Distortions in energy related decision-making at households – An MCP approach incorporating system perspective

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Agenda

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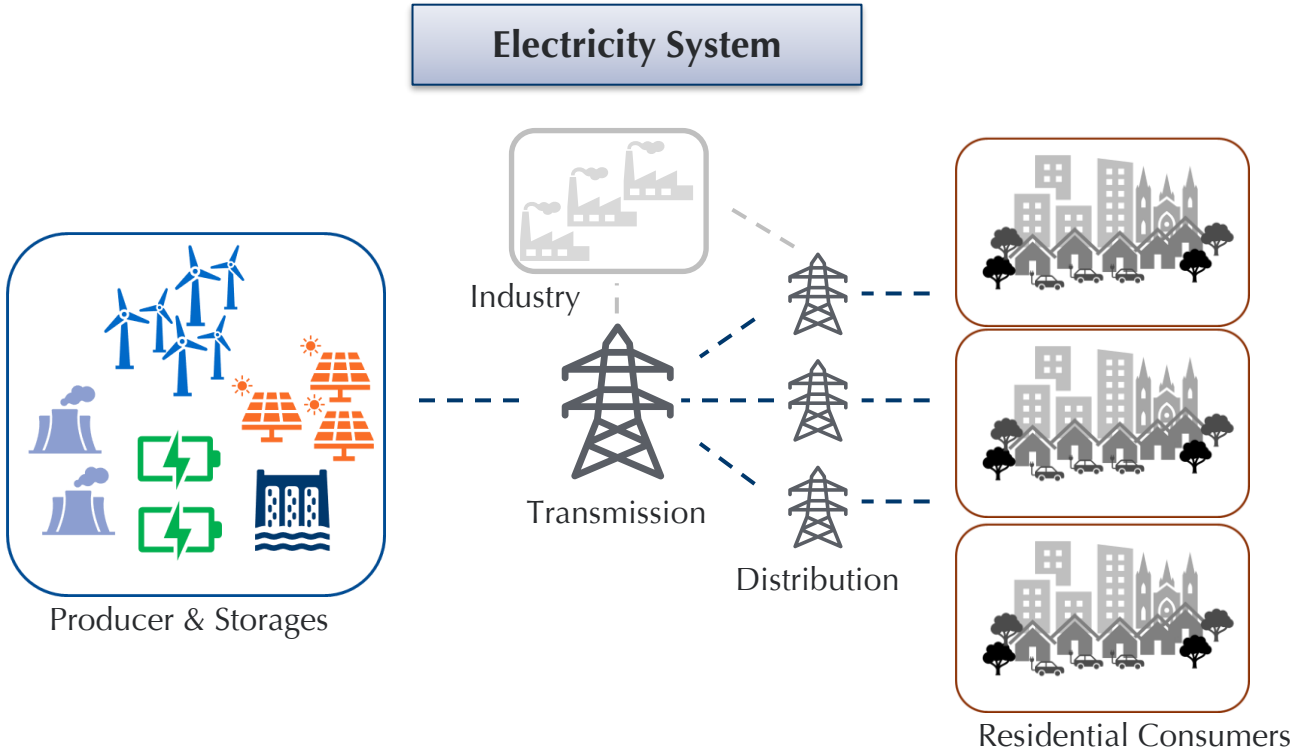
Motivation

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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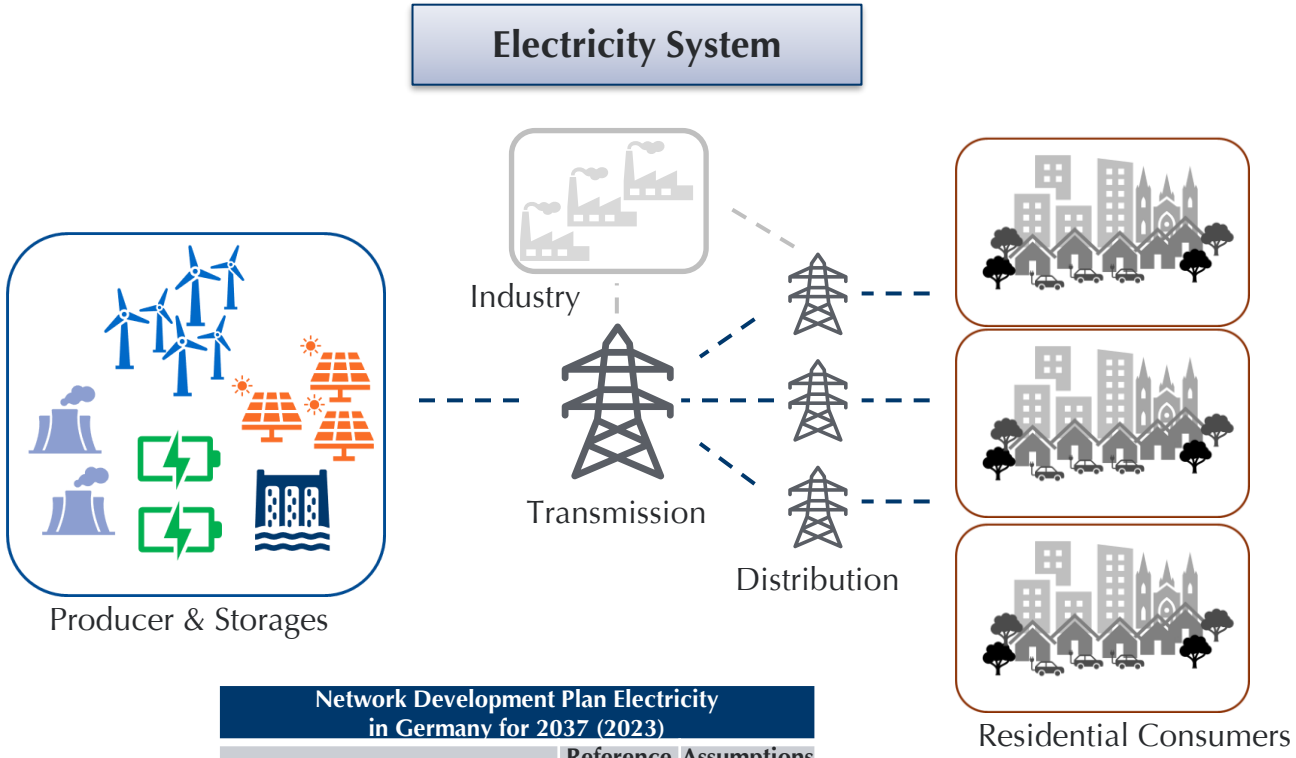

Network Development Plan Electricity in Germany for 2037 (2023)		
	Reference 2020/2021	Assumptions 2037
Heat Pumps (HPs) in million	1.2	14.7
Electric Vehicles (EVs) in million	1.2	25.2-31.7
Photovoltaic (PV) & Battery Storage Systems (BSS) in GW	1.3	67.4

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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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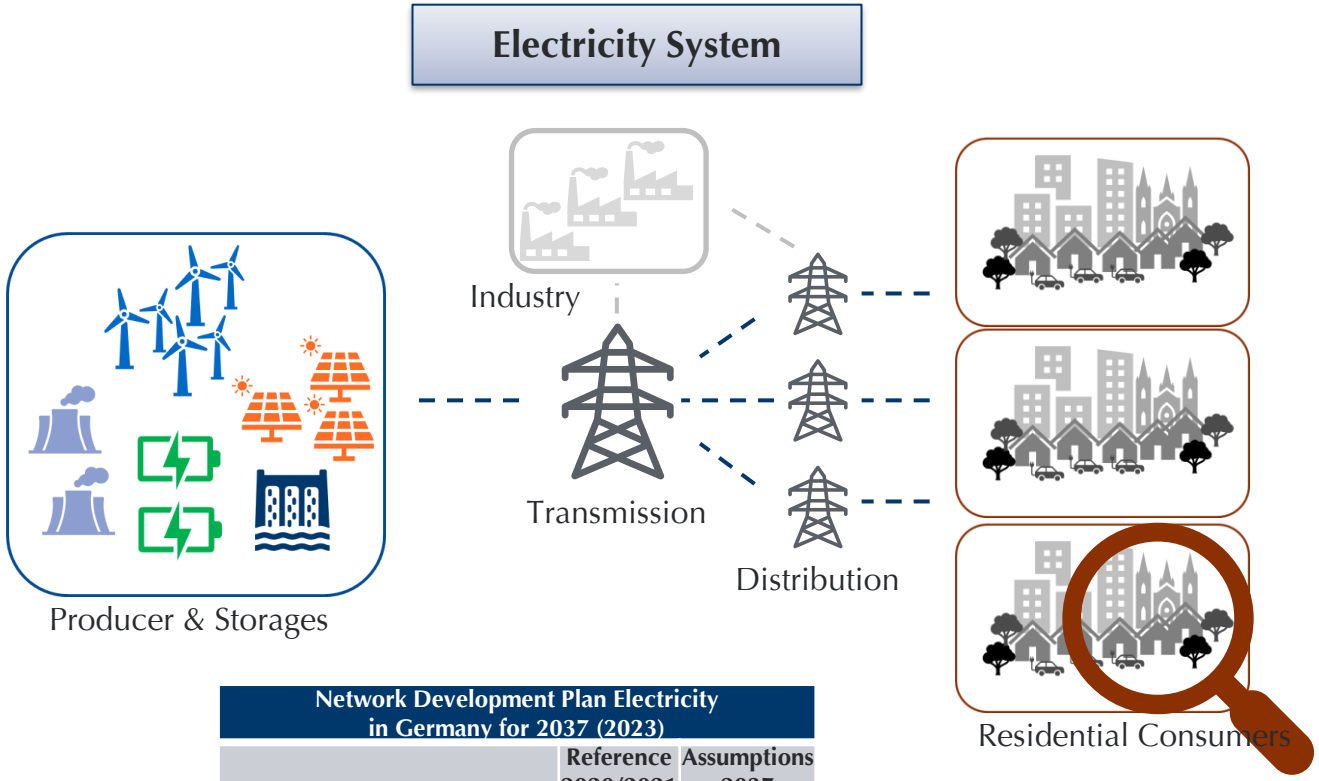

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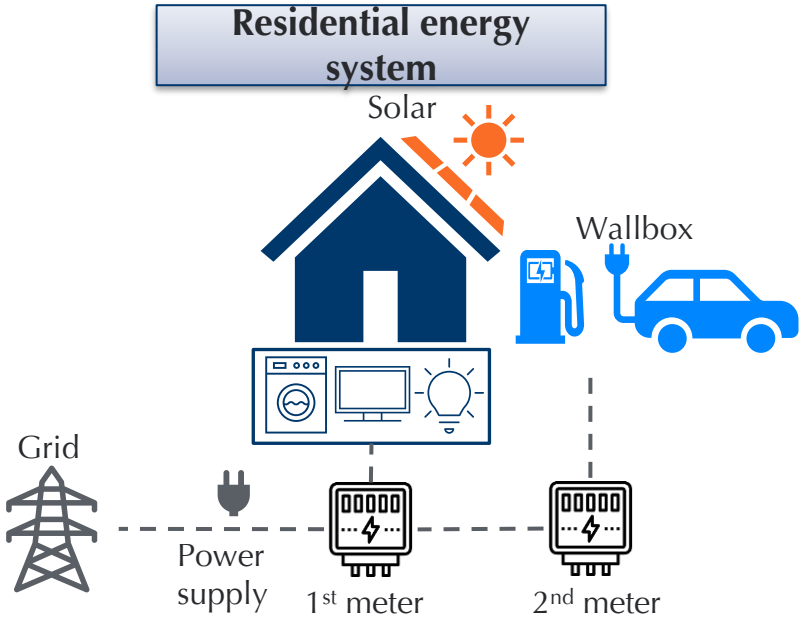
➢ Normative View: The efficient implementation relies on efficient configuration of **meters** and **tariffs**

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

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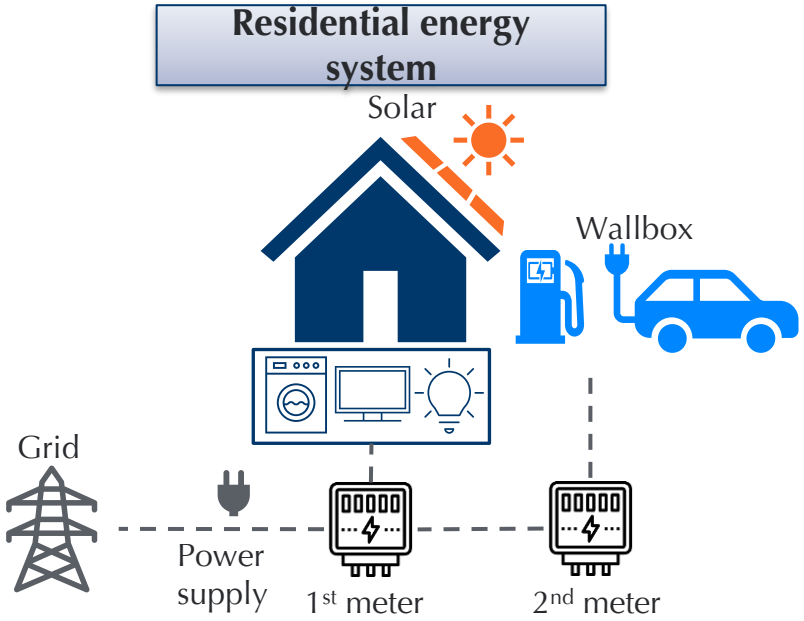

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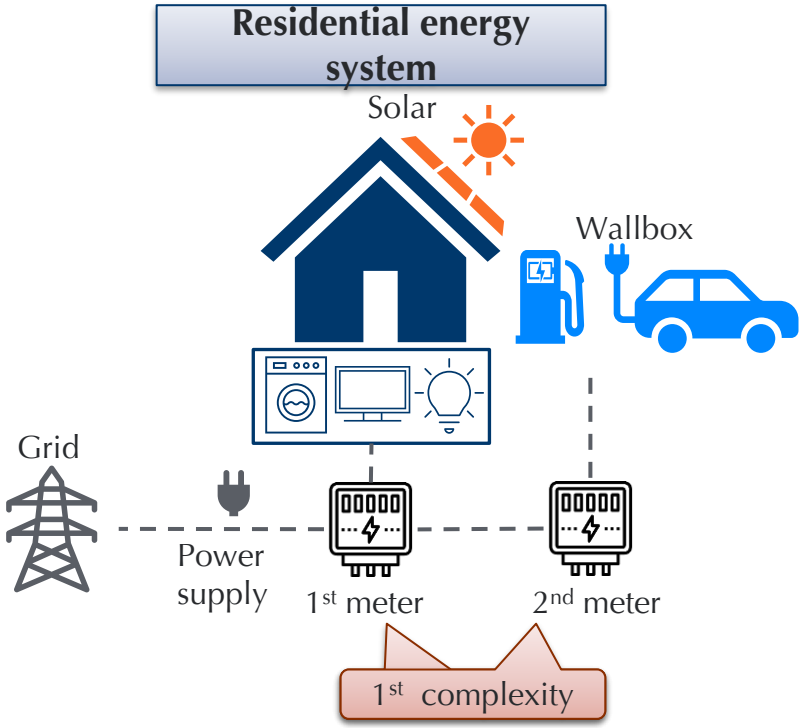

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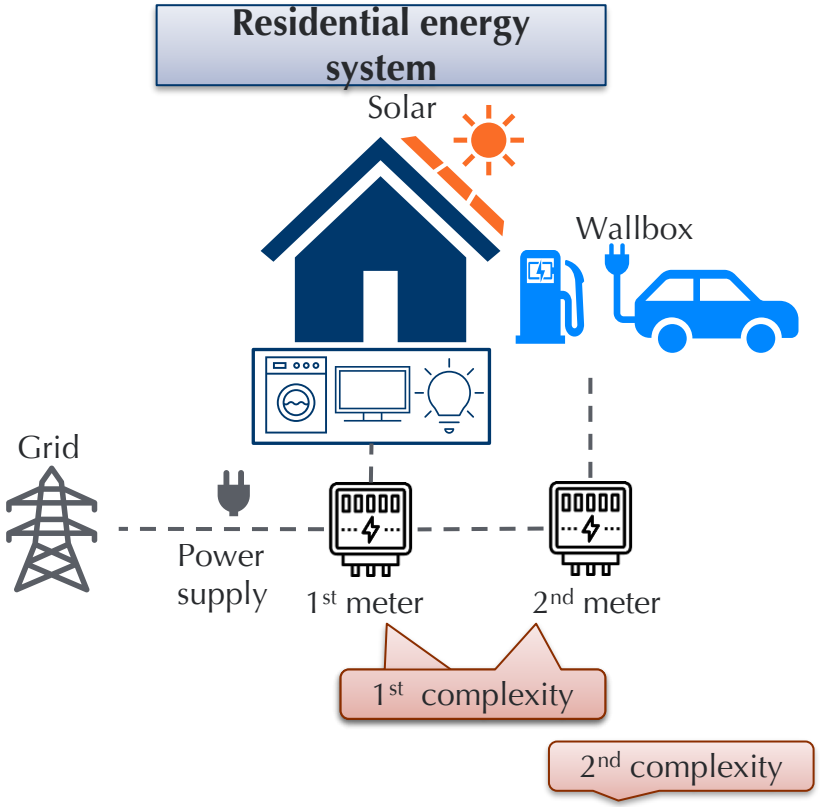

$$\textit{Electricity Tariff} = \textit{Basic Charge} + \textit{Energy charge} + \textit{Grid charge} + \textit{other components}$$

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

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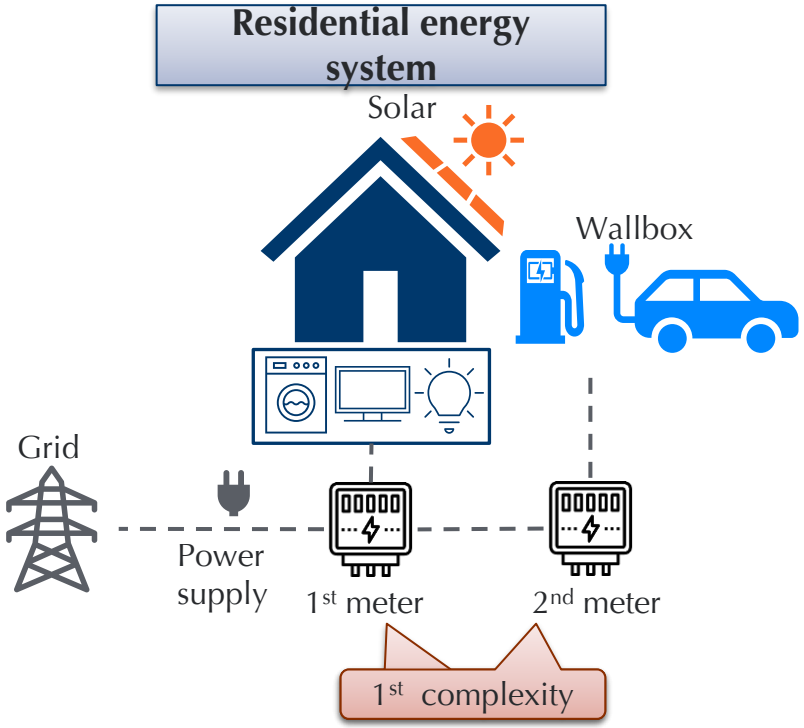

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  2. Pricing module
  3. Grid charge module

Market-oriented

Grid-oriented

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- **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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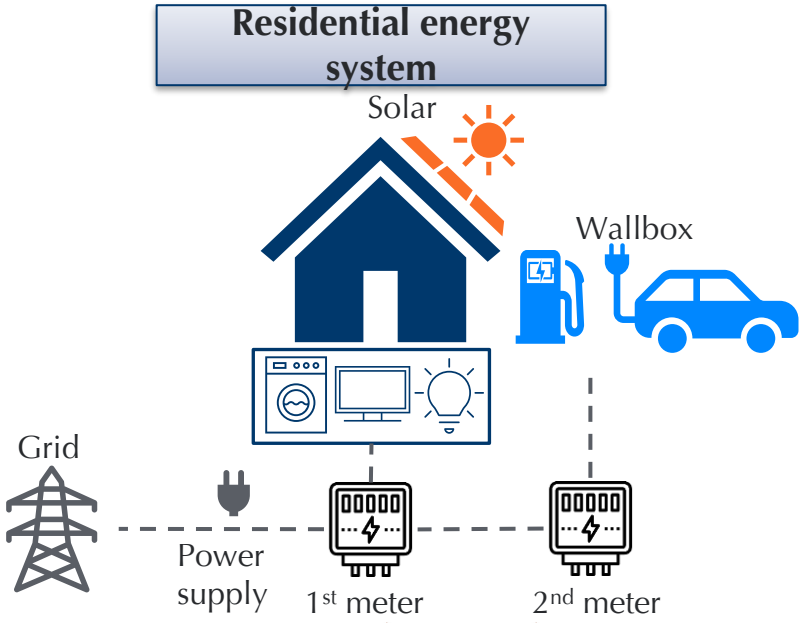

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- Disentangling the influence of electricity meter and tariff configurations on the operational and investment decisions of residential consumers
- The focus is on three complexities:
  1. Number of meters (1 meter = 1 tariff)
  2. Pricing module
  3. Grid charge module
     - How do electricity meter and tariff configurations incentivize residential consumers' provision of flexibility and investment in PV & Storages

Literature Review

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 analyzes
  - 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 considers
  - Various combinations of tariff components
  - Different levels of electrification of residential consumers

➢ But predominantly relies on static data inputs

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➢ But lacks interactions with markets

- Relevant literature considers
  - 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

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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

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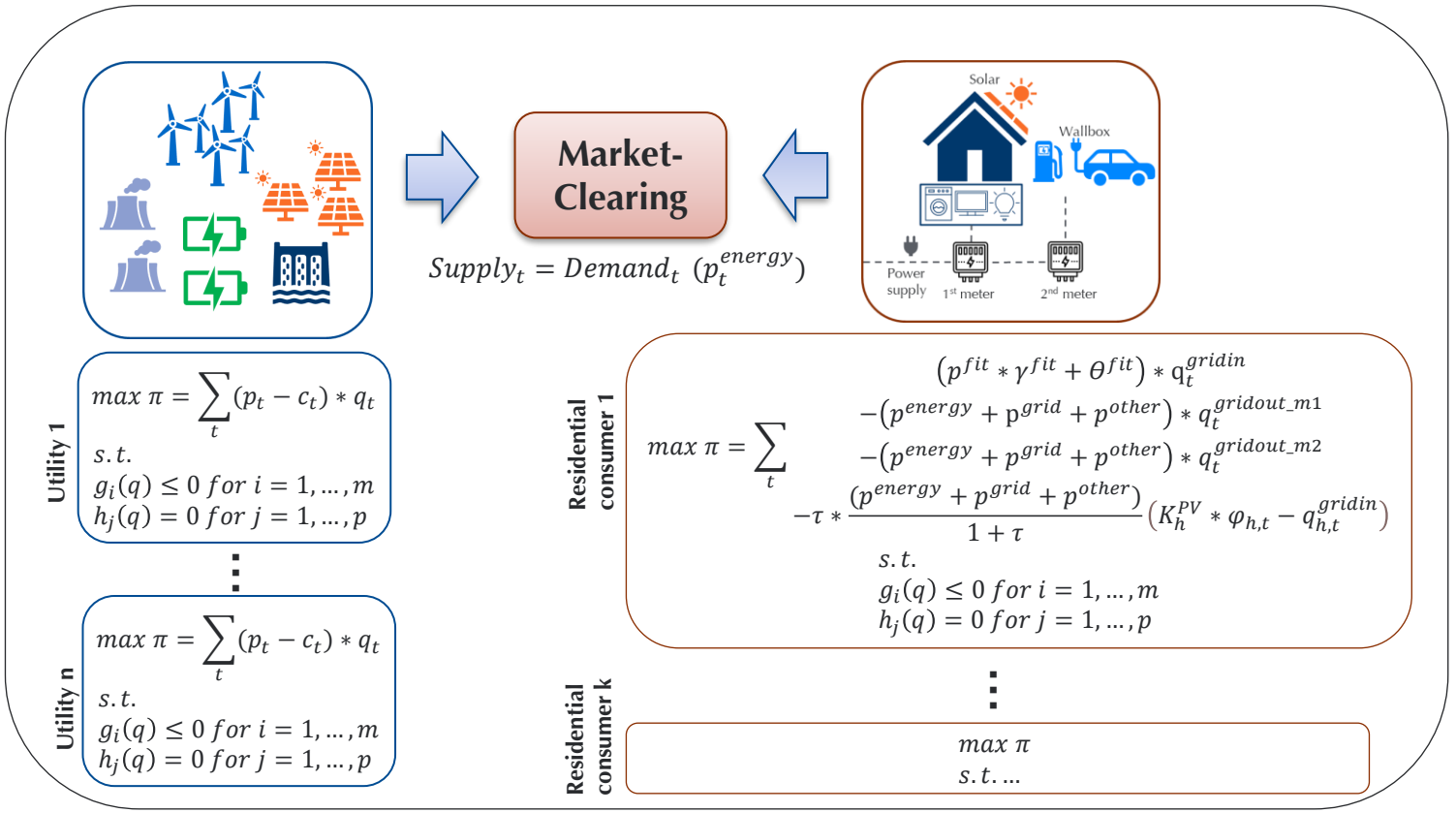
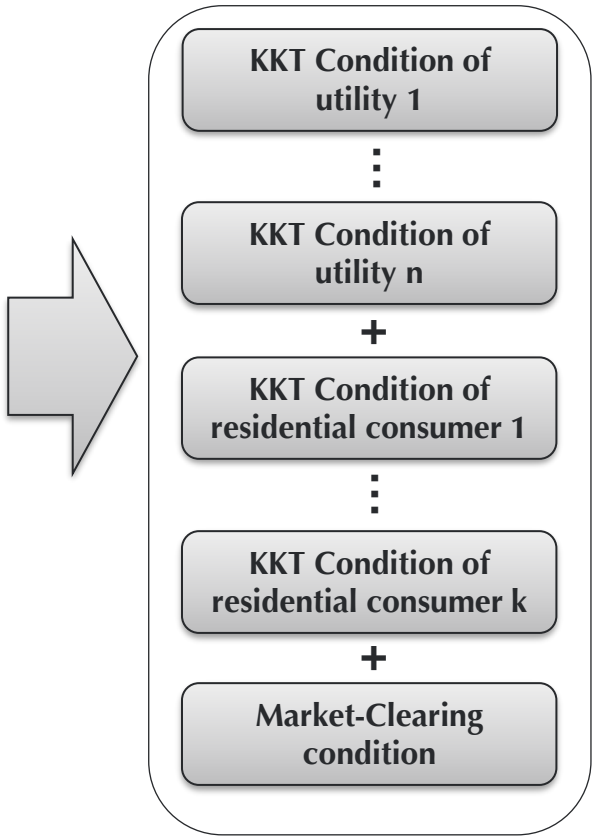
Interrelated optimization problems and equilibrium problem (KKT)



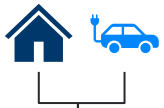


* Agents are Conventional, Renewables & Storages, each with specific constraints tailored to their operational characteristics and market roles.
** Constraints consider PV BSS limits, Wallbox-EV limits, internal clearing condition; Dumb or smart charging possible.

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

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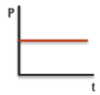
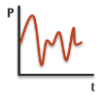
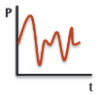
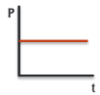
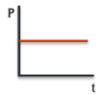
Tariff: Energy Charge							
Tariff: Grid Charge							
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Bill per Meter (ΔBase in %)							
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➢ Dynamic energy price and time-variant grid fee most preferable

Preliminary Results

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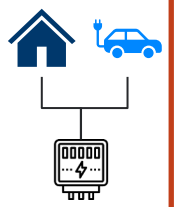
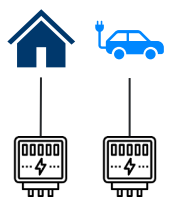
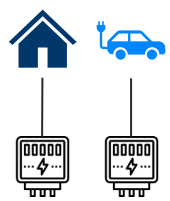
Electrical Devices							
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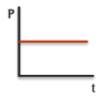
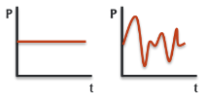
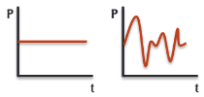
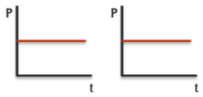
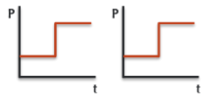
Tariff: Energy Charge							
Tariff: Grid Charge							
Total Bill (ΔBase in %)	54.22 €	52.58 € -3%	43.13 € -20%	51.99 € -4%	41.79 € -23%		
Bill per Meter (ΔBase in %)				33.30 € 0% 18.69 € -11%	32.91 € -1% 8.88 € -58%		
	Base	2	3	4	5	6	7

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

➢ Distinguishing applications leads to further reductions

Preliminary Results

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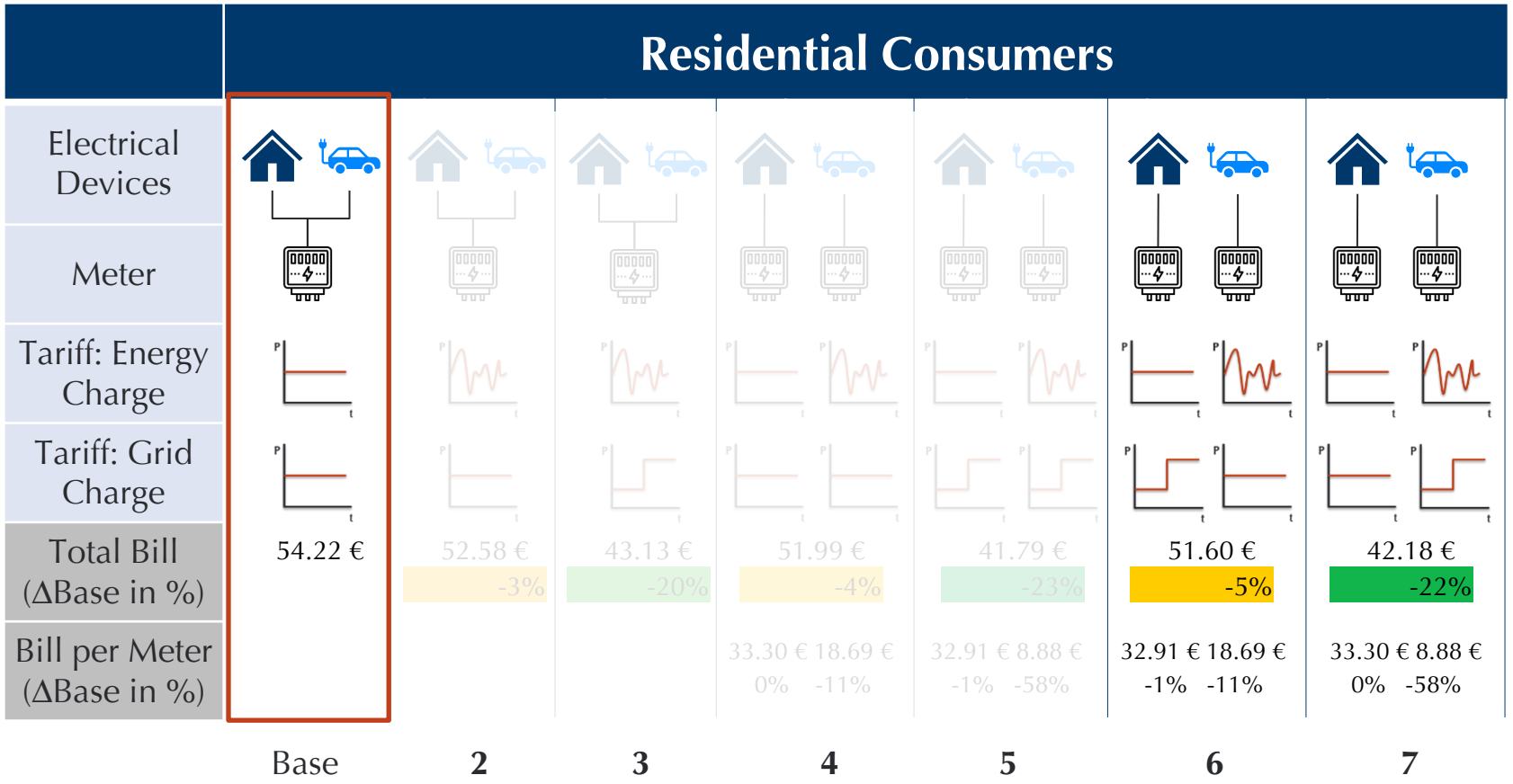

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➢ The level of reduction depends on tariff configuration

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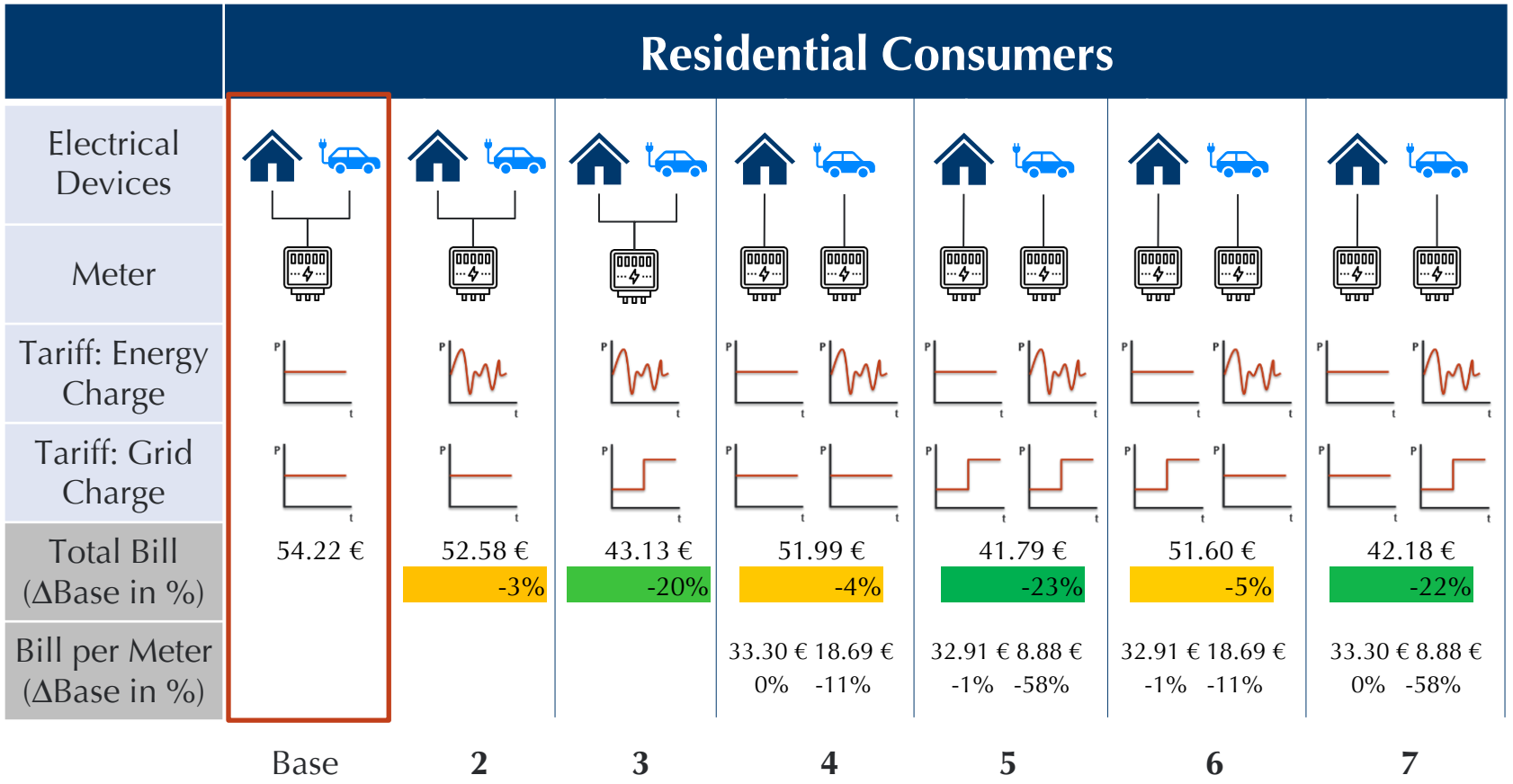

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➢ Assuming application-dependent cost reflection, the meter-tariff configuration influence individual electricity bills - non-robust first estimate

Outlook

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

- Reduction in computational complexity
  - temporal aggregation into representative segments

- Reflection of uncertainty:
  - Uncertainty regarding weather & driving profiles
    - Impact on residential PV & BSS, HP, Air Conditioner, EV charging, Renewables (Wind & Solar at Wholesale market)

➢ From deterministic to stochastic

Approach to energy markets given in:

- Chanpiwat & Gabriel (2024)
- Egging (2013, 2010)
- Devine & Bertsch (2018)

Thank you for your attention!

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