Welfare redistribution through flexibility - Who pays?

Polina Emelianova and Nils Namockel

12.04.2024

Motivation: Quantifying economic benefits of flexibility from the system and end-consumer perspective

- Deployment of RES requires flexibility
  - **Heat pumps** can provide demand flexibility by deploying passive and active storages
  - **Electric vehicles** can provide both positive (V2G) and negative (flexible charging) flexibility
- Unfolding flexibility potential of these technologies has economic consequences for both the system and end-users.

Market clearing and electricity price formation

- Top-down analysis of system-wide effects of flexibility
- E.g., Härtel and Korpas (2021), Böttger and Härtel (2022), Nagel et al. (2022), Felling and Fortenbacher (2022)
- Depict the end-users as a homogenous group
- ➢ Overlook the behavior of specific user groups

Welfare effects and technology-specific market values

- The impact of the variability of solar and wind power (Hirth, 2013), sector coupling (Bernath et al., 2021) or electrolyzers (Ruhnau, 2022) on the market values of renewables
- Welfare effects of flexibility deployment on flexibility suppliers (Böttger and Härtel, 2022; Nagel et al., 2022)
  - ➢ No variation in flexibility strategies and user group specifics

- The distinct behavioral limitations due to diverse flexibility options have an impact on the corresponding financial gains or drains of various producer and consumer groups

Research Questions and Research Design

How do different degrees of flexibility deployment among heterogeneous end-consumers affect total system costs?

How do electricity costs and revenues change for different consumer and producer groups by varying flexibility deployment?

1. **Modeling** of the European energy system dispatch of 2030 using DIMENSION. Normative scenario with national technology and climate targets. Focus on Germany and the following end-use sectors
   - Road transport: 10 heterogeneous mobility clusters
   - Decentral Heating: different building types and heat pump technologies
2. **Use Case definition** in relation to the use of flexibility in end-use sectors

Use Cases for end-use sectors		Heating sector	
		inflexible (only with buildings' inertia)	flexible (with additional heat storage)
Transport sector	inflexible	M0/H0	M0/H1
	flexible (DSM)	M1/H0	M1/H1
	flexible + V2X	M2/H0	M2/H1

3. **Analysis**
   - Without flexibility (M0/H0): Electricity prices, producers' revenues and consumer's electricity costs
   - With flexibility: Changes of electricity prices, producers' revenues and consumer's electricity costs; total system effects

EWI building tool is used to simulate German buildings stock for 2030 and introduce distinct heating user groups in DIMENSION

Building stock

Building type
Heating type
Energy demand

Building stock development

Renovation rate
Construction rate
Demolition rate

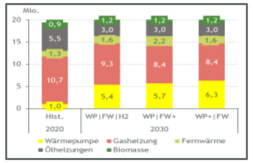
Technology development

Heating systems (new and existing)
Replacement rates

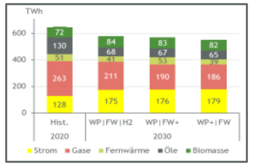
EWI Building Tool

Results

Heating stock



Final energy demand



- Final energy demand for residential and commercial buildings
- Number of heat pumps per building type

Inflexible heat pump use

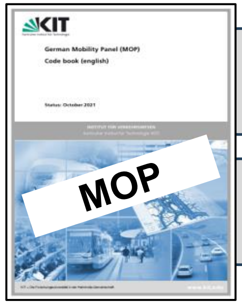
- In the inflexible use case heat pump deployment can deviate from the exogenous heating demand profile according to the storage volume of the building's inertia

Flexible heat pump use

- In the flexible heat pump use case, an additional active thermal storage (+1h) enables a more flexible electricity consumption of a heat pump

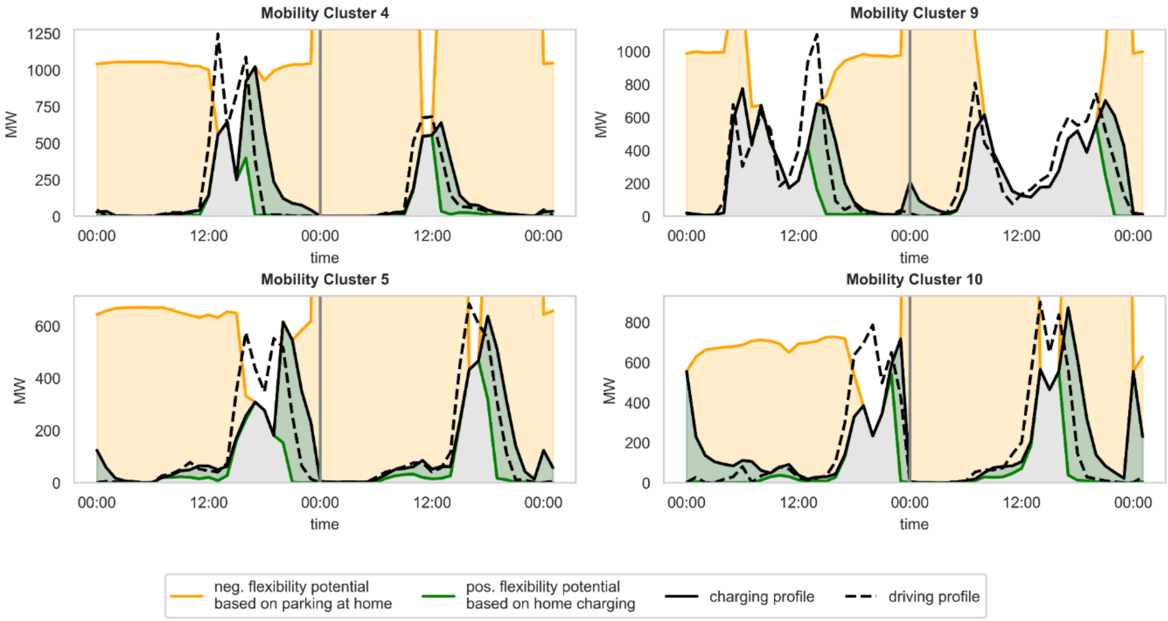
Residential buildings				Commercial buildings		
	Build1	Build2	Build3		Build4	Build5
ASHP	Build1 ASHP	Build2 ASHP	Build3 ASHP	ASHP	Build4 ASHP	Build5 ASHP
GSHP	Build1 GSHP	Build2 GSHP	Build3 GSHP	GSHP	Build4 GSHP	Build5 GSHP

Electric vehicles are represented with different mobility cluster accounting for heterogeneity in the road transport sector



Information on trips and locations
(we only focus on home charging)

Computation of hourly driving, parking and charging profiles



Non-flexible charging

- Electric vehicle charge according to the fixed charging profile

Flexibility

- Flexibility is limited by positive and negative potentials.
- Electric vehicle can adjust charging processes within these boundaries
- The storage daysaldo must be equal to the daily electricity demand according to the non-flexible charging profile

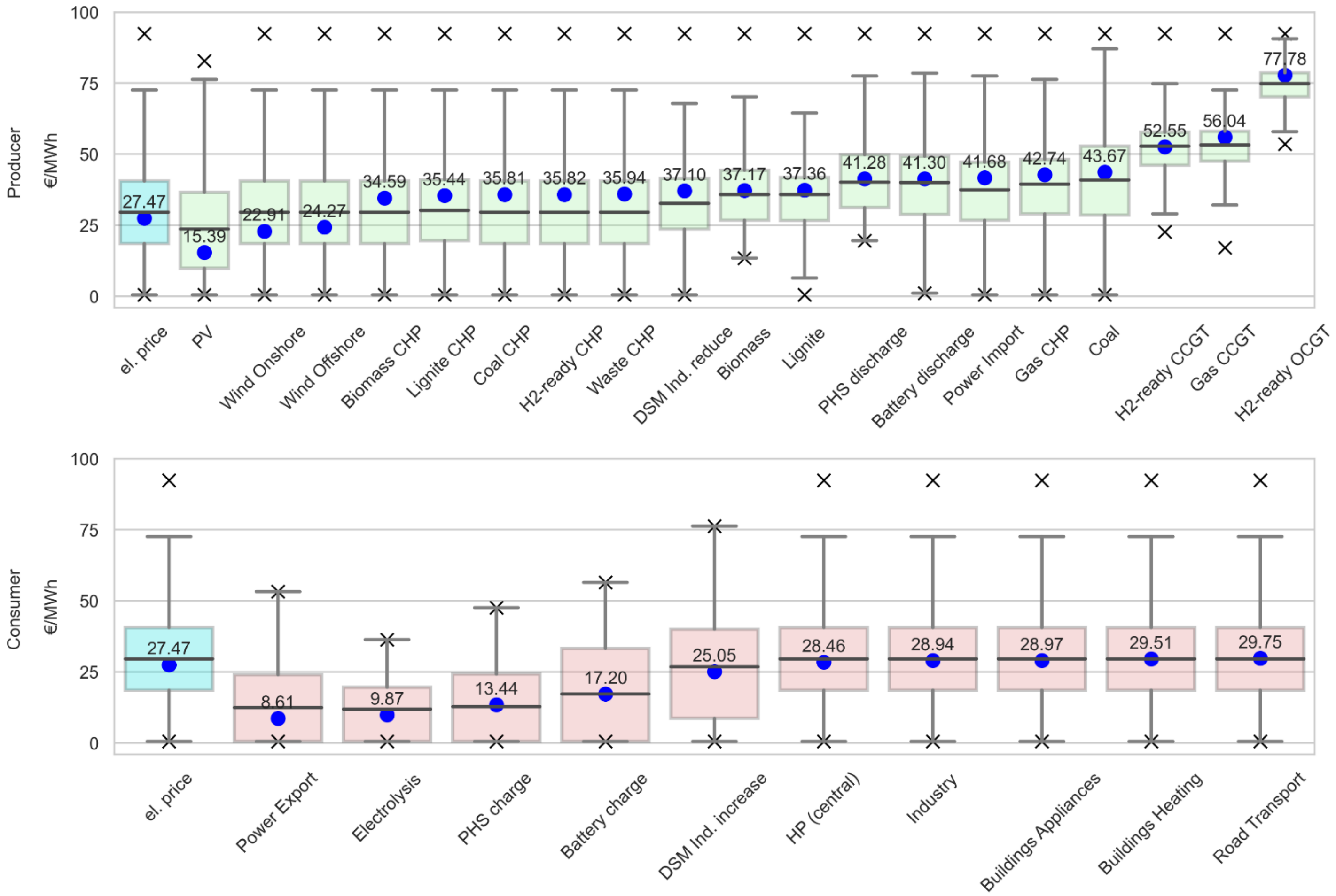
Vehicle to Grid / Building (V2X)

- Additionally, electric vehicle can provide electricity to the market
- The potential is limited by the negative sum of the positive and negative flexibility potential
- The storage daysaldo must be equal to the daily electricity demand according to the non-flexible charging profile

Modelling optimal dispatch decisions for Germany for the year 2030 under different flexibility use cases

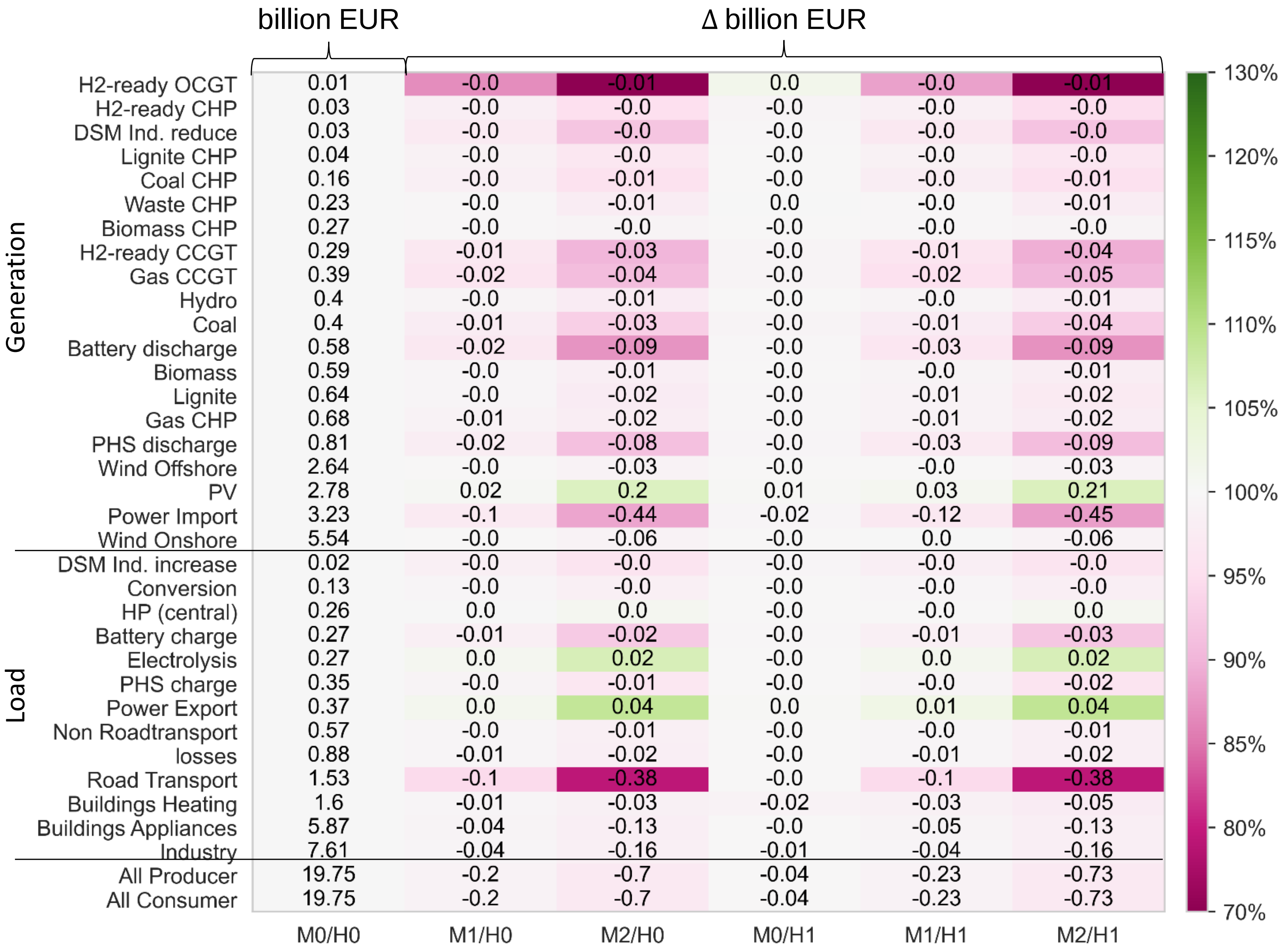
Use Cases for end-use sectors		Heating sector: inflexible (only with buildings' inertia)	Heating sector: flexible (with additional heat storage)
Transport sector	inflexible	M0/H0	M0/H1
Transport sector	flexible (DSM)	M1/H0	M1/H1
Transport sector	flexible + V2X	M2/H0	M2/H1

Market values of electricity generating technologies indicate the merit order function. On the demand side, average electricity prices paid by the end-consumers reflects their load flexibility



- In the absence of flexibility deployment (M0/H0), the average electricity price (marginal electricity generation cost) equals 27.47 EUR/MWh
- Market values - defined as the average revenue from each unit of electricity sold – indicate the merit order function
  - Blue dots reflect the volume weighted market values for producers/electricity costs for consumers
  - Box plot visualize distribution of hourly data points without volume weights
  - Crosses represent minimum and maximum values

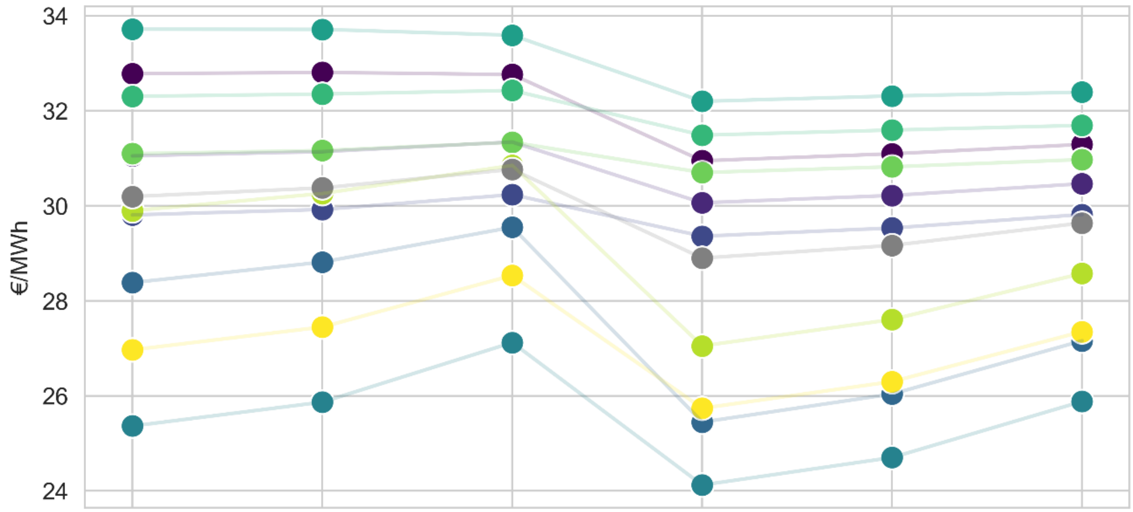
Revenues and costs for generation and consumer groups vary under different flexibility use cases



	M0/H0	M1/H0	M2/H0	M0/H1	M1/H1	M2/H1
H2-ready OCGT	0.01	-0.0	-0.01	0.0	-0.0	-0.01
H2-ready CHP	0.03	-0.0	-0.0	-0.0	-0.0	-0.0
DSM Ind. reduce	0.03	-0.0	-0.0	-0.0	-0.0	-0.0
Lignite CHP	0.04	-0.0	-0.0	-0.0	-0.0	-0.0
Coal CHP	0.16	-0.0	-0.01	-0.0	-0.0	-0.01
Waste CHP	0.23	-0.0	-0.01	0.0	-0.0	-0.01
Biomass CHP	0.27	-0.0	-0.0	-0.0	-0.0	-0.0
H2-ready CCGT	0.29	-0.01	-0.03	-0.0	-0.01	-0.04
Gas CCGT	0.39	-0.02	-0.04	-0.0	-0.02	-0.05
Hydro	0.4	-0.0	-0.01	-0.0	-0.0	-0.01
Coal	0.4	-0.01	-0.03	-0.0	-0.01	-0.04
Battery discharge	0.58	-0.02	-0.09	-0.0	-0.03	-0.09
Biomass	0.59	-0.0	-0.01	-0.0	-0.0	-0.01
Lignite	0.64	-0.0	-0.02	-0.0	-0.01	-0.02
Gas CHP	0.68	-0.01	-0.02	-0.0	-0.01	-0.02
PHS discharge	0.81	-0.02	-0.08	-0.0	-0.03	-0.09
Wind Offshore	2.64	-0.0	-0.03	-0.0	-0.0	-0.03
PV	2.78	0.02	0.2	0.01	0.03	0.21
Power Import	3.23	-0.1	-0.44	-0.02	-0.12	-0.45
Wind Onshore	5.54	-0.0	-0.06	-0.0	0.0	-0.06
DSM Ind. increase	0.02	-0.0	-0.0	-0.0	-0.0	-0.0
Conversion	0.13	-0.0	-0.0	-0.0	-0.0	-0.0
HP (central)	0.26	0.0	0.0	-0.0	-0.0	0.0
Battery charge	0.27	-0.01	-0.02	-0.0	-0.01	-0.03
Electrolysis	0.27	0.0	0.02	-0.0	0.0	0.02
PHS charge	0.35	-0.0	-0.01	-0.0	-0.0	-0.02
Power Export	0.37	0.0	0.04	0.0	0.01	0.04
Non Roadtransport	0.57	-0.0	-0.01	-0.0	-0.0	-0.01
losses	0.88	-0.01	-0.02	-0.0	-0.01	-0.02
Road Transport	1.53	-0.1	-0.38	-0.0	-0.1	-0.38
Buildings Heating	1.6	-0.01	-0.03	-0.02	-0.03	-0.05
Buildings Appliances	5.87	-0.04	-0.13	-0.0	-0.05	-0.13
Industry	7.61	-0.04	-0.16	-0.01	-0.04	-0.16
All Producer	19.75	-0.2	-0.7	-0.04	-0.23	-0.73
All Consumer	19.75	-0.2	-0.7	-0.04	-0.23	-0.73

- For electricity **generators**, the numbers indicate earnings from electricity generation
- Renewables exhibit the highest revenues, mainly due to the high installed capacities, while RES market values are the lowest compared to conventional power plants
- Gas and H2-ready power plants exhibit low total revenues, associated with low full load hours as well as installed capacities compared to RES
- All generating technologies, except PV, consistently exhibit a downtrend in revenues across all evaluated flexibility use cases
- For **consumers**, the numbers represent expenditures on the procurement component of the final electricity price
- Industry and end-user applications experience the highest electricity costs, whereas central heating and electrolysis account for lower expenditures
- For mostly all consumer groups, except electrolyzers, electricity expenditures diminish with additional flexibility

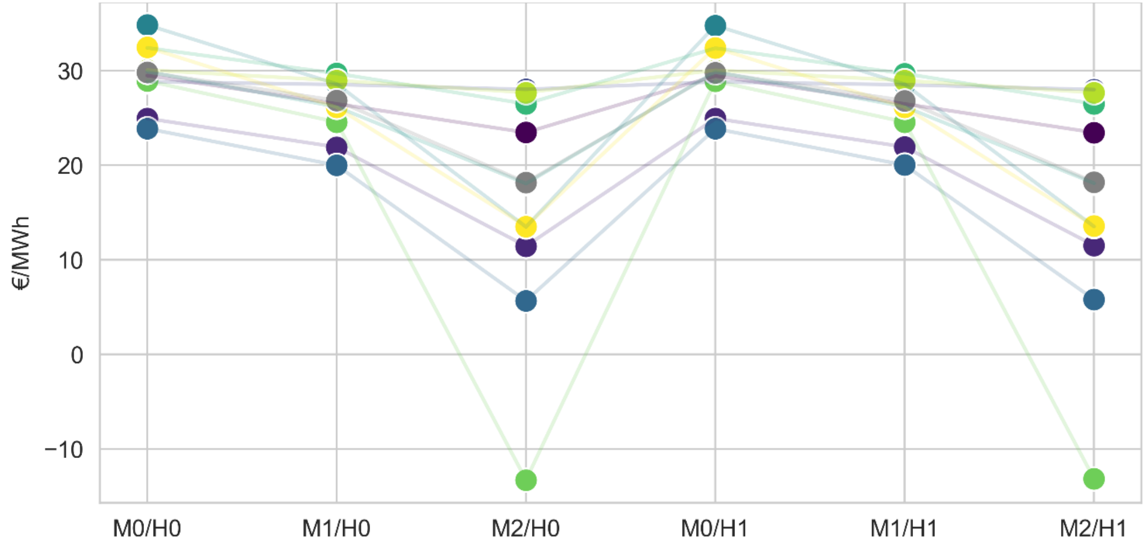
Average electricity costs decline significantly for all buildings types with increasing flexibility deployment



Buildings	M0/H0	M1/H0	M2/H0	M0/H1	M1/H1	M2/H1
Air B1	32.78	32.81	32.76	30.95	31.1	31.29
Air B2	31.05	31.14	31.34	30.06	30.22	30.46
Air B3	29.81	29.92	30.23	29.36	29.53	29.82
Air B4	28.38	28.82	29.55	25.45	26.04	27.16
Air B5	25.36	25.87	27.12	24.12	24.7	25.88
Ground B1	33.72	33.71	33.59	32.2	32.31	32.39
Ground B2	32.31	32.35	32.43	31.49	31.6	31.69
Ground B3	31.1	31.16	31.34	30.7	30.82	30.97
Ground B4	29.9	30.26	30.85	27.05	27.61	28.58
Ground B5	26.97	27.45	28.53	25.74	26.3	27.35
All	30.2	30.38	30.77	28.9	29.17	29.64

- Strong heterogeneity in terms of average electricity costs across the observed building types
- More efficient building constitution leads to lower average electricity costs
- Ground source heat pumps outweighs air source heat pumps in terms of average electricity costs. Instead, it terms of total expenditures, ground source heat pumps exhibit lower electricity costs compared to air heat pumps.
  - Due to weather-dependency of COPs shifts in heat pump operation can lead to higher or lower electricity input required to the generation of the same amount of heat
- Substantial economic advantages of integrating advanced heat storage systems into the operation of heat pumps

Flexible charging leads to a significant reduction in average electricity costs across all user types



Mobility Cluster	M0/H0	M1/H0	M2/H0	M0/H1	M1/H1	M2/H1
MC1	29.49	26.49	23.46	29.44	26.49	23.46
MC2	24.94	21.92	11.45	24.94	21.94	11.52
MC3	28.84	28.53	28.02	28.82	28.51	28.0
MC4	23.86	20.0	5.67	23.86	20.02	5.8
MC5	34.83	28.6	13.48	34.77	28.56	13.52
MC6	29.9	26.18	18.06	29.88	26.18	18.1
MC7	32.41	29.7	26.49	32.38	29.69	26.49
MC8	28.91	24.57	-13.28	28.89	24.57	-13.17
MC9	30.07	28.96	27.69	30.05	28.95	27.68
MC10	32.46	26.13	13.53	32.42	26.12	13.58
All	29.83	26.84	18.19	29.8	26.83	18.22

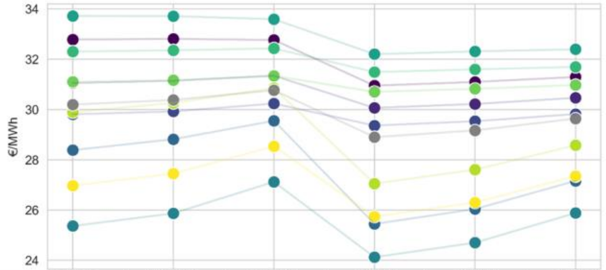
- The transition from baseline to EV demand shifting (M0/H0 to M1/H0) results in an average cost reduction of approximately 8.6% across all MCs, emphasizing the immediate benefits of EV charging flexibility
- Bidirectional charging (M1/H0 to M2/H0) yields further reductions, with MCs experiencing an average additional 28.6% decrease in charging costs
- Additional consideration of heat pump flexibility leads only to a minor change of charging costs

Summary, outlook and discussion

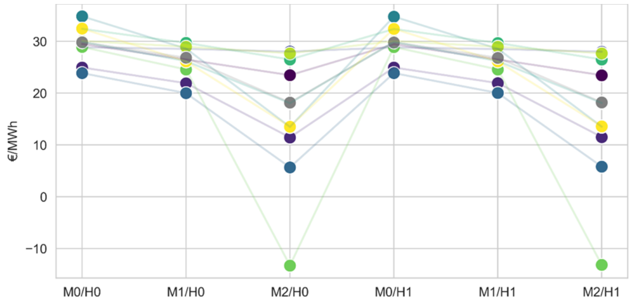
Conclusion:

- For electricity producers, apart from PV systems, revenue decreases with increasing system-oriented flexibility
- For consumers, flexibility deployment leads to decreasing average electricity procurement costs. This trend does not extend to electrolyzers and batteries which compete with end-users’ flexible assets for low electricity prices.
- However, cost savings for most consumers are relatively modest, except in the case of bidirectional charging

		billion EUR	Δ billion EUR				
		M0/H0	M1/H0	M2/H0	M0/H1	M1/H1	M2/H1
Generation	H2-ready OCGT	0.01	-0.0	-0.01	0.0	-0.0	-0.01
	H2-ready CHP	0.03	-0.0	-0.0	-0.0	-0.0	-0.0
	DSM Ind. reduce	0.03	-0.0	-0.0	-0.0	-0.0	-0.0
	Lignite CHP	0.04	-0.0	-0.0	-0.0	-0.0	-0.0
	Coal CHP	0.16	-0.0	-0.01	-0.0	-0.0	-0.01
	Waste CHP	0.23	-0.0	-0.01	0.0	-0.0	-0.01
	Biomass CHP	0.27	-0.0	-0.0	-0.0	-0.0	-0.0
	H2-ready CCGT	0.29	-0.01	-0.03	-0.0	-0.01	-0.04
	Gas CCGT	0.39	-0.02	-0.04	-0.0	-0.02	-0.05
	Hydro	0.4	-0.0	-0.01	-0.0	-0.0	-0.01
	Coal	0.4	-0.01	-0.03	-0.0	-0.01	-0.04
	Battery discharge	0.58	-0.02	-0.09	-0.0	-0.03	-0.09
	Biomass	0.59	-0.0	-0.01	-0.0	-0.0	-0.01
	Lignite	0.64	-0.0	-0.02	-0.0	-0.01	-0.02
	Gas CHP	0.68	-0.01	-0.02	-0.0	-0.01	-0.02
	PHS discharge	0.81	-0.02	-0.08	-0.0	-0.03	-0.09
	Wind Offshore	2.64	-0.0	-0.03	-0.0	-0.0	-0.03
	PV	2.78	0.02	0.2	0.01	0.03	0.21
	Power Import	3.23	-0.1	-0.44	-0.02	-0.12	-0.45
	Wind Onshore	5.54	-0.0	-0.06	-0.0	0.0	-0.06
Load	DSM Ind. increase	0.02	-0.0	-0.0	-0.0	-0.0	-0.0
	Conversion	0.13	-0.0	-0.0	-0.0	-0.0	-0.0
	HP (central)	0.26	0.0	0.0	-0.0	-0.0	0.0
	Battery charge	0.27	-0.01	-0.02	-0.0	-0.01	-0.03
	Electrolysis	0.27	0.0	0.02	-0.0	0.0	0.02
	PHS charge	0.35	-0.0	-0.01	-0.0	-0.0	-0.02
	Power Export	0.37	0.0	0.04	0.0	0.01	0.04
	Non Roadtransport	0.57	-0.0	-0.01	-0.0	-0.0	-0.01
	losses	0.88	-0.01	-0.02	-0.0	-0.01	-0.02
	Road Transport	1.53	-0.1	-0.38	-0.0	-0.1	-0.38
	Buildings Heating	1.6	-0.01	-0.03	-0.02	-0.03	-0.05
	Buildings Appliances	5.87	-0.04	-0.13	-0.0	-0.05	-0.13
	Industry	7.61	-0.04	-0.16	-0.01	-0.04	-0.16
	All Producer	19.75	-0.2	-0.7	-0.04	-0.23	-0.73
	All Consumer	19.75	-0.2	-0.7	-0.04	-0.23	-0.73



Buildings	M0/H0	M1/H0	M2/H0	M0/H1	M1/H1	M2/H1
Air B1	32.78	32.81	32.76	30.95	31.1	31.29
Air B2	31.05	31.14	31.34	30.06	30.22	30.46
Air B3	29.81	29.92	30.23	29.36	29.53	29.82
Air B4	28.38	28.82	29.55	25.45	26.04	27.16
Air B5	25.36	25.87	27.12	24.12	24.7	25.88
Ground B1	33.72	33.71	33.59	32.2	32.31	32.39
Ground B2	32.31	32.35	32.43	31.49	31.6	31.69
Ground B3	31.1	31.16	31.34	30.7	30.82	30.97
Ground B4	29.9	30.26	30.85	27.05	27.61	28.58
Ground B5	26.97	27.45	28.53	25.74	26.3	27.35
All	30.2	30.38	30.77	28.9	29.17	29.64



Mobility Cluster	M0/H0	M1/H0	M2/H0	M0/H1	M1/H1	M2/H1
MC1	29.49	26.49	23.46	29.44	26.49	23.46
MC2	24.94	21.92	11.45	24.94	21.94	11.52
MC3	28.84	28.53	28.02	28.82	28.51	28.0
MC4	23.86	20.0	5.67	23.86	20.02	5.8
MC5	34.83	28.6	13.48	34.77	28.56	13.52
MC6	29.9	26.18	18.06	29.88	26.18	18.1
MC7	32.41	29.7	26.49	32.38	29.69	26.49
MC8	28.91	24.57	-13.28	28.89	24.57	-13.17
MC9	30.07	28.96	27.69	30.05	28.95	27.68
MC10	32.46	26.13	13.53	32.42	26.12	13.58
All	29.83	26.84	18.19	29.8	26.83	18.22

Thank you for your attention!

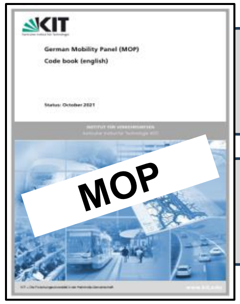
Contact
Nils Namockel
Nils.namockel@ewi.uni-koeln.de

Developed DIMENSION dispatch model enables an investigation of the competition between flexibility options

Sector	Subsector	CO_2	Positive flexibility	Negative flexibility
Energy	Electricity	✓	Storage Out, Import, Ramp-Up	Curtailment, Storage In
	PtX	✓	No flexibility	PtX
	District heating	✓	No flexibility	PtH
	Others	✓	No flexibility	No flexibility
Transport	Road transport	✓	Electric vehicles DSM / V2X	Electric vehicles DSM
	Non-road transport dom.	✓	No flexibility	No flexibility
	Non-road transport intl.	✗	No flexibility	No flexibility
Buildings	Heating, cooling, cooking	✓	Heat pump DSM	Heat pump DSM
	Lighting, el. appliances	✓	No flexibility	No flexibility
Industry	Processes	✓	DSM (reduction)	DSM (increase)
	Non-energy use	✗	No flexibility	No flexibility
Agriculture, LULUCF, waste and others		✓	No flexibility	No flexibility

Electric vehicles are represented with different mobility cluster accounting for heterogeneity in the road transport sector

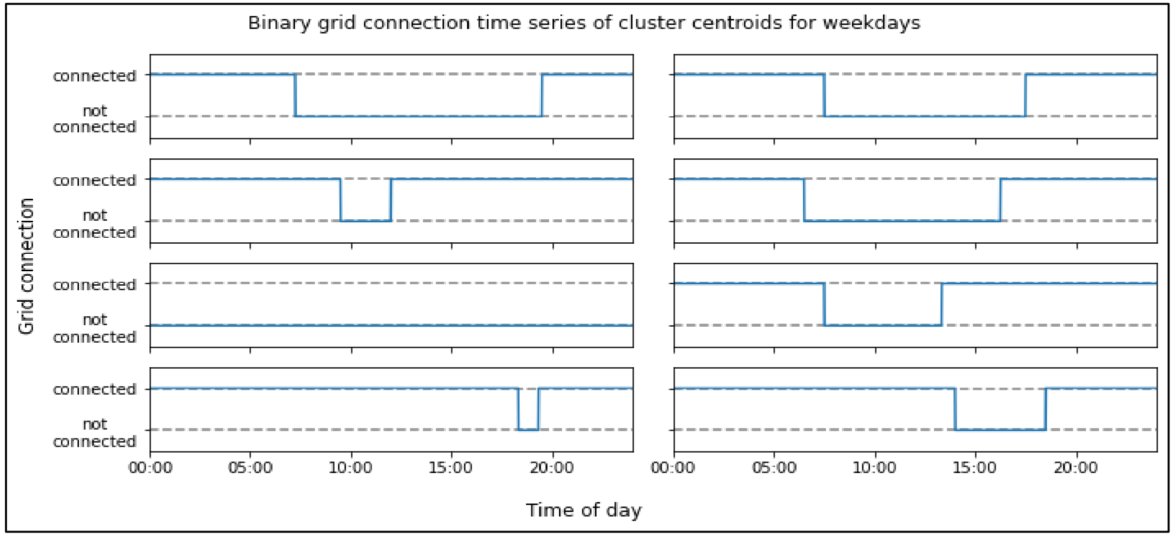
Definition of different mobility user groups



Information on trips and locations
(we only focus on home charging)

Computation of hourly driving, parking and charging profiles

Clustering of parking profiles



Profile generation for each cluster

- For charging profiles
  (1) aggregate all charging profiles within one cluster
  (2) Only consider intersection with connection profile of cluster center

- For flexibility profiles:
  (1) aggregate all connection profiles within one cluster
  (2) Only consider intersection with connection profile of cluster center