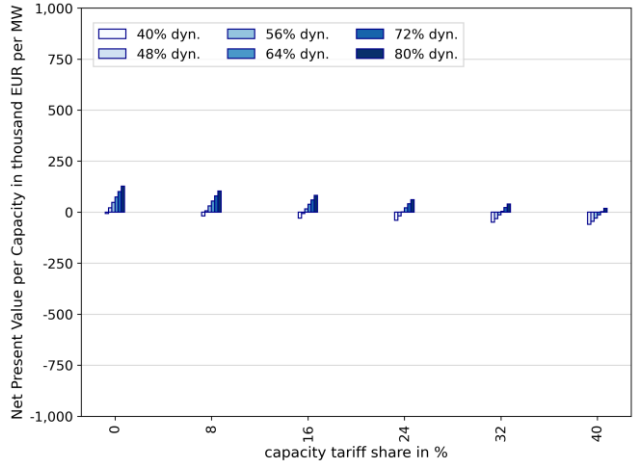
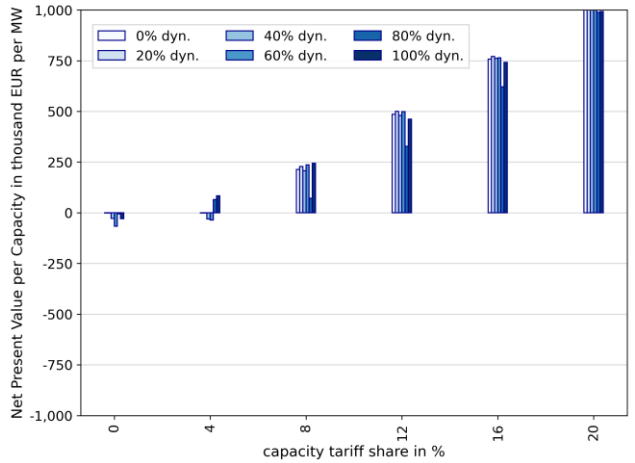


- Large impact of **scenario** on micro-economic attractiveness
- Large impact of **capacity payment** for scenario DR 50
- **Dynamic tariff incentive** is especially visible for cases with smaller capacity tariff shares → **Trade-off!**

Results: Congruence indicated by specific NPVs (€/MW)

Large differences in levels; different tariffs dependent on cluster and scenario

Load Shifting Focus Cluster

Demand Response Scenario	Households, shifting	Households, shifting & shedding	Industry, shifting
DR 50			
DR 95			

Results: Congruence indicated by specific NPVs (€/MW)

Large differences in levels; different tariffs dependent on cluster and scenario

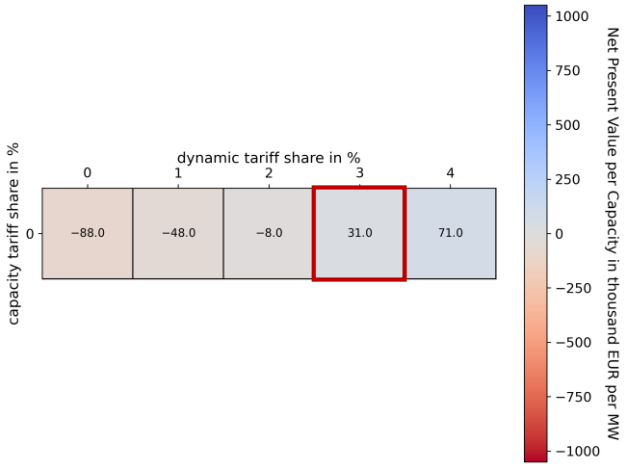
marked:
pos. NPVs with
smallest distance to 0

Load Shifting Focus Cluster

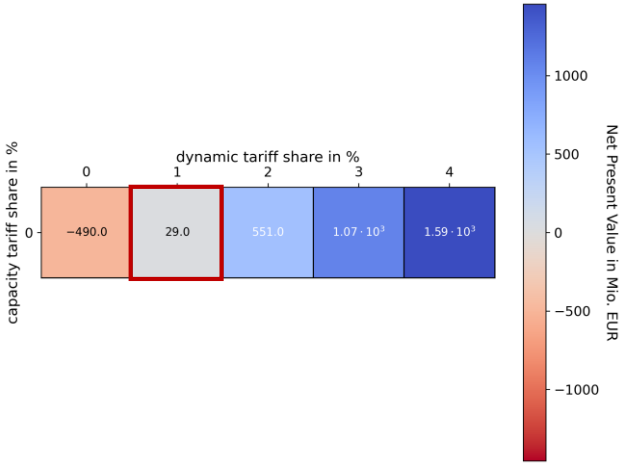
Households, shifting

Demand Response Scenario

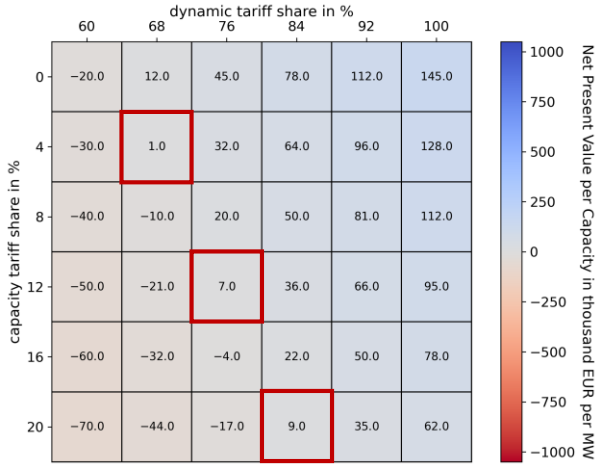
DR 50

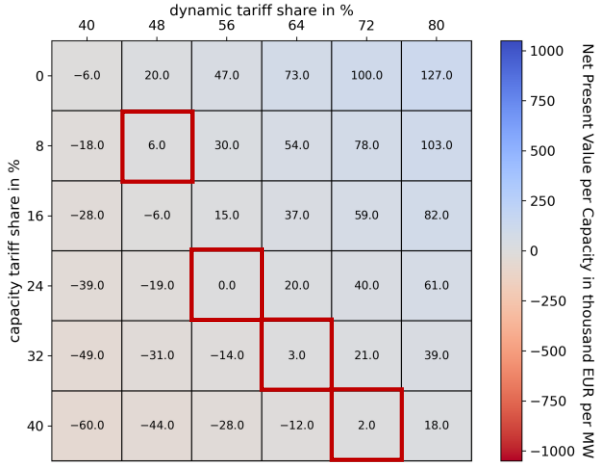


DR 95

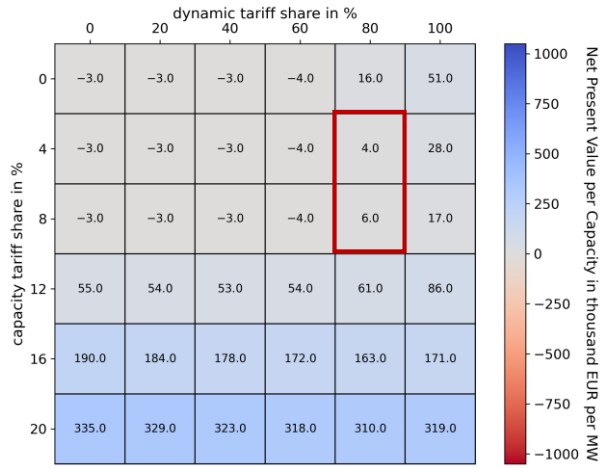


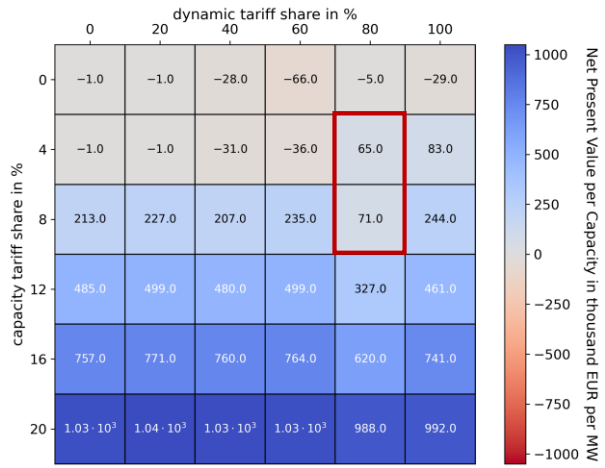
Households, shifting & shedding





Industry, shifting



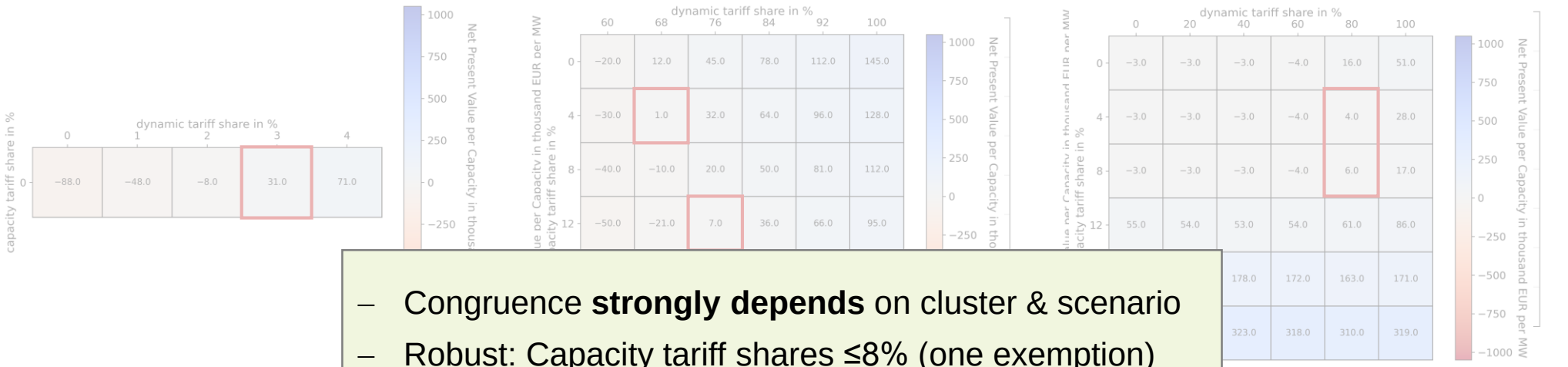
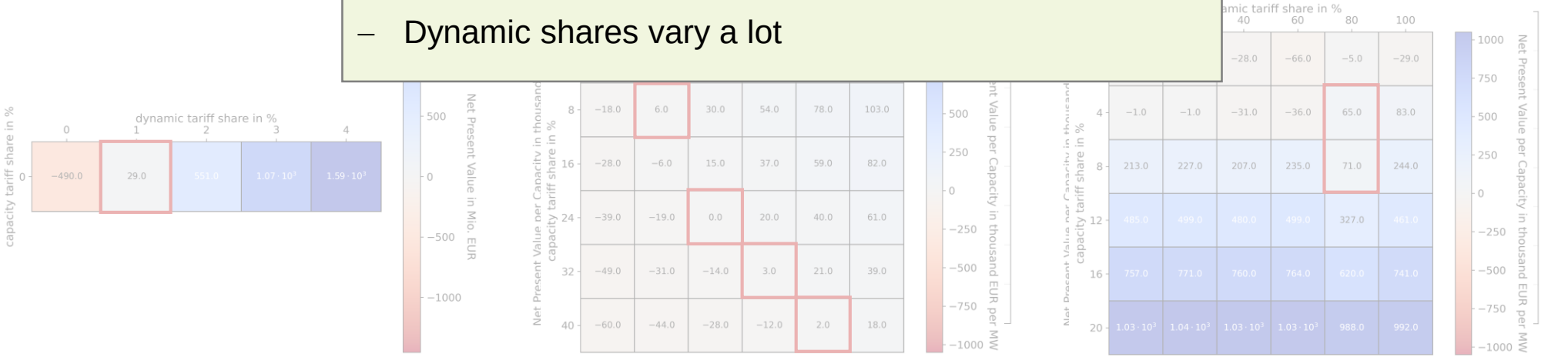


Results: Congruence indicated by specific NPVs (€/MW)

Large differences in levels; different tariffs dependent on cluster and scenario

marked:
pos. NPVs with
smallest distance to 0

Load Shifting Focus Cluster

Demand Response Scenario	Households, shifting	Households, shifting & shedding	Industry, shifting
DR 50			
DR 95			

- Congruence **strongly depends** on cluster & scenario
- Robust: Capacity tariff shares ≤8% (one exemption)
- Dynamic shares vary a lot

Conclusions

Summary

1
- Overall **economic potentials**
  - 20.6 GW for the average scenario
  - Up to 48 GW for the optimistic scenario
- Substitutional **competition** with batteries and H_2

2
- **Incentive effects**
  - For households, **dynamic** tariff is major driver
  - For industry and tcs **capacity** tariff dominates
  - **Trade-off** capacity vs. energy clearly visible

3
- **Power tariff design**
  - *No „One Size Fits It All“ solution*
  - Clear differences in level among clusters & scenarios
  - **None** or **small capacity tariffs** ≤8% prove robust

Implications & Outlook

1
- Regulatory **feasibility** of dynamization
  - Dynamic share up to 20% possible
  - Up to ≈65% in principle with regulatory changes
  - Problems: Network charges vs. market requirement
- **No plea** for high(er) capacity tariffs

2
- **Coordination among actors**
  - Number of actors involved → potential conflicts
  - **Options**: Dynamic tariffs with time-varying or dynamic network charges; or simple curtailments if needed

3
- **Further research needs**
  - Competition among & revenue cannibalization of flexibility options in the power sector
  - Studying risk aversion and imperfect foresight

Contact

M.Sc. **Johannes Kochems**

Research Associate

E Mail: johannes.kochems@dlr.de

Phone: +49 711 6862 8521

GitHub: @jokochems; @dlr-jk

GitLab: @dlr_jk

Deutsches Zentrum für Luft- und Raumfahrt e. V. (DLR)

German Aerospace Center

Institute of Networked Energy Systems | Energy System Analyses | Curiestraße 4 | 70563 Stuttgart | Germany

DLR.de/ve

Parts of this work were created in the course of the research project ERAFlex II (FKZ: 93EI1033A). The author does appreciate the funding.

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

Sources

- [1] Gerhardt, Norman; Böttger, Diana; Trost, Tobias; Scholz, Angela; Pape, Christian; Gerlach, Ann-Katrin; Härtel, Philipp; Ganal, Irina (2017): Analyse eines europäischen -95%-Klimazielszenarios über mehrere Wetterjahre. Teilbericht im Rahmen des Projektes: Klimawirksamkeit Elektromobilität - Entwicklungsoptionen des Straßenverkehrs unter Berücksichtigung der Rückkopplung des Energieversorgungssystems in Hinblick auf mittel- und langfristige Klimaziele. im Auftrag des BMUB. Fraunhofer IWES, Kassel.
- [2] Apel, Rolf; Aundrup, Thomas; Buchholz, Bernd Michael; Domels, Hans Peter; Funke, Stephan; Gesing, Thomas et al. (2012): Demand Side Integration. Lastverschiebungspotenziale in Deutschland (Gesamttext). Studie der Energietechnischen Gesellschaft im VDE (ETG). Hg. v. VDE. Frankfurt am Main.
- [3] Aryandoust, Arsam; Lilliestam, Johan (2017): The potential and usefulness of demand response to provide electricity system services. In: Applied Energy 204, S. 749–766. DOI: 10.1016/j.apenergy.2017.07.034.
- [4] Blum, Anne-Kathrin; Braun, Marco (2013): Potentialanalyse für das Demand Side Management im deutschen Industriesektor und die Integration in die Stromwirtschaft. In: Karlsruher Hochschulschriften für Wirtschaftsingenieurwesen und International Management (1).
- [5] Buber, Tim; Gruber, Anna; Klobasa, Marian; Roon, Serafin von (2013): Lastmanagement für Systemdienstleistungen und zur Reduktion der Spitzenlast. In: DIW Vierteljahreshefte zur Wirtschaftsforschung 82 (3), S. 89–106.
- [6] Focken, Ulrich; Bümmerstede, Jens; Klobasa, Marian (2011): Kurz- bis mittelfristig realisierbare Marktpotenziale für die Anwendung von Demand Response im gewerblichen Sektor. Öffentlicher Abschlussbericht. Hg. v. energy & meteo GmbH und Fraunhofer ISI. Oldenburg, Karlsruhe.
- [7] Gils, Hans Christian (2014): Assessment of the theoretical demand response potential in Europe. In: Energy 67, S. 1–18. DOI: 10.1016/j.energy.2014.02.019.
- [8] Gils, Hans Christian (2015): Balancing of Intermittent Renewable Power Generation by Demand Response and Thermal Energy Storage. Dissertation. Universität Stuttgart, Stuttgart.
- [9] Gils, Hans Christian (2016): Economic potential for future demand response in Germany – Modeling approach and case study. In: Applied Energy 162, S. 401–415. DOI: 10.1016/j.apenergy.2015.10.083.
- [10] Gobmaier, Thomas; Mauch, Wolfgang; Beer, Michael; Roon, Serafin von; Schmid, Tobias; Mezger, Thomás et al. (2012): Simulationsgestützte Prognose des elektrischen Lastverhaltens. im Auftrag von E.ON Energie, StMWFK und StMWIVT. Forschungsstelle für Energiewirtschaft. München.
- [11] Grote, Fabian; Drees, Tim; Budke, Jan; Moser, Albert (2013): Einfluss des Demand Side Managements auf den Kraftwerkseinsatz in Europa. In: et Energiewirtschaftliche Tagesfragen 63 (12), S. 32–36.

Sources

- [12] Gruber, Anna-Maria (2017): Zeitlich und regional aufgelöstes industrielles Lastflexibilisierungspotenzial als Beitrag zur Integration Erneuerbarer Energien. Dissertation. Technische Universität München, München. Lehrstuhl für Energiewirtschaft und Anwendungstechnik.
- [13] Gruber, Anna; Biedermann, Franziska; Roon, Serafin von; Carr, Luis (2014): Regionale Lastmanagement-Potenziale stromintensiver Prozesse. In: IEE TU Graz (Hg.): 13. Symposium Energieinnovation. 13. Symposium Energieinnovation. Graz, 12.-14.2.2014. Graz.
- [14] Haasz, Thomas (2017): Entwicklung von Methoden zur Abbildung von Demand Side Management in einem optimierenden Energiesystemmodell. Fallbeispiele für Deutschland in den Sektoren Industrie, Gewerbe, Handel, Dienstleistungen und Haushalte. Dissertation. Universität Stuttgart, Stuttgart. IER.
- [15] Henning, Hans-Martin; Sauer, Dirk Uwe (2015): Demand-Side-Management im Wärmemarkt. Technologiesteckbrief zur Analyse „Flexibilitätskonzepte für die Stromversorgung 2050“. Hg. v. acatech. Fraunhofer ISE; KIT; RWTH Aachen. München (Schriftenreihe Energiesysteme der Zukunft).
- [16] Klobasa, Marian (2009): Dynamische Simulation eines Lastmanagements und Integration von Windenergie in ein Elektrizitätsnetz. Stuttgart: Fraunhofer-IRB-Verl. (ISI-Schriftenreihe "Innovationspotenziale"), zuletzt geprüft am 07.09.2018.
- [17] Klobasa, Marian; Angerer, Gerhard; Lüllmann, Arne; Schleich, Joachim; Buber, Tim; Gruber, Anna; Hünecke, Marie (2013): Lastmanagement als Beitrag zur Deckung des Spitzenlastbedarfs in Süddeutschland. Endbericht. Hg. v. Agora Energiewende. Fraunhofer ISI, Forschungsgesellschaft für Energiewirtschaft. Karlsruhe, München, Berlin.
- [18] Ladwig, Theresa (2018): Demand Side Management in Deutschland zur Systemintegration erneuerbarer Energien. Dissertation. Technische Universität Dresden, Dresden.
- [19] Langrock, Thomas; Achner, Siggi; Jungbluth, Christian; Marambio, Constanze; Michels, Armin; Weinhard, Paul et al. (2015): Potentiale regelbarer Lasten in einem Energieversorgungssystem mit wachsendem Anteil erneuerbarer Energien. Im Auftrag des Umweltbundesamts. Hg. v. UBA. BET, Trianel. Aachen, Dessau-Roßlau.
- [20] Liebe, Andrea; Wissner, Matthias (2015): Der flexible Verbraucher - Potenziale zur Lastverlagerung im Haushaltsbereich. Studie für das Ministerium für Ländlichen Raum und Verbraucherschutz Baden-Württemberg und das Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg. WIK. Bad Honnef.
- [21] Molly, Jens Peter; Neddermann, Bernd; Schorer, Till; Callies, Doron; Knorr, Kaspar; Rohrig, Kurt et al. (2010): dena-Netzstudie II. Integration erneuerbarer Energien in die deutsche Stromversorgung im Zeitraum 2015 – 2020 mit Ausblick 2025. Endbericht. Unter Mitarbeit von Thomas Benz, Ervin Spahic, Adrian Amelung, Fritz Crotogino, Holger Müller, Ronald Völzke et al. Hg. v. dena. EWI; 50Hertz; Amprion; DEWI; EnBW TNG; Fraunhofer IWES; TenneT; FH Köln; Uni Kassel. Berlin.

Sources

- [22] Paulus, Moritz; Borggrefe, Frieder (2011): The potential of demand-side management in energy-intensive industries for electricity markets in Germany. In: Applied Energy 88 (2), S. 432–441. DOI: 10.1016/j.apenergy.2010.03.017.
- [23] Pellinger, Christoph; Schmid, Tobias (2016): Verbundforschungsvorhaben Merit Order der Energiespeicherung im Jahr 2030. Teil 2: Technoökonomische Analyse Funktionaler Energiespeicher. FfE. München, zuletzt geprüft am 20.03.2019.
- [24] r2b (2014): Endbericht Leitstudie Strommarkt. Arbeitspaket Funktionsfähigkeit EOM & Impact-Analyse Kapazitätsmechanismen. im Auftrag des Bundesministeriums für Wirtschaft und Energie. Köln.
- [25] Roon, Serafin von; Gobmaier, Thomas (2010): Demand Response in der Industrie. Status und Potenziale in Deutschland. München.
- [26] Scholz, Yvonne; Gils, Hans Christian; Pregger, Thomas; Heide, Dominik; Cebulla, Felix; Cao, Karl-Kiên et al. (2014): Möglichkeiten und Grenzen des Lastausgleichs durch Energiespeicher, verschiebbare Lasten und stromgeführte KWK bei hohem Anteil fluktuierender erneuerbarer Stromerzeugung. BMWI, DLR. Stuttgart.
- [27] Stadler, Ingo (2006): Demand Response. Nichtelektrische Speicher für Elektrizitätsversorgungssysteme mit hohem Anteil erneuerbarer Energien. Zugl.: Kassel, Univ., Habil., 2006. Berlin: dissertation.de (Habilitation), zuletzt geprüft am 19.09.2018.
- [28] Steurer, Martin (2017): Analyse von Demand Side Integration im Hinblick auf eine effiziente und umweltfreundliche Energieversorgung. Dissertation. Universität Stuttgart, Stuttgart. Institut für Energiewirtschaft und Rationelle Energieanwendung (IER).
- [29] Steurer, Martin; Klempp, Nikolai; Hufendiek, Kai; Baumgart, Bastian; Steinhausen, Burkhard (2015): Identifikation und Realisierung wirtschaftlicher Potenziale für Demand Side Integration in der Industrie in Deutschland. IER; Trianel. Stuttgart, Aachen.
- [30] Stötzer, Martin (2012): Demand Side Integration in elektrischen Verteilnetzen. Potenzialanalyse und Bewertung. Dissertation an der Otto-von-Guericke-Universität Magdeburg. Magdeburg (Res electricae Magdeburgenses, 45).
- [31] Styczynski, Zbigniew A.; Sauer, Dirk Uwe; Aundrup, Thomas; Hanson, Jutta; Madlener, Reinhard; Markowz, Georg et al. (2015): Demand-Side-Management im Strommarkt. Technologiesteckbrief zur Analyse „Flexibilitätskonzepte für die Stromversorgung 2050“. Hg. v. Zbigniew A. Styczynski und Dirk Uwe Sauer. Otto-von-Guericke-Universität Magdeburg; RWTH Aachen. München (Energiesysteme der Zukunft).
- [32] Sauer, Alexander; Abele, Eberhard; Buhl, Hans Ulrich (2019): Energieflexibilität in der deutschen Industrie. Ergebnisse aus dem Kopernikus-Projekt - Synchronisierte und energieadaptive Produktionstechnik zur flexiblen Ausrichtung von Industrieprozessen auf eine fluktuierende Energieversorgung (SynErgie).

Sources

- [33] Ausfelder, Florian; Seitz, Antje; Roon, Serafin von (Hg.) (2018): Flexibilitätsoptionen in der Grundstoffindustrie. Methodik, Potenziale, Hemmnisse: Bericht des AP V.6 "Flexibilitätsoptionen und Perspektiven in der Grundstoffindustrie" im Kopernikus-Projekt "SynErgie - synchronisierte und erngieadaptive Produktionstechnik zur flexiblen Ausrichtung von Industrieprozessen auf eine fluktuierende Energieversorgung". Kopernikus-Projekt "SynErgie". DECHEMA; DLR; FfE; BFI; DIW; FGF; HVG; TUM; VDZ; Wuppertal Institut. 1. Auflage. Frankfurt am Main: DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V.
- [34] Heitkötter, Wilko; Schyska, Bruno U.; Schmidt, Danielle; Medjroubi, Wided; Vogt, Thomas; Agert, Carsten (2021): Assessment of the regionalised demand response potential in Germany using an open source tool and dataset. In: Advances in Applied Energy 1, S. 100001. DOI: 10.1016/j.adapen.2020.100001.
- [35] Müller, Mathias; Reinhard, Janis; Ostermann, Adrian; Estermann, Thomas; Köppel, Simon (2019): Regionales Flexibilitäts-Potenzial dezentraler Anlagen. Modellierung und Bewertung des regionalen Flexibilitäts-Potenzials von dezentralen Flexibilitäts-Typen im Verteilnetz. Tagung "Zukünftige Stromnetze für Erneuerbare Energien“. FfE München.
- [36] Wohlfarth, Katharina; Klobasa, Marian; Gutknecht, Ralph (2020): Demand response in the service sector – Theoretical, technical and practical potentials. In: Applied Energy 258, S. 114089. DOI: 10.1016/j.apenergy.2019.114089.
- [37] Märkle-Huß, Joscha; Feuerriegel, Stefan; Neumann, Dirk (2018): Large-scale demand response and its implications for spot prices, load and policies: Insights from the German-Austrian electricity market. In: Applied Energy 210, S. 1290–1298. DOI: 10.1016/j.apenergy.2017.08.039.
- [38] Jetter, Fabian; Veitengruber, Frank; Schmid, Tobias; Guminski, Andrej; Roon, Serafin von; Hübner, Tobias; Staschus, Konstantin; Creutzburg, Philipp; Sach, Thobias (2021): Regionale Lastmanagementpotenziale. Quantifizierung bestehender und zukünftiger Lastmanagementpotenziale in Deutschland
- [39] Ashok, S.; Banerjee, R. (2001): An optimization mode for industrial load management. In: IEEE Trans. Power Syst. 16 (4), S. 879–884. DOI: 10.1109/59.962440.
- [40] Babu, C. A.; Ashok, S. (2008): Peak Load Management in Electrolytic Process Industries. In: IEEE Trans. Power Syst. 23 (2), S. 399–405. DOI: 10.1109/TPWRS.2008.920732.
- [41] Su, Chua Liang (2007): Optimal Demand-Side Participation in Day-Ahead Electricity Markets. University of Manchester, Manchester.
- [42] Gholian, A.; Mohsenian-Rad, H.; and (2013): Optimal industrial load control in smart grid: A case study for oil refineries. In: IEEE (Hg.): IEEE Power Energy Society General Meeting 2013. 2013 IEEE Power Energy Society General Meeting, 2013/07, S. 1–5.
- [43] Shrouf, Fadi; Ordieres-Meré, Joaquin; García-Sánchez, Alvaro; Ortega-Mier, Miguel (2014): Optimizing the production scheduling of a single machine to minimize total energy consumption costs. In: Journal of Cleaner Production 67, S. 197–207. DOI: 10.1016/j.jclepro.2013.12.024.

Sources

- [44] Ding, Y. M.; Hong, S. H.; Li, X. H. (2014): A Demand Response Energy Management Scheme for Industrial Facilities in Smart Grid. In: IEEE Transactions on Industrial Informatics 10 (4), S. 2257–2269. DOI: 10.1109/TII.2014.2330995.
- [45] Luo, Zhe; Hong, Seung-Ho; Kim, Jong-Beom (2016): A Price-Based Demand Response Scheme for Discrete Manufacturing in Smart Grids. In: Energies 9 (8), S. 650. DOI: 10.3390/en9080650.
- [46] Geipel, Jasper (2016): Marktanalyse von Demand Response Maßnahmen.
- [47] Schwabeneder, Daniel; Lettner, Georg; Burgholzer, Bettina; Wien, T. U.: Ökonomische Analyse des Demand- Response-Potentials von aggregierten Lasten am Spotmarkt, S. 15.
- [48] Gartner, Mathias; Kochems, Johannes; Seim, Stephan; Müller-Kirchenbauer, Joachim (2019): Ein einzelwirtschaftliches Bewertungsmodell für Nachfrageflexibilisierung im Stromsektor. TU Berlin, Fachgebiet Energie- und Ressourcenmanagement; E.ON Inhouse Consulting. Berlin (Working Paper Energie und Ressourcen).
- [49] Allcott, Hunt (2011): Rethinking real-time electricity pricing. In: Resource and Energy Economics 33 (4), S. 820–842. DOI: 10.1016/j.reseneeco.2011.06.003.
- [50] Alsalloum, Hala; Merghem-Boulahia, Leila; Rahim, Rana (2020): A systematical analysis on the dynamic pricing strategies and optimization methods for energy trading in smart grids. In: Int Trans Electr Energ Syst 30 (9). DOI: 10.1002/2050-7038.12404.
- [51] Bejan, Ioana; Jensen, Carsten Lynge; Andersen, Laura M.; Hansen, Lars Gårn (2021): Inducing flexibility of household electricity demand: The overlooked costs of reacting to dynamic incentives. In: Applied Energy 284, S. 116283. DOI: 10.1016/j.apenergy.2020.116283.
- [52] Blaschke, Maximilian J. (2022): Dynamic pricing of electricity: Enabling demand response in domestic households. In: Energy Policy 164, S. 112878. DOI: 10.1016/j.enpol.2022.112878.
- [53] Bonin, Michael; Dörre, Elias; Al-Khzouz, Hadi; Braun, Martin; Zhou, Xian (2022): Impact of Dynamic Electricity Tariff and Home PV System Incentives on Electric Vehicle Charging Behavior: Study on Potential Grid Implications and Economic Effects for Households. In: Energies 15 (3), S. 1079. DOI: 10.3390/en15031079.
- [54] Chen, Lu; Yang, Yongbiao; Xu, Qingshan (2021): Retail dynamic pricing strategy design considering the fluctuations in day-ahead market using integrated demand response. In: International Journal of Electrical Power & Energy Systems 130, S. 106983. DOI: 10.1016/j.ijepes.2021.106983.
- [55] Ensslen, Axel; Ringler, Philipp; Dörr, Lasse; Jochem, Patrick; Zimmermann, Florian; Fichtner, Wolf (2018): Incentivizing smart charging: Modeling charging tariffs for electric vehicles in German and French electricity markets. In: Energy Research & Social Science 42, S. 112–126. DOI: 10.1016/j.erss.2018.02.013.

Sources

- [56] Faruqui, Ahmad; Hledik, Ryan; Palmer, Jennifer (2012): Time-Varying and Dynamic Rate Design. Hg. v. RAP. The Brattle Group. Montpelier, Vermont (Global Best Practice Series).
- [57] Faruqui, Ahmad; Sergici, Sanem (2010): Household response to dynamic pricing of electricity: a survey of 15 experiments. In: J Regul Econ 38 (2), S. 193–225.
- [58] Fikru, Mahelet G.; Atherton, Jeorge; Canfield, Casey I. (2022): Cost-reflective dynamic electricity pricing for prosumers. In: The Electricity Journal 35 (1), S. 107075. DOI: 10.1016/j.tej.2022.107075.
- [59] Freier, Julia; Arnold, Mark; Hesselbach, Jens (2019): Introduction of an approach to develop dynamic. In: 2019 16th International Conference on the European Energy Market (EEM). 2019 16th International Conference on the European Energy Market (EEM). Ljubljana, Slovenia, 18.09.2019 - 20.09.2019: IEEE, S. 1–6.
- [60] Freier, Julia; Loessl, Victor von (2022): Dynamic electricity tariffs: Designing reasonable pricing schemes for private households. In: Energy Economics 112, S. 106146. DOI: 10.1016/j.eneco.2022.106146.
- [61] Frontier Economics; BET (2016): Kosten und Nutzen einer Dynamisierung von Strompreiskomponenten als Mittel zur Flexibilisierung der Nachfrage. Bericht für das Bundesministerium für Wirtschaft und Energie. Köln, Aachen. Online verfügbar unter https://www.bmwi.de/Redaktion/DE/Publikationen/Studien/kosten-nutzen-dynamisierung-strompreiskomponenten.pdf?__blob=publicationFile&v=4, zuletzt geprüft am 03.02.2022.
- [62] Gambardella, Christian; Pahle, Michael; Schill, Wolf-Peter (2020): Do Benefits from Dynamic Tariffing Rise? Welfare Effects of Real-Time Retail Pricing Under Carbon Taxation and Variable Renewable Electricity Supply. In: Environ Resource Econ 75 (1), S. 183–213. DOI: 10.1007/s10640-019-00393-0.
- [63] Hayn, Marian (2016): Modellgestützte Analyse neuer Stromtarife für Haushalte unter Berücksichtigung bedarfsorientierter Versorgungssicherheitsniveaus. Dissertation, Karlsruher Institut für Technologie (KIT), Fakultät für Wirtschaftswissenschaften, 2016. Karlsruhe: KIT Scientific Publishing (Produktion und Energie, Band 13).
- [64] Jahn, Andreas (2014): Netzentgelte in Deutschland. Herausforderungen und Handlungsoptionen. Hg. v. Agora Energiewende. RAP. Berlin.
- [65] Karg, Ludwig; Kleine-Hegermann, Kerstin; Wedler, Michael; Jahn, Christopher (2014): E-Energy Abschlussbericht. Ergebnisse und Erkenntnisse aus der Evaluation der sechs Leuchtturmprojekte. B.A.U.M. Consult. München, Berlin.
- [66] Khan, Ahsan Raza; Mahmood, Anzar; Safdar, Awais; Khan, Zafar A.; Khan, Naveed Ahmed (2016): Load forecasting, dynamic pricing and DSM in smart grid: A review. In: Renewable and Sustainable Energy Reviews 54, S. 1311–1322. DOI: 10.1016/j.rser.2015.10.117.

Sources

- [67] Klein, Martin; Ziade, Ahmad; Vries, Laurens (2019): Aligning prosumers with the electricity wholesale market – The impact of time-varying price signals and fixed network charges on solar self-consumption. In: Energy Policy 134, S. 110901. DOI: 10.1016/j.enpol.2019.110901.
- [68] Krishnamurthy, Chandra Kiran B.; Vesterberg, Mattias; Böök, Herman; Lindfors, Anders V.; Svento, Rauli (2018): Real-time pricing revisited: Demand flexibility in the presence of micro-generation. In: Energy Policy 123, S. 642–658. DOI: 10.1016/j.enpol.2018.08.024.
- [69] Löschel, Andreas; Werthschulte, Madeline (2017): Smart Energy zur Flexibilisierung und Senkung des Energieverbrauchs - Handlungsoptionen und offene Fragen. In: et Energiewirtschaftliche Tagesfragen 67 (8), 19-23.
- [70] Nabe, Christian; Beyer, Carina; Brodersen, Nils; Schäffer, Harald; Adam, Dietmar; Heinemann, Christoph et al. (2009): Einführung von lastvariablen und zeitvariablen Tarifen. Im Auftrag der Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen. Ecofys, EnCT, BBH. Berlin.
- [71] Nezamoddini, Nasim; Wang, Yong (2017): Real-time electricity pricing for industrial customers: Survey and case studies in the United States. In: Applied Energy 195, S. 1023–1037. DOI: 10.1016/j.apenergy.2017.03.102.
- [72] Saumweber, Andrea; Wederhake, Lars; Cardoso, Gonçalo; Fridgen, Gilbert; Heleno, Miguel (2021): Designing Pareto optimal electricity retail rates when utility customers are prosumers. In: Energy Policy 156, S. 112339. DOI: 10.1016/j.enpol.2021.112339.
- [73] Schnurre, Sebastian (2014): Variable Tarife aus dem Blickwinkel der Lastverlagerung. In: Energiewirtschaftliche Tagesfragen 64 (6), S. 53–57.
- [74] Schreiber, Michael; Wainstein, Martin E.; Hochloff, Patrick; Dargaville, Roger (2015): Flexible electricity tariffs. Power and energy price signals designed for a smarter grid. In: Energy 93, S. 2568–2581. DOI: 10.1016/j.energy.2015.10.067.
- [75] Kochems, Johannes (2020): Lastflexibilisierungspotenziale in Deutschland – Bestandsaufnahme und Entwicklungsprojektionen, Langfassung: In: Tagungsband 16. Symposium Energieinnovation, 12.-14.02.2020, Graz.

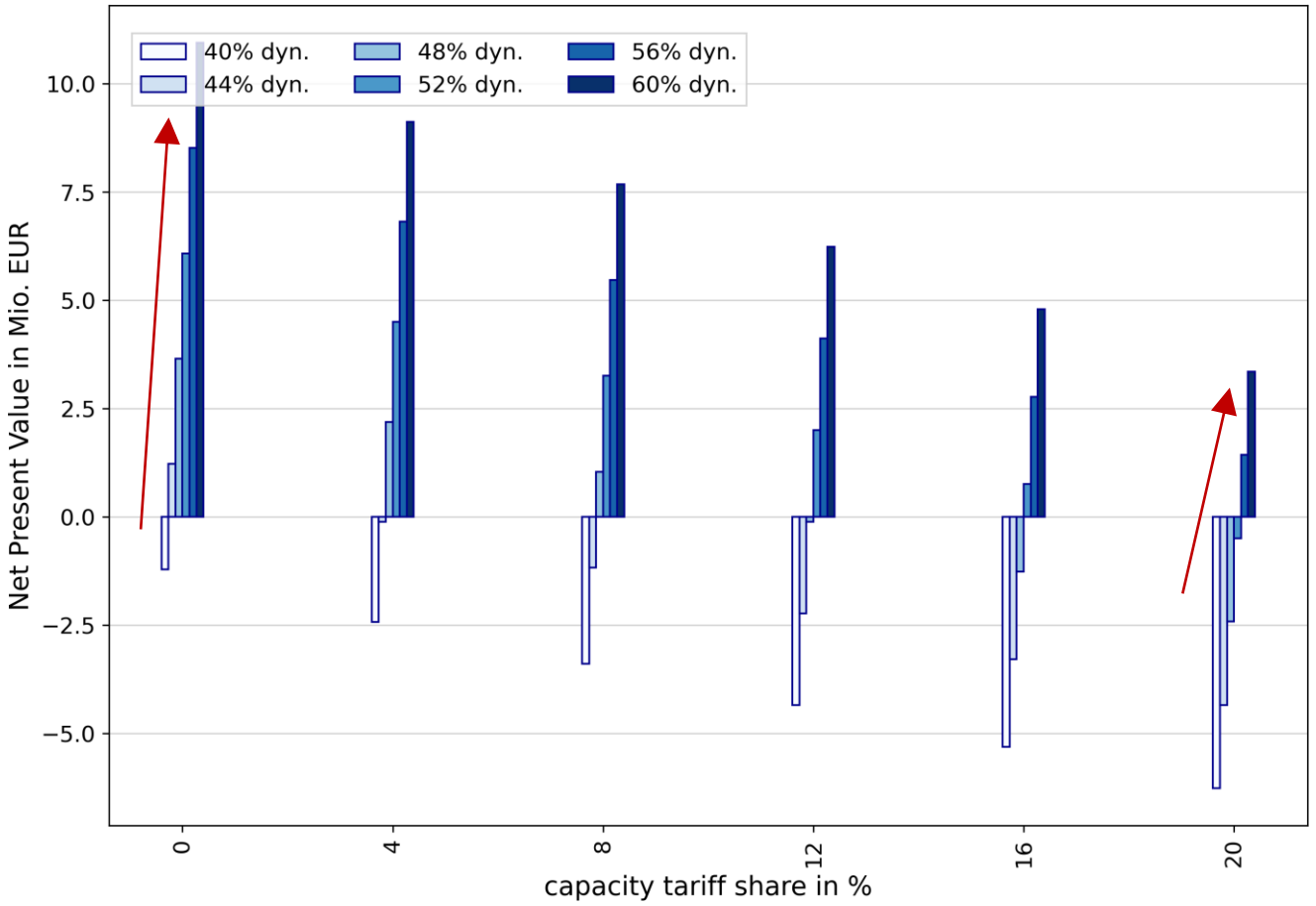
BACKUP

Evaluating Demand Response Potentials in the climate-neutral German Power System

Results: Micro-economic assessments (ctd.)

NPVs for investments into demand response

Cluster: Households, shifting & shedding



- Profitability **decreases** for increasing capacity tariff shares
- *Explanation*: For selected cluster, there is an unavailability for load shifting at peak load times
- **Trade-off** between dynamic incentive and capacity tariff incentive again obvious