WIP

Assessing the role of electricity tariffs for the provision of flexibility by households - A stochastic MCP approach including the system perspective

Marco Sebastian Breder

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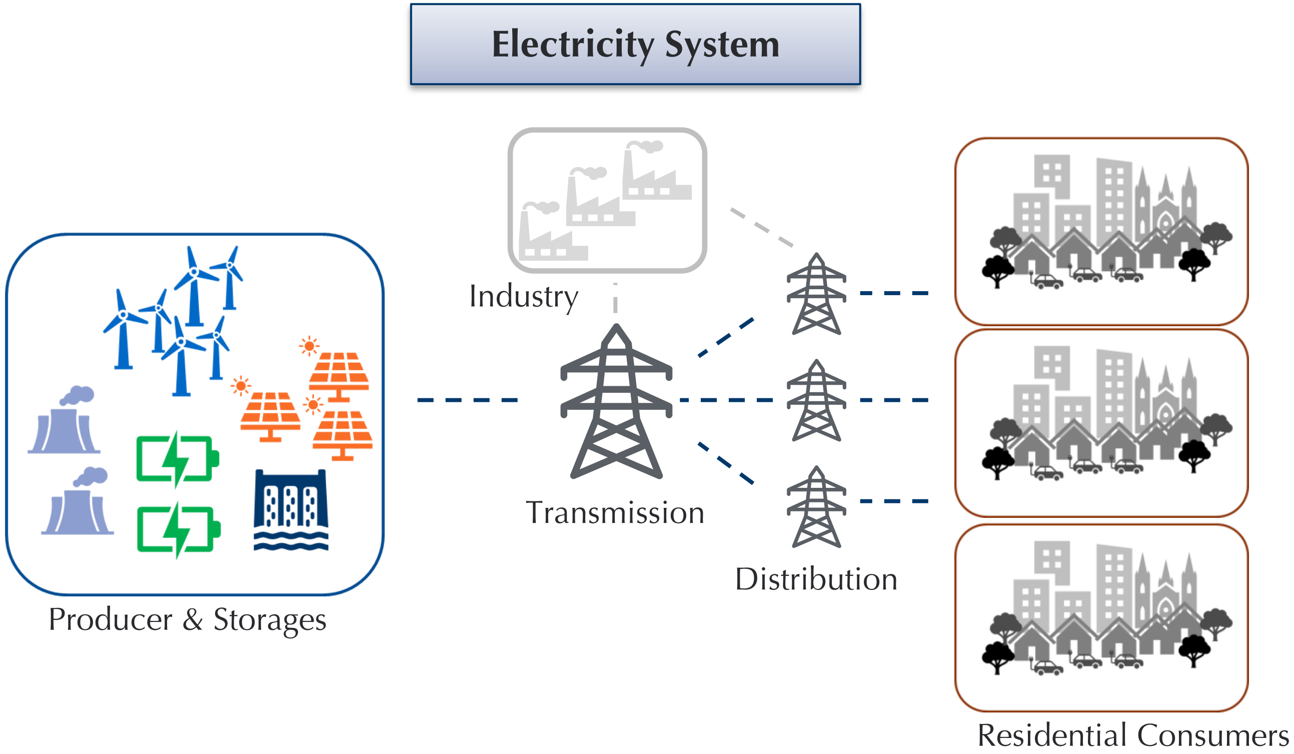
Agenda

Motivation

Demand response by residential consumers is of pivotal relevance to meet transformation challenges



- Challenges from overall energy system perspective:
  - Integration of renewables
  - Decarbonization (cross-sectoral)
  - Grid / system resilience
  - (price-driven) **Demand response**

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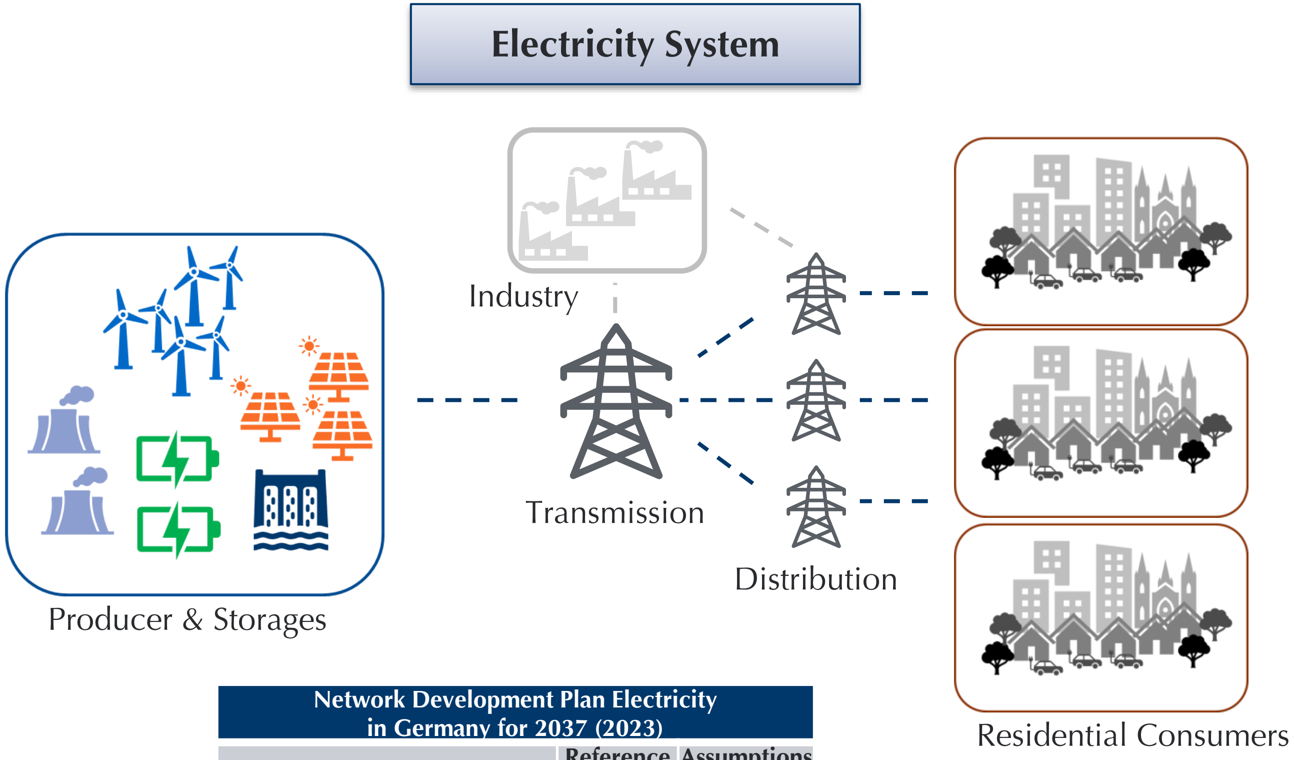

Network Development Plan Electricity in Germany for 2037 (2023)		
	Reference 2020/2021	Assumptions 2037
Heat Pumps (HPs) in million	1.2	14.7
Electric Vehicles (EVs) in million	1.2	25.2-31.7
Photovoltaic (PV) & Battery Storage Systems (BSS) in GW	1.3	67.4

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    - Small-scale flexibilities are crucial:

Market-oriented	Grid-oriented
Renewables integration **Balancing energy costs of Balance Groups** **Peak-demand reduction**	**Grid stability** **Avoidance of congestion**

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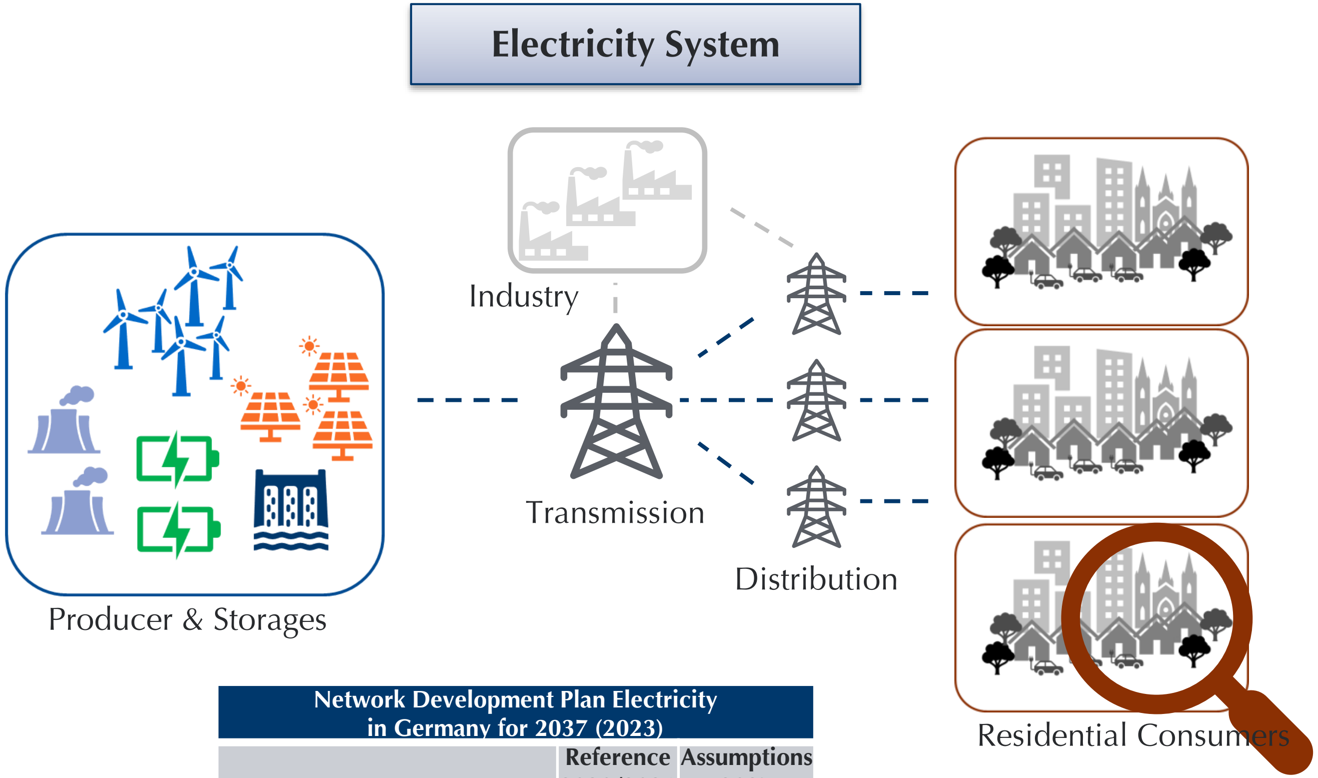

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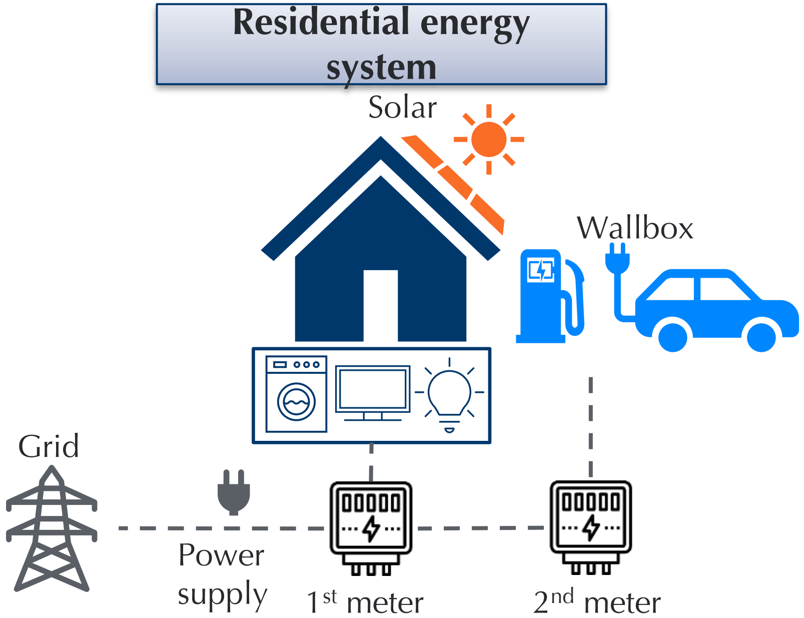
➢ Normative View: The efficient implementation relies on efficient configuration of **meters** and **tariffs**

Motivation

Residential consumer face several decision-making hurdles for an efficient (system-oriented) configuration of meters and tariffs



- Disentangling the influence of electricity meter and tariff configurations on the operational and investment decisions of residential consumers

$\boldsymbol{Electricity\ Tariff} = \boldsymbol{Basic\ Charge + Energy\ charge + Grid\ charge + other\ components}$

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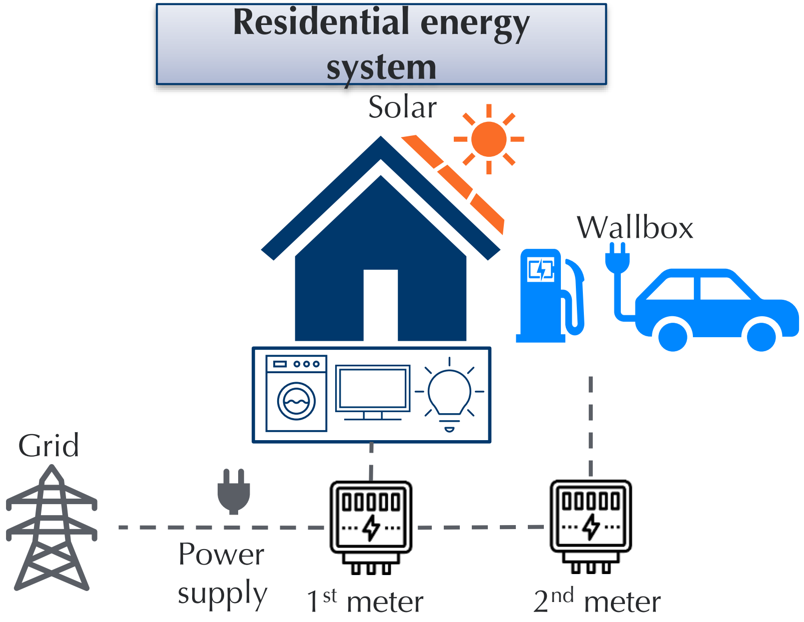

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- The focus is on three complexities:

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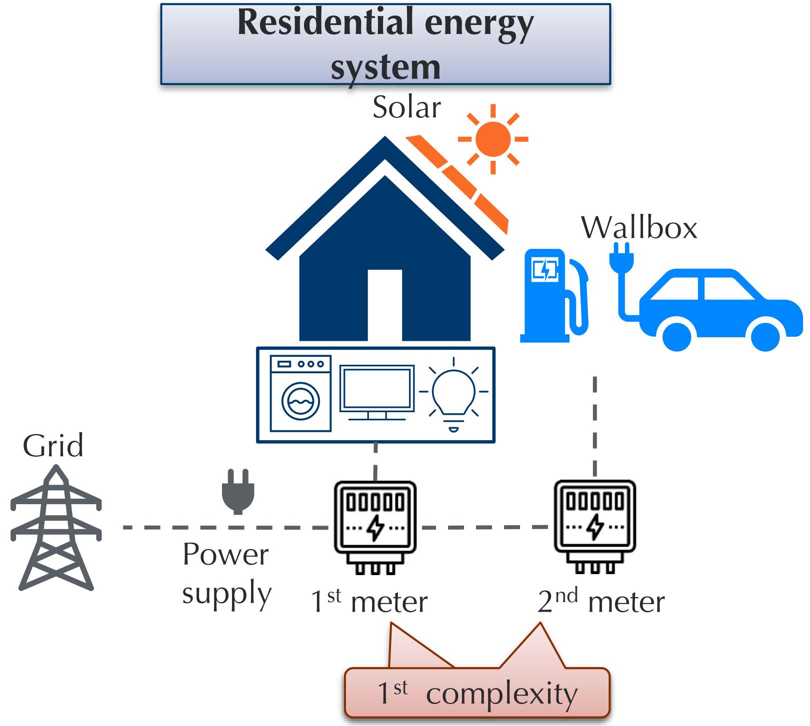

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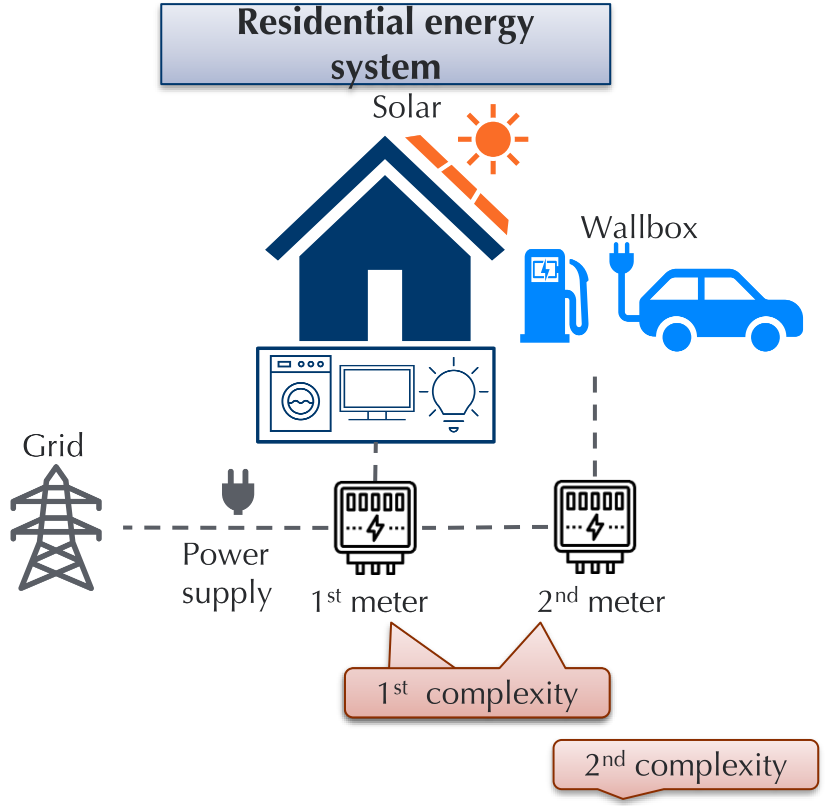

$$\boldsymbol{Electricity\,Tariff} = Basic\ Charge + \boldsymbol{Energy\ charge} + Grid\ charge + other\ components$$

- **Static price [€/kWh]**
- **Time-variant price [$€_t/kWh_t$]**
- **Dynamic price [$€_t/kWh_t$]**

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  2. Pricing module

Market-oriented

Motivation

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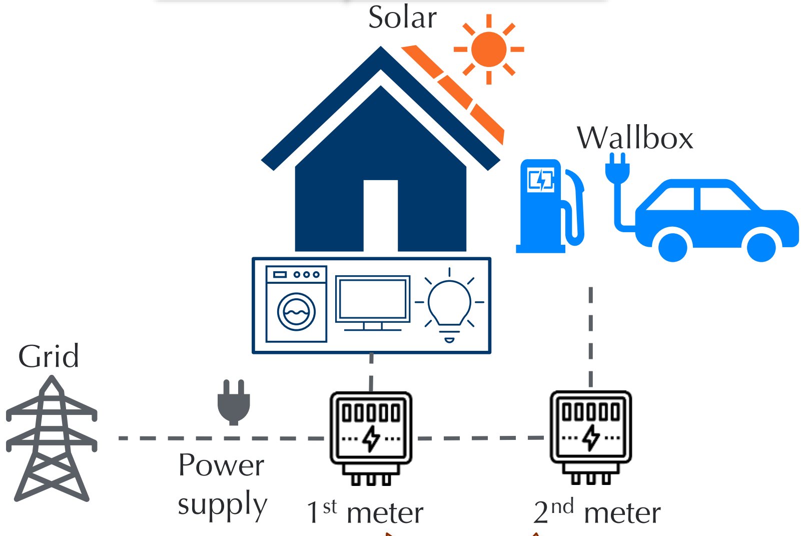
Residential energy system



1st complexity

2nd complexity

3rd complexity

$$\textbf{Electricity Tariff} = \text{Basic Charge} + \textbf{Energy charge} + \textbf{Grid charge} + \text{other components}$$

- **Static price [€/kWh]**
- **Time-variant price [$€_t$/kWh_t]**
- **Dynamic price [$€_t$/kWh_t]**

- **Module 1 lump sum [€ p.a.]**
- **Module 2 consumption-dependent fee [€/kWh]**
- **Module 3 time-variant fee [$€_t$/kWh_t]**

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  3. Grid charge module

Market-oriented

Grid-oriented

Motivation

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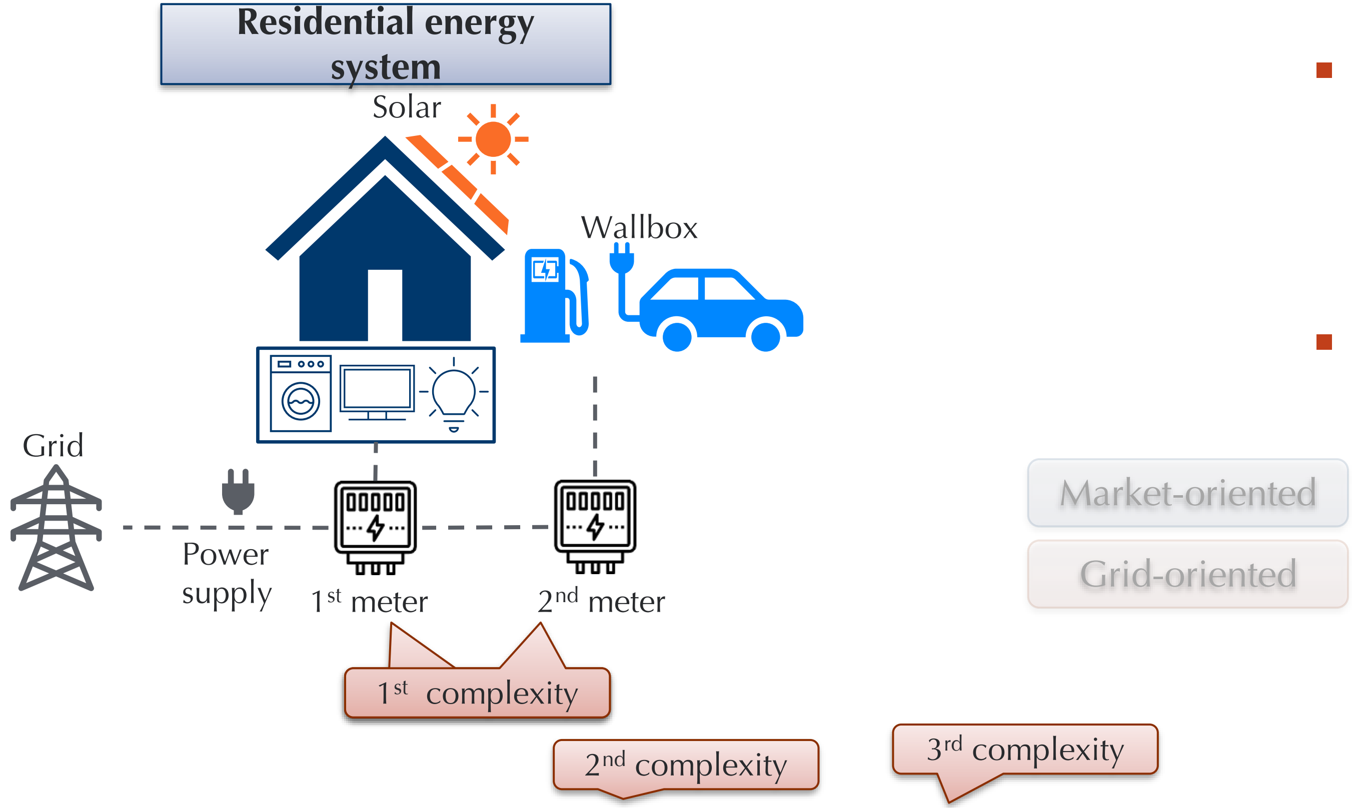

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  3. Grid charge module
  - ➢ How do electricity meter and tariff configurations incentivize residential consumers' provision of flexibility and investment in PV & Storages

$$\boldsymbol{Electricity\,Tariff} = Basic\ Charge + \boldsymbol{Energy\ charge} + \boldsymbol{Grid\ charge} + other\ components$$

Energy charge:
- **Static price [€/kWh]**
- **Time-variant price [$€_t$/kWh$_t$]**
- **Dynamic price [$€_t$/kWh$_t$]**

Grid charge:
- **Module 1 lump sum [€ p.a.]**
- **Module 2 consumption-dependent fee [€/kWh]**
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Motivation

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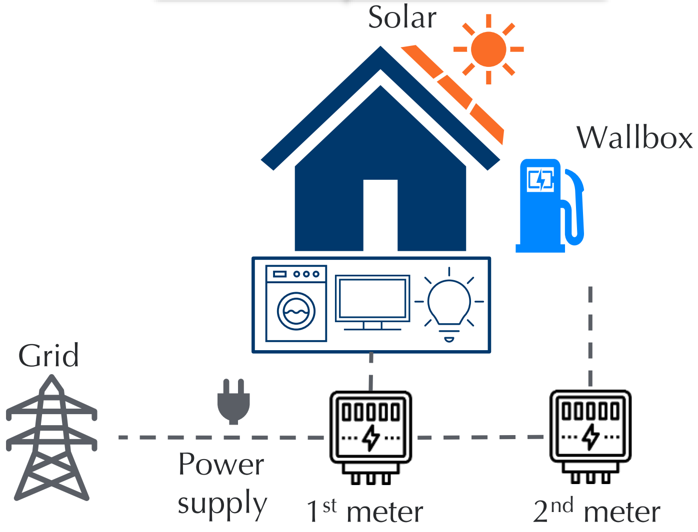
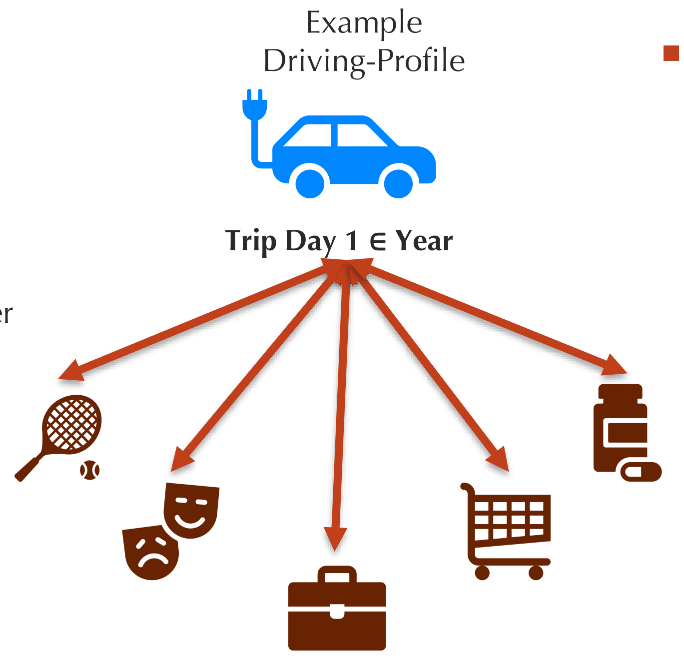


Uncertainty in daily trips leads to uncertainty in charging and V2G/V2H patterns



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Literature Review

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Literature review reveals a gap on wholesale market interaction, consideration of uncertainty and future technological options (meter)

	Objective	Scope
Stute & Klobasa (2024)	Interplay between **dynamic tariffs and different grid charge** designs	Households & Grid
Spiller et al. (2023)	Effect of tariffs on household **adoption of small-scale flexibilities**	Households
Vom Scheidt et al. (2019)	Potential **individual economic consequences** of tariff selection	Households
Andruszkiewicz et al. (2021)	**Effectiveness of ToU tariffs**, used as price-based demand response programs	Households
Pallonetto et al. (2016)	Effectiveness of demand response **(All-electric)** strategies using ToU tariffs	Household & Utility perspective
Schreck et al. (2022)	Effect of **grid tariff design on demand and feed-in peaks** and the resulting financial effects	Households vs. Local Energy Markets
Pinel et al. (2019)	Relationship between **grid tariffs and investment**	Neighborhoods & Grids

- Relevant literature <u>analyzes</u>
  - Interplay of tariff components
  - Incentives for investments
  - Financial consequences
  - Interaction with distribution system operators

➢ But lacks interactions with markets

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- Relevant literature <u>considers</u>
  - Various combinations of tariff components
  - Different levels of electrification of residential consumers
- But predominantly relies on static data inputs

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- Relevant literature <u>considers</u>
  - Various combinations of tariff components
  - Different levels of electrification of residential consumers

➢ But predominantly relies on static data inputs

- Relevant literature does not consider
  - differentiation of small-scale flexibilities in the tariff selection decision

➢ Individual tariff heterogeneity

Literature Review

Literature review reveals a gap on wholesale market interaction, consideration of uncertainty and future technological options (meter)

	Objective	Scope	Tariff: Energy Charge			Tariff: Grid charge				Electrical devices				Metering
			Static	ToU	Dyn.	energy-based (€/kWh)*	power based (€/kW)	Combination CAP-VOL	Critical-Peak pricing	PV & BSS	HP	EV	Others	Number of
Stute & Klobasa (2024)	Interplay between **dynamic tariffs and different grid charge** designs	Households & Grid	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Res. Demand	1
Spiller et al. (2023)	Effect of tariffs on household **adoption of small-scale flexibilities**	Households	✓	✓	✓	×	×	×	✓	✓ (endog. Inv.)	✓ (endog. Inv.)	×	-	1
Vom Scheidt et al. (2019)	Potential **individual economic consequences** of tariff selection	Households	✓	✓	✓	minor relevance				-	-	-	consump-tion profiles	1
Andruszkiewicz et al. (2021)	**Effectiveness of ToU tariffs**, used as price-based demand response programs	Households	✓	✓	×	✓	×	×	×	-	-	-	SLP assumed	1
Pallonetto et al. (2016)	Effectiveness of demand response **(All-electric)** strategies using ToU tariffs	Household & Utility perspective	×	✓	×	minor relevance				✓	✓	✓	Heat recovery ventilation	1
Schreck et al. (2022)	Effect of **grid tariff design on demand and feed-in peaks** and the resulting financial effects	Households vs. Local Energy Markets	minor relevance			✓	✓	×	×	✓	✓	✓	-	1
Pinel et al. (2019)	Relationship between **grid tariffs and investment**	Neighborhoods & Grids	✓	✓	✓	✓	✓	×	×	✓ (endog. Inv.)	✓ (endog. Inv.)	×	Electr. Boilers	1

*energy-based grid charge is defined as static, time-variant or dynamic price.

- Derived objectives:
  - Economic effects on residential consumers when faced with individual tariff heterogeneity
    - operational decisions and investments in PV-BSS under uncertainty
  - Implications for the energy system, particularly regarding the aforementioned challenges

Method & Data

Input of current work

Economic analysis of behavioral aspects of electromobility with a focus on consumers – A Review


House of Energy Markets & Finance

Economic analysis of behavioral aspects of electromobility with a focus on consumer behavior – A Review

- Further relevant literature
- Driving and charging patterns
- Tariffication & choice

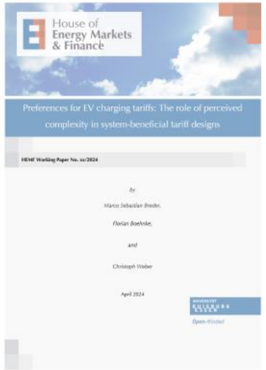
Local Stock Diffusion of Electric Vehicles in Germany: Spatio-Temporal Insights and the Impact of the Secondary Car Market


House of Energy Markets & Finance

Economic analysis of behavioral aspects of electromobility with a focus on consumer behavior – A Review

- Distribution of Cars for different Years on Nuts3 level

Tariff Preferences for Electric Vehicle Charging: The Role of Complexity in Fostering System-Beneficial Designs


House of Energy Markets & Finance

Preferences for EV charging tariffs: The role of perceived complexity in system-beneficial tariff designs

- First guess on tariff choice and design

Effects of distortionary tariffs on long-term equilibria with a high share of Prosumage households


House of Energy Markets & Finance

Electric vehicle ramp-up in Germany: An analytical framework for incorporating the secondary automotive market

- Illustration of Wholesale-Retailer-Household interaction (iterative LP)

➢ **Driving Profiles: Transformed "Mobilität in Deutschland (MiD) 2017 – data set**

Method & Data

Mixed Complementarity Problem

- Solving of multiple individual (different agents) optimization problems **simultaneously** and **in equilibrium***
  – by combining the **Karush-Khun-Tucker**** (KKT) conditions for optimality of each of the agents and connecting them via market clearing conditions
  – primal variables (eg., power generation) and dual variables (eg., prices) can be constrained together
  – Possibility to reflect market power

- Solve the problem represented by the function $F\colon \mathbb{R}^n \longrightarrow \mathbb{R}^n$
  – find vectors x ∈ $\mathbb{R}^{n2}$, y ∈ $\mathbb{R}^{n2}$ such that for all i:
  1. $F_i(x,y) \geq 0, x_i \geq 0, x_i * F_i(x,y) = 0$ for i=1, …, n_1
  2. $F_{j+n_1}(x,y) = 0, y_i\ free,$ for j=1, …, n_2

The first condition is often written more compactly

$$0 \leq F_i(x) \perp x \geq 0,$$

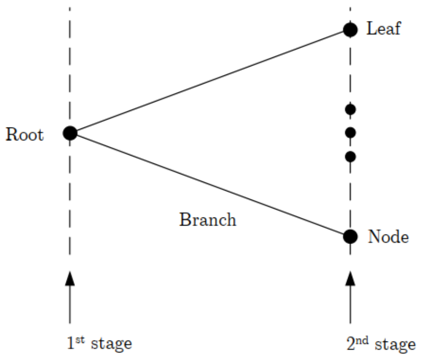
with the “perp” operator ⊥ denoting the inner product of two vectors equal to zero

* A state of the modeled system where there is no incentive for it to change.
****KKT** conditions are **first-order conditions**, i.e., conditions that are formulated using first derivative vectors and matrices (gradients and Jacobians). To formulate the KKT conditions it is convenient to define **the Lagrangian function.**

Method & Data

Implementation of uncertainty as Two-Stage Problem

- First-stage ('here-and-now decisions')
  - decisions made before realization of stochastic process
- Second-stage ('wait-and-see decisions')
  - decisions made after knowing actual realization of stochastic process
  - Decision variable is defined for each scenario realization



MiD 2017

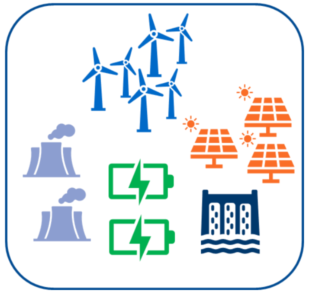
Day	Count
Monday	75,568
Tuesday	79,899
Wednesday	80,223
Thursday	76,509
Friday	79,401
Saturday	60,293
Sunday	42,403

$$\min_x c^\top x + E_\omega Q(x,\omega)$$
$$\text{s.t. } Ax = b$$
$$x \in X$$
$$where$$
$$Q(\omega) = \left\{ \begin{array}{c} \min y(\omega) \;\; q(\omega)^\top y(\omega) \\ subject\ to\ T(\omega)x + W(\omega)y(\omega) = h(\omega) \\ y(\omega) \epsilon Y \end{array} \right\}, \forall \omega \epsilon \Omega$$

- where x and y(ω) are the first- and second-stage decision variable vector, respectively, and c, q(ω), b, h(ω), A, T(ω), and W(ω) are known vectors and matrices of appropriate size. ω is the scenario index.
- Possibility to use decomposition techniques (e.g. Benders Decomp.)
  - Chanpiwat & Gabriel (2024); Devine & Bertsch (2024); Egging (2013, 2010)

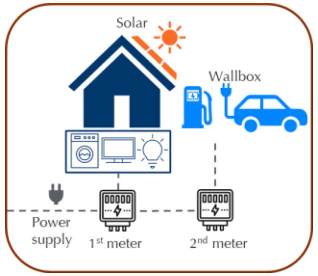
Method & Data

Interrelated optimization problems and equilibrium problem (KKT)



Market-Clearing

$$Supply_t = Demand_t \; (p_t^{energy})$$



Utility 1

$$\max \pi = \sum_t (p_t - c_t) * q_t$$
$$s.t.$$
$$g_i(q) \le 0 \; for \; i = 1, \dots, m$$
$$h_j(q) = 0 \; for \; j = 1, \dots, p$$

⋮

Utility n

$$\max \pi = \sum_t (p_t - c_t) * q_t$$
$$s.t.$$
$$g_i(q) \le 0 \; for \; i = 1, \dots, m$$
$$h_j(q) = 0 \; for \; j = 1, \dots, p$$

Residential consumer 1

$$\max \pi = \sum_t \Big[(p^{fit} * \gamma^{fit} + \theta^{fit}) * q_t^{gridin} - (p^{energy} + p^{grid} + p^{other}) * q_t^{gridout\_m1} - (p^{energy} + p^{grid} + p^{other}) * q_t^{gridout\_m2} - \tau * \frac{(p^{energy} + p^{grid} + p^{other})}{1 + \tau} (K_h^{PV} * \varphi_{h,t} - q_{h,t}^{gridin}) \Big]$$
$$s.t.$$
$$g_i(q) \le 0 \; for \; i = 1, \dots, m$$
$$h_j(q) = 0 \; for \; j = 1, \dots, p$$

⋮

Residential consumer k

$$\max \pi$$
$$s.t. \dots$$

KKT Condition of utility 1

⋮

KKT Condition of utility n

\+

KKT Condition of residential consumer 1

⋮

KKT Condition of residential consumer k

\+

Market-Clearing condition

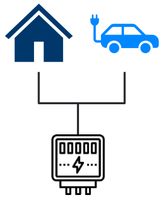
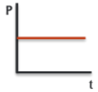
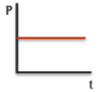
* Agents are Conventional, Renewables & Storages, each with specific constraints tailored to their operational characteristics and market roles.

** Constraints consider PV BSS limits, Wallbox-EV limits, internal clearing condition; Dumb or smart charging possible.

Data for preliminary results based on SLP, MID 2017 Driving Profiles, Smard (BNetzA).

Preliminary Results

Stylized setting with focus on residential consumer

	Residential Consumers						
Electrical Devices							
Meter							
Tariff: Energy Charge							
Tariff: Grid Charge							
Total Bill (ΔBase in %)	54.22 €						
Bill per Meter (ΔBase in %)							
	Base	**2**	**3**	**4**	**5**	**6**	**7**

- 7 configurations
  - Residential consumer w/o PV & BSS, w EV-Wallbox 22 kW
  - Demand 3700 kWh + 2600 kWh
- Preliminary results based on 4 weeks (one week per quarter)

➢ Base Case most common (in Germany)

Preliminary Results

Stylized setting with focus on residential consumer

	Residential Consumers						
Electrical Devices							
Meter							
Tariff: Energy Charge							
Tariff: Grid Charge							
Total Bill (ΔBase in %)	54.22 €	52.58 € -3%	43.13 € -20%				
Bill per Meter (ΔBase in %)							
	Base	2	3	4	5	6	7

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➢ Dynamic energy price and time-variant grid fee most preferable

Preliminary Results

Stylized setting with focus on residential consumer

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Meter							
Tariff: Energy Charge							
Tariff: Grid Charge							
Total Bill (ΔBase in %)	54.22 €	52.58 € -3%	43.13 € -20%	51.99 € -4%	41.79 € -23%		
Bill per Meter (ΔBase in %)				33.30 € 18.69 € 0% -11%	32.91 € 8.88 € -1% -58%		
	Base	2	3	4	5	6	7

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  - Residential consumer w/o PV & BSS, w EV-Wallbox 22 kW
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➢ Distinguishing applications leads to further reductions

Preliminary Results

Stylized setting with focus on residential consumer

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Electrical Devices							
Meter							
Tariff: Energy Charge							
Tariff: Grid Charge							
Total Bill (ΔBase in %)	54.22 €	52.58 € -3%	43.13 € -20%	51.99 € -4%	41.79 € -23%	51.60 € -5%	42.18 € -22%
Bill per Meter (ΔBase in %)				33.30 € 18.69 € 0% -11%	32.91 € 8.88 € -1% -58%	32.91 € 18.69 € -1% -11%	33.30 € 8.88 € 0% -58%
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- 7 configurations
  - Residential consumer w/o PV & BSS, w EV-Wallbox 22 kW
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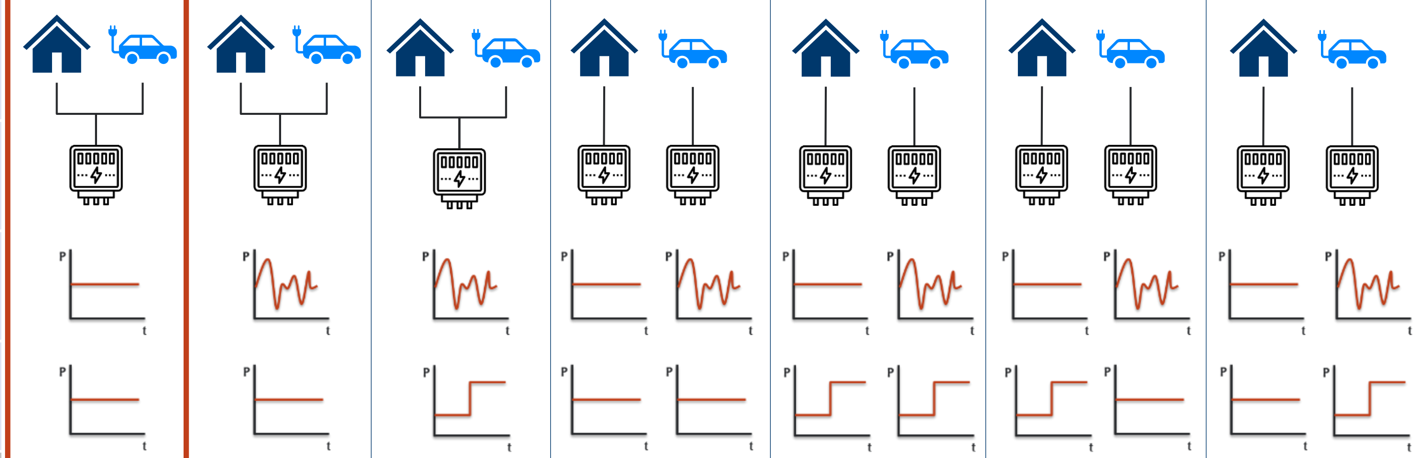
➢ The level of reduction depends on tariff configuration

Preliminary Results

Stylized setting with focus on residential consumer

Residential Consumers



	Base	2	3	4	5	6	7
Electrical Devices							
Meter							
Tariff: Energy Charge							
Tariff: Grid Charge							
Total Bill (ΔBase in %)	54.22 €	52.58 € -3%	43.13 € -20%	51.99 € -4%	41.79 € -23%	51.60 € -5%	42.18 € -22%
Bill per Meter (ΔBase in %)				33.30 € 18.69 € 0% -11%	32.91 € 8.88 € -1% -58%	32.91 € 18.69 € -1% -11%	33.30 € 8.88 € 0% -58%

- 7 configurations
  - Residential consumer w/o PV & BSS, w EV-Wallbox 22 kW
  - Demand 3700 kWh + 2600 kWh
- Preliminary results based on 4 weeks (one week per quarter)

➢ Assuming application-dependent cost reflection, the meter-tariff configuration influence individual electricity bills - non-robust first estimate

Outlook

- Model extension (tbd):
  - Detailed representation of agents: Retailer
  - Bidirectional charging
    - V2H, V2G
  - Scenario setting and data
    - E.g. driving/charging profiles

- Reduction in computational complexity
  - temporal aggregation into representative segments

- Implementation of uncertainty:
  - Uncertainty regarding driving profiles
    - Impact on residential PV & BSS, HP, Air Conditioner, EV charging,

Thank you for your attention!

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