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

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Abstract

Decentralized sector coupling and flexibility options are expected to play a pivotal role in the integration of renewable energies into energy systems. Recent developments include increased investments in PV battery systems underlining the increasing importance of decentralized flexibility. However, the current structure of retail tariffs incentivizes private households to operate integrated photovoltaic (PV) and battery storage systems (BSS) primarily to maximize self-consumption. This operational strategy, however, disregards the potential flexibility these systems could provide to support the electricity system.

Against this backdrop, we examine to what extent adjustments to the regulatory framework may provide stringent incentives for the system-oriented operation of decentralized flexibilities from PV battery storage systems (PV-BSS). We investigate the longer-term market equilibrium including competitive wholesale markets under a carbon budget constraint and prosumage households with capabilities to invest in PV-BSS. We iteratively couple the linear optimization problems of the decentralized agents at the household level, the retailers and the generation companies at the wholesale level. We examine the effect of various distortions in tariffication schemes that induce deviations of prosumage households' behavior from system-oriented outcomes. The results reveal the consequences of time-independent retail tariffs, fixed feed-in tariffs and surcharges on investments, wholesale market prices and system cost.

In addition to prosumage households' investment decisions and operations, we assess the long-term effects of prosumage incentives on the system development under realistic market conditions as well as the distributional effects on prosumage households and other end-users.

Keywords: Electricity System, Electricity Tariffs, Consumer Behavior

JEL-Classification: Q420 , Q410, D160

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1 Introduction

Previous studies indicate that decentralized sector coupling and flexibility options have a pivotal role to play in the integration of renewable energies into energy systems (Bernath et al., 2021; BNetzA, 2018; Dietrich and Weber, 2018; Gea-Bermúdez et al., 2021). Recent developments include increased investments in Photovoltaic (PV) and battery storage systems (BSS), underlining the growing importance of decentralized flexibility. Here, the term prosumage emerged to describe a household that not only consumes electricity but generates PV electricity, enhanced by battery storage, while still being connected to the grid (Von Hirschhausen, 2017). At the same time, the present design of retail tariffs means that private households operate combined systems of Photovoltaic and battery storage systems (PV-BSS) primarily with the aim of increasing self-consumption, although the flexibility could be utilized to support the power system (Luthander et al., 2015). Moreover, self-supply optimization leads to an undersizing of photovoltaic systems relative to available roof space (Prognos, 2016).

Studies with a focus on techno-economic analysis of households mostly neglect interaction with the power sector or simplify this interaction by neglecting retailers as linkage between households and markets (cf. section 2). The incentives for prosumage-households are furthermore distorted compared to competitive long-term equilibria as flat retail tariffs do not reflect temporal incentives from wholesale markets. Thus, we provide a model that investigates the interplay between wholesale market agents, retailers as well as prosumage households. We control for different retail tariffication schemes to evaluate the impact of distortions on investments decisions for PV-BSS. Our analysis highlights how the regulatory framework may be modified to induce more system-oriented investments and operations of prosumage households, taking into account market feedbacks in the long run.

Hence, this paper is motivated by the repercussions of prosumage on wholesale markets, the role of Prosumage in achieving carbon reduction targets, the effects of time-invariant retail prices on Prosumage behavior and the reflection of market conditions into prosumage models and long-term system-wide effects of prosumage incentives. Our novel modelling approach allows to answer questions on the impact of distortionary tariffs on long-term equilibria with high share PV-BSS and how adjustments improve system-resiliency and efficiency.

The remainder of this paper is structured as follows. Section 2 reviews relevant literature on prosumage. Section 3 introduces our framework and provides methodological insights. In section 4, we define the scenarios and describe the applied data sources. Based on this, we present and discuss the numerical results of the model in section 5. Section 6 outlines avenues for future research and concludes with policy implications.

2 Literature review

Prosumage households might play a crucial role in future electricity systems as costs for residential photovoltaic installations and stationary BSS have decreased over the last decade (Dietrich and Weber, 2018; Hoppmann et al., 2014). Next to this, we further observe rising end-consumer electricity prices (BDEW, 2024). Thus, the switch from pure consumer households to prosumer or even prosumage-households is beneficial, especially in Germany. To date, an extensive literature reflects the high level of attention paid to the prosumer and prosumage issue. Khalilpour and Vassallo (2015) discuss different modelling approaches for PV-BSS.

One stream in the literature focuses on the household perspective, discussing the relations between system size and rates of self-consumption and self-sufficiency (Weniger et al., 2014) or evaluating the cost-effectiveness of different battery technologies and capacities (Bruch and Müller, 2014). Johann and Madlener (2014) compare different types of households and locations to examine the economic merit of battery systems and self-consumption. The influence of different charging strategies on household's self-consumption and annual electricity cost is analyzed by Li and Danzer (2014). Dietrich and Weber (2018) analyze the profitability of PV-BSS based on data with a temporal resolution of 5 minutes. Further analyses on household perspective are provided by Bertsch et al. (2017), Kaschub et al. (2016), Moshövel et al. (2015) and Waffenschmidt (2014).

Another stream emphasizes the interaction between prosumage-households and electricity markets as well as the corresponding agents. Günther et al. (2021) investigate how tariffication schemes incentivize households to invest in PV-BSS and explore selected electricity sector effects. The authors do not consider retailer interaction and neglect endogenous price formation. Thus, no price-driven market feedbacks are possible. The effects of a widespread adoption of residential PV-BSS on both prosumage households and further agents are discussed in Agnew and Dargusch (2015) and Schill et al. (2019, 2017). Also several papers point at economic inefficiencies that might occur due to inappropriate incentives leading to suboptimal behavior in the short and long term (Green and Staffell, 2017; Say et al., 2020; Schill et al., 2017). Incentivizing PV investment without aligning it with market mechanisms can, from a system perspective, lead to suboptimal sizing and operation of rooftop PV systems. This often results in energy being fed into the grid during solar peak times, when residual load is at its lowest. Finally, the role of regulatory framework for expansion of the electricity distribution grid infrastructure in the context of prosumage is discussed in Moshövel et al. (2015) and Young et al. (2019). Young et al. (2019) investigate for an Australian region the beneficial effects of prosumage on system level.

A third crucial stream, the regulatory policy perspective, addresses the question how to price consumption and generation of prosumage households. Ossenbrink (2017) analyzes the implications of feed-in and retail tariff schemes for residential PV systems without batteries. Thomsen and Weber (2021) investigate the impact of tariffication schemes on profitability and operation of small-scale PV-BSS in Germany, yet they do not consider endogenous investments. Focusing on tariffication schemes, Hinz et al. (2018), Kubli (2018), Roulot and Raineri (2018), Schittekatte et al. (2018), Laws et al. (2017), Simshauser (2016) and Costello and Hemphill (2014), indicate that a growing prosumage segment may induce distributive justice concerns at the consumer level and cost recovery issues for utility operators since prosumage households consume less energy from the grid and consequently contribute less to its financing.

In summary, there are various literature sources providing an in-depth treatment of specific households yet neglecting interactions between prosumagers and the power sector. An exception is Günther et al. (2021), where the authors use a simple dispatch model at wholesale level while allowing for investments at household level. Yet with this mix of short-run and long-run decisions the resulting equilibria are difficult to interpret and do not provide a consistent picture of distortionary effects. General power sector studies yet neglect incentives for prosumage households and the role of retailers and tariffication schemes. And in regulatory studies, results are rarely underpinned by numerical assessments.

Our novel contribution hence consists in an analysis of tariffication schemes for prosumage households, including the explicit modelling of agents at the wholesale level as well as retailers. We consistently allow for endogenous investments of both, households and power sector agents to analyze system feedback effects in the long run. Moreover, we apply a welfare analysis to assess impacts on producers, consumers and public finance. Although we focus on the German context, the essence of our results is transferable to the multitude of other markets where prosumage is expected to play a major role.

3 Methodology

To capture the interactions and systems feedbacks in a detailed and structured manner, we formulate two iteratively coupled linear programs (LP). As indicated in Figure 1, these LPs represent the optimization calculus of decentralized agents at the retail level, such as prosumage households, alongside with the decisions of generation companies and retailers at the wholesale level.

The first LP focuses on a representative prosumage household, minimizing electricity-related costs while accounting for endogenous investments in PV systems and storage. In the general case, these investments are central to prosumage behavior, i.e. determining production, consumption, grid feed-in, and electricity storage of electricity. The prosumage household receives a (possibly time-dependent) remuneration p_t^{fit}, for the energy supplied to the grid, and pays a different, possibly also time-variant retail rate, p_t^{ret}, for the energy withdrawn from the grid.

Both, net metering and a perfect non-distortionary real-time-pricing of electricity may be modeled as special cases in this general setting.

The second LP models the wholesale market agents including a representative retailer under the assumption of a competitive equilibrium. This is equivalent to a minimization of total system costs. Thereby also endogenous investments in renewables and storage systems as well as conventional generation are considered. The representative retailer aggregates the household demand for procurement at the wholesale market and charges prices to the household customers for their consumption. In a competitive market environment, such a retailer will break even without making any excess profits – and this condition may be used to determine the prices for end users for a given demand profile and under a prespecified tariffication scheme. For the infeed of renewable electricity into the grid, we assume a similar mechanism, with the feed-in tariff being reflective of the wholesale market prices and possibly some government-backed support mechanism. Subsequently we first discuss the details of the prosumage modeling (cf. Section 3.1), then the wholesale market representation is summarized in Section 3.2. Section 3.3 is finally devoted to the retailer acting as intermediary between wholesale market and households.

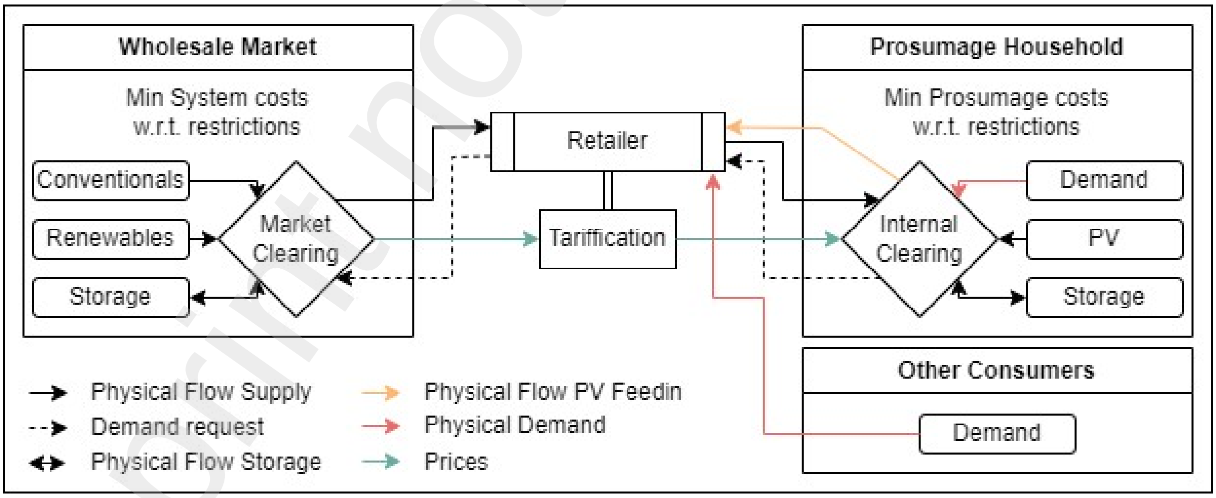

Figure 1: Flow Diagram.

3.1 Prosumage household

Model description:

The representative prosumage household optimizes investment decisions regarding PV-BSS as well as operational decisions (dispatch) in order to minimize its energy-related costs, cf. Eq. 1. The prosumage household feeds electricity into the grid ($q_{h,t}^{gridin}$) and is compensated with a feed-in-price (p_t^{fit}). Electricity purchased from the retailer ($q_{h,t}^{gridout}$) is paid on an energy base with a possibly time-variant retail price p_t^{ret}. To reduce electricity purchases from the grid, the household can invest in PV (k_h^{pv}) and battery capacity (k_h^{bat}). The investments costs ($C^{invPV}, C^{invBatK}$) are annualized to the planning horizon. Since battery energy and power capacities are correlated for household applications, we scaled the volume as a fixed factor relative to the power.

$$\max_{q_{h,t}^{gridin}, q_{h,t}^{gridout}, k_h^{PV}, k_h^{bat}} \sum_t \left(p_t^{fit} \cdot q_{h,t}^{gridin} - p_t^{ret} \cdot q_{h,t}^{gridout} - C^{invPV} \cdot k_h^{PV} - C^{invBatK} \cdot k_h^{bat}\right) \cdot \Delta t \tag{1}$$

According to Eq. 2, household demand ($Q_{h,t}^{con}$) must be satisfied in each hour either through electricity purchased from the grid, own PV-production based on capacity ($K_h^{PV} + k_h^{PV}$) producing at capacity factors ($\varphi_{h,t}$) or discharged storage energy ($s_{h,t}^{-}$), while storage charging ($s_{h,t}^{+}$) and grid-infeed reduce the electricity available for consumption.

$$Q_{h,t}^{con} \leq \left(K_h^{PV} + k_h^{PV}\right) \cdot \varphi_{h,t} + q_{h,t}^{gridout} - q_{h,t}^{gridin} + s_{h,t}^{-} - s_{h,t}^{+} \;\; \forall\, h,t \tag{1}$$

The feed-in may be constrained by regulatory (ρ) and physical ($\varphi_{h,t}$) constraints, cf. Eq. 3. The latter prevents the use of the battery storage for pure arbitrage trades based on time-varying prices with the feed-in tariff exceeding sometimes the purchase price. The former may take the form of a regulation that the infeed is limited a certain share of the installed capacity, e.g. 70% in Germany until 2023.

$$\begin{aligned} q_{h,t}^{gridin} &\leq \left(K_h^{PV} + k_h^{PV}\right) \cdot \rho \;\; \forall\, h,t \\ q_{h,t}^{gridin} &\leq \left(K_h^{PV} + k_h^{PV}\right) \cdot \varphi_{h,t} \;\; \forall\, h,t \end{aligned} \tag{2}$$

Purchase of electricity is limited to consumption and battery power according to Eq. 4.

$$q_{h,t}^{gridout} \leq Q_{h,t}^{con} + \left(K_h^{Bat} + k_h^{Bat}\right) \forall\ h,t \tag{3}$$

The storage balance equation (5) accounts for self-discharge (θ) as well as charging and discharging activities. The charging process is limited by an efficiency factor (η_h). Both charging and discharging are constrained by the storage power ($K_h^{Bat} + k_h^{Bat}$) and storage filling level is restricted by the volume scaling factor ψ_h multiplied by the storage power capacity.

$$bl_{h,t} = bl_{h,t-1} \cdot (1-\theta) + \left(s_{h,t}^{+} \cdot \eta_h - s_{h,t}^{-}\right) \cdot \Delta t\ \ \forall\ h,t \tag{4}$$

$$s_{h,t}^{-} \leq \left(K_h^{Bat} + k_h^{Bat}\right) \cdot \Delta\mathrm{t}\ \ \forall\ h,t$$

$$s_{h,t}^{+} \leq \left(K_h^{Bat} + k_h^{Bat}\right) \cdot \Delta\mathrm{t}\ \ \forall\ h,t$$

$$bl_{h,t} \leq \psi_h \cdot \left(K_h^{Bat} + k_h^{Bat}\right)\ \cdot \Delta\mathrm{t}\ \ \forall\ h,t$$

For the capacity of the PV and storage systems, additionally upper bounds K_h^{PVmax}, respectively K_h^{Batmax} are imposed, cf. Equation (5).

$$\left(K_h^{PV} + k_h^{PV}\right) \leq\ K_h^{PVmax}\ \ \forall\ h \tag{5}$$

$$\left(K_h^{Bat} + k_h^{Bat}\right) \leq\ K_h^{Batmax}\ \ \forall\ h$$

Prosumage metrics:

Two key indicators are introduced to describe the behavior of prosumage households: the rate of self consumption (RSC) and the rate of self sufficiency (RSS) (cf. Eqs. (6) and (7)).

$$RSC = \frac{\sum_{t=1}^{T} Q_t^{SC} \cdot \Delta t}{\sum_{t=1}^{T} \left(PV_t \cdot (1-\alpha) - PV_t^{Curt}\right) \cdot \Delta t} \quad (6)$$

With:

$$PV_t = \sum_h \left(K_h^{PV} + k_h^{PV}\right) \cdot \varphi_{h,t} \cdot \Delta t$$

$$Q_t^{SC} = PV_t - \sum_h q_{h,t}^{gridin} \cdot \Delta t$$

The RSC is calculated according to Eq. (9) by examining the ratio of the total electricity that is self-consumed ($Q_{t,y}^{SC}$) to the total electricity generated by the PV system(PV_t), except for curtailment. This metric measures how much of the generated solar power is used directly on-site rather than being fed into the grid. The RSS is defined in Eq. (7) by the proportion of total load consumption that is met through direct consumption of generated power ($Q_{t,y}^{DC}$) combined with electricity discharged from the storage system ($Q_{t,y}^{StoOut}$). The RSS is also called "degree of autarky" as it indicates the extent to which the prosumage household can operate independently of the external power grid, relying on its own renewable generation and storage capabilities.

$$RSS = \frac{\sum_{t=1}^{T} (Q_{t,y}^{DC} + Q_{t,y}^{StoOut}) \cdot \Delta t}{\sum_{t=1}^{T} D_t \cdot \Delta t} \quad (7)$$

With:

$$Q_t^{DC} = PV_t - \sum_h q_{h,t}^{gridin} - s_{h,t}^{-} \cdot \Delta t$$

The total surplus of prosumage households (CS) is the sum of their consumer surplus and their producer surplus. The consumer surplus is calculated as the difference between the value of lost load and the retail price, multiplied by the hourly demand. The producer surplus, in the absence of variable production costs, is the revenue from grid feed-in. Due to endogenous investment decisions, the annualized investment expenditures must be subtracted from this revenue.

For other consumers without own production, the consumer surplus is solely derived from the difference between the value of lost load (p^{VOLL}) and the market price, multiplied by the quantity demanded (cf. equation (8)).

$$CS = \sum_{t,h} ((p^{VOLL} - p_t^{ret}) \cdot Q_{h,t}^{con}) - C^{invPV} \cdot k_h^{PV} - C^{invBatK} \cdot k_h^{bat} \tag{8}$$

3.2 Wholesale market

Model description:

At the wholesale market, the efficient market coordination leads to a minimization of system costs considering operational and investment decisions (cf. eq (9)). Operational decisions cause variable costs c^{var} for conventional (c_i^{var}) and renewable (c_j^{var}) production q. Investments are considered for conventional (cap_i^{new}), renewable (cap_j^{new}) and storage (cap_k^{new}) capacities, with costs obtained by multiplying the annualized investment costs (c^{inv}) with the installed capacity.

$$\min \sum_t \begin{pmatrix} c_i^{var} \cdot q_{t,i}^{conv} + c_i^{inv} \cdot cap_i^{new} + c_j^{var} \cdot q_{t,j}^{res} \\ + c_j^{inv} \cdot cap_j^{new} + curt_{t,j}^{res} \cdot pen_j^{penalty} + c_k^{inv} \cdot cap_k^{new} \end{pmatrix} \tag{9}$$

Market clearing ensures that supply covers the retailer's demand at each timestep, considering possible curtailment of renewable energy (cf. eq. (10)). The dual variable of the demand-balance equation can be interpreted as the wholesale price (p_t^{who}).

$$q_{t,i}^{conv} + q_{t,j}^{res} + q_{t,k}^{sto|out} - q_{t,k}^{sto|in} - curt_{t,j}^{res} = q_t^{ret|dem} \tag{10}$$

The retailer demand at the wholesale market consists of the difference in demand and PV feed-in from prosumage households and demand of the residual consumers (cf. eq. (11).

$$q_t^{ret|dem} = \sum_h \left(q_{h,t}^{gridout} - q_{h,t}^{gridin}\right) + Q_t^{residual} \tag{11}$$

The CO2 budget serves to limit emissions to meet political decarbonization objectives. The dual variable can be interpreted as the resulting CO_2 price, cf. eq. (12).

$$CO2^{Bound} \geq \sum_{i,t} f_i^{CO2} \cdot q_{t,i}^{conv} \tag{12}$$

Further constraints include capacity constraints, investment restrictions, storage filling levels, charge and discharge limits and curtailment restrictions[1].

Wholesale metrics:

To evaluate the effects at the wholesale level, further metrics are introduced. We thereby evaluate the changes relative to a scenario without distortions (denoted "base", cf. Section 4.1) in operational contribution, indicating the level of system integration of storages, price movements, production volumes and curtailment of renewable energy. Therefore, we measure relative differences in price movements and changes in production volumes. The storage utilization is approximated using the Full Storage Cycles (FSC), calculated as the ratio between the total amount of energy charged and discharged over the course of a year and the storage capacity (cf. eq. (14)).

$$FSC = \frac{\sum_{t,k}(q_{t,k}^{sto|out} + q_{t,k}^{sto|in})}{\sum_k cap_k^{new}} \tag{13}$$

Additionally, we extend our analysis to changes in system costs C^{sys}, differentiating between system-wide investment C^{inv} and system-wide operational costs C^{opr} (cf. eq. (14)).

$$C^{sys} = C^{inv} + C^{opr} \tag{14}$$

[1] The complete model code, input data, and a detailed model description can be found in our Git repository.

Analogous to consumer surplus on the demand side, we calculate the producer surplus (PS) for all technologies active in the wholesale market (cf. equation (15)). In this simple model, the producer surplus equals the sum of the contribution margins, calculated as the difference between the hourly wholesale price received (p_t^{who}) and the variable costs ($c_{i,j,k}^{var}$), multiplied by the hourly production volumes ($q_{t,i,j,k}$). Since we allow endogenous investments, the annualized investment expenditures ($c_{i,j,k}^{inv} \cdot cap_{i,j,k}^{new}$) are subtracted from these contribution margins.

$$PS = \sum_{t,i,j,k} (p_t^{who} - c_{i,j,k}^{var}) \cdot q_{t,i,j,k} - c_{i,j,k}^{inv} \cdot cap_{i,j,k}^{new} \tag{15}$$

3.3 Retailer as intermediary

Between the wholesale market on the one hand and the retail market on the other, we model a representative retailer. The retailer serves as intermediary coupling the prosumage households and the wholesale level.

For the prosumage households, the retailer acts as an electricity supplier, i.e. it sells electricity to consumers. Thereby it applies a tariffication scheme imposed by governmental regulation and/or sector standards and practices. In the application part, we focus on the impact of the tariffication scheme. We notably consider the following variants: the retail price may be time-dependent or time-independent and there may or may not be additional (volumetric) surcharges such as grid fees or energy taxes.

In a competitive environment, a retailer will recover its own cost (including the cost of capital) yet not make any excess profit. This implies that the retail market corresponds to the wholesale market price plus eventually the surcharge (including the costs of the retailer). In case the retail price is time-invariant, the retailer will charge a price p_{fix}^{ret} which corresponds to the demand-weighted average of the wholesale market prices plus the surcharge (ω^{ret}) (cf. eq. (17)).

$$p_{fix}^{ret} = \frac{\sum_t (p_t^{who} \cdot q_t^{ret|dem})}{\sum_t q_t^{ret|dem}} + \omega^{ret} \tag{17}$$

At the wholesale level, the retailer acts as a client of the producers (and storage operators). The retailer buys at the time-dependent price (p_t^{ret}) resulting from hourly market clearing (cf. eq. (18)). The amount of electricity demanded is the difference between the total consumer demand and the prosumage households' PV feed-in.

$$p_t^{ret} = p_t^{who} + \omega^{ret} \tag{18}$$

The solution of the overall problem requires an iterative procedure as the retailer demand is exogenous in the wholesale market model, yet it is impacted by the retail prices which drive the household investments in PV and storage systems. Conversely in the prosumage model, the retail prices are exogenous yet they are driven by wholesale prices which in turn impacted by the retailer demand (cf. Figure 1). As the two optimization problems are convex and also the optimization problem underlying the retailer pricing is convex, we can expect the iterative procedure to converge towards a unique market equilibrium. Also, the numerical experiments undertaken did not provide evidence of multiple local optima.

In the numerical implementation, the two models run sequentially in a loop until a convergence threshold is reached. The prosumage LP generates purchase and feed-in quantities as variables ($q_{h,t}^{gridout}$, $q_{h,t}^{gridin}$), which are stored and converted into parameters used as input for the wholesale LP. In turn, the wholesale LP provides prices (p_{fix}^{ret}, p_t^{ret},p_t^{fit},p_{fix}^{fit}) that are fed back into the prosumage LP as part of the iterative process.

4 Scenarios and data

This section introduces the scenario framework and data sources. Given our modelling framework, we analyze the impact of distortionary electricity tariffs on long-term equilibria across six distinct scenarios. Therefore, the model of the prosumage households is configured according to two key attributes: the households tariffication scheme and the compensation mechanism for solar grid feed-in. Specifically, the scenarios differentiate between time-dependent and time-independent tariffication schemes as well as varying feed-in compensation structures.

Additionally, surcharges are applied to both pricing and compensation mechanisms to explore their effects on capacity investments, wholesale market prices, and overall system costs. The data employed in the analysis represents assumptions for the year 2030, with demand profiles, power plant portfolios, and other relevant parameters calibrated to reflect conditions expected in that year.

4.1 Scenarios

We define five distinct settings to explore potential considerations for retail pricing and the broader market participation of PV rooftop systems. To underline our chosen settings, we briefly explain the issues assumed to be distortionary in decision making of prosumage-households. First, the prevailing tariffication schemes mostly rely on time-independent pricing, which may partly stem from technical limitations, such as the lacking rollout of smart meters. However, this approach ultimately impedes market-driven incentives. In contrast, time-dependent pricing, based on day-ahead or intraday auctions, can provide market-aligned signals but is currently seldom offered or utilized by end-users. Additionally, surcharges reflecting retailer costs or profit margins can dilute these market-driven effects. To examine the interaction of these price components, we vary both the temporal structure of retail prices and the presence of surcharges.

Second, regarding compensation for solar feed-in, fixed payments are the standard in Germany. Setting aside the interaction with retail prices for the moment, this time-independent incentive fails to encourage market-oriented behavior. Alternatively, a market-driven approach based on time-dependent wholesale prices is also feasible. Additionally, surcharges on time-dependent feed-in remunerations can be implemented to increase incentives for PV uptake. These additional compensation mechanisms allow for an in-depth analysis of changes in the self-consumption behavior of prosumage households.

From the previous aspects we take as reference case a market setting with all distortions, i.e., time-independent electricity prices plus time-independent feed-in remuneration. From this baseline, we explore the impact of four specific market distortions:

1. Time-independent retail prices (***TIRP***)
2. Retail prices including surcharges (***RPWS***)
3. Time-independent feed-in remunerations, i.e. fixed feed-in tariffs (***TIFR***)
4. Feed-in remuneration including support payments (***FRWS***).

In total there are 16 possible combinations of these distortions, but we focus on five key scenarios plus a hypothetical case as pure market setting devoid of any distortions. These include: the reference scenario with *All Distortions*, one for each single distortion, i.e. *TIRP* Only, *RPWS* Only, *TIFR* Only, *FRWS* Only, and a scenario incorporating *No Distortions* (cf. Table 1). The primary aim is to examine the main effects of these distortions without delving into interaction effects.

Scenario	***Name***	***Description***
1	***All Distortions***	All four mentioned distortions are applied simultaneously, i.e. the setting is TIRPWS & TIFRWS.
2	***TIRP Only***	The RP is time-independent and based on the consumption-weighted average of wholesale market prices.
3	***RPWS Only***	The RP includes a (volumetric) surcharge which is applied on top of the time-dependent wholesale market prices.
4	***TIFR Only***	The FR is time-independent and based on the infeed-weighted market prices in the wholesale market (i.e. the solar market value).
5	***FRWS Only***	The FR includes a volumetric support payment (feed-in premium) on top of the time-dependent wholesale prices.
6	***No Distortions***	The retail price (RP) and the feed-in remuneration (FR) are aligned with the market prices at the wholesale level.

Table 1: Scenario Description.

The tariff parameterization in the study includes several distinct components. The TIRP is based on the weighted average price of the wholesale market. This is in line with a flat energy component in electricity tariffs. The *TIFR* is determined by the solar market value, reflecting the economic viability of solar energy generation. For the *RPWS*, historical values of the surcharge are derived from the Monitoring Report 2023 issued by the Federal Network Agency, ensuring they reflect real-world data and trends. Lastly, the support payment in the *FRWS* is calculated as the difference between the "EEG" (Renewable Energy Sources Act) feed-in tariff for small solar rooftop installations and the solar market value, corresponding to the discrepancy between policy-driven and market-driven pricing for renewable energy.

4.2 Data

While the growth of prosumage households and their integration into electricity markets is of global interest, this study focuses on Germany. As a frontrunner in the energy transition, Germany serves as an exemplary case study, providing insights that may guide other countries. The temporal scope of this analysis is set to the year 2030, a pivotal year marked by significant milestones. By 2025, dynamic tariffs will become a mandatory service to retailer, and the rollout of smart meters is expected to have advanced substantially. Additionally, electric vehicles will likely constitute a larger share of the national vehicle fleet. Furthermore, new construction and building renovations will be required to comply with stringent energy standards, fostering the development of smart energy homes, or at least buildings with PV systems. Table X presents the data sources selected to align with the scope of our analysis:

Data	***Source***
Ten-Years Network Development Plan (TYNDP) 2022 (ENTSOG and ENTSO-E, 2022)	Investment costs
German Grid Development Plan (NEP) 2030 (BNetzA, 2018)	Installed capacities (incl. investment limits) at wholesale market, number of prosumage households
Draft on immediate energy measures in Germany (BMWK, 2022)	maximum capacities for wind and solar power at wholesale market
EWI Merit Order Tool (EWI, 2022)	Operational expenditures of wholesale market agents
Standard Load Profiles (BDEW, 2017)	Prosumage household electricity demand
ENTSO-E Transparency Platform (ENTSO-E, 2022)	Residual electricity demand (industry, commerce, other households

Table 2: Overview of data sources

The number of prosumage households is initially set to one million, as specified in the NEP 2030. We assume a potential of 10 million households suitable for PV battery systems, a value estimated by (Prognos, 2016). Since the prosumage agent represents the aggregation of all households, we scale the upper PV investment limit to 10 kW per household to align with the threshold for exemption from paying the renewable surcharge on self-consumed electricity.

For operational expenditures, we utilized the EWI Merit Order Tool, an open-source model for merit order simulations (EWI, 2022). The model incorporates all relevant parameters for short-term cost projections, including CO_2 costs. Data for the wind and solar infeed profiles are sourced from Open Power System Data (OPSD), a platform that aggregates data particularly from transmission system operators (OPSD, 2022).

Household demand is represented as standard load profile, a calculated, sufficiently accurate forecast of electricity demand for Germany (BDEW, 2017). We assume an annual load of 5 MWh per prosumage household, reflecting the average for German single-family households (Günther et al., 2021). The data is calibrated to the scenario year 2030 if not initially provided. Some relevant parameters are given in Table 3, while additional parameters are listed in Appendix B1.

Description	***Value***
Gross electricity consumption in 2030	643 TWh
Thereof private households	129 TWh
Number of private households	41 million
Thereof prosumage households	10 million
Emission cap energy industry	88.2 Mt CO_2 eq.
PV potential prosumage households	100 GW

Table 3: Key parameters

5 Results and discussion

To address the questions regarding the impact of distortionary retail pricing and feed-in schemes on long-term equilibria under high shares of PV-BSS, this section follows the structure of Section 3. We thus begin with an analysis at the household level. Subsequently, we expand the scope to examine the interactions between prosumage households and electricity markets. Finally, we assess welfare effects, incorporating societal considerations, as the system-oriented perspective does not necessarily align with maximum benefits for the concerned consumers. To assess the changes induced by modifications in the tariffication schemes for both prosumage households and other households, we apply the metrices introduced in Section 3.

5.1 Prosumage level

The different pricing schemes play a crucial role in shaping the behavior of prosumage households, affecting both their investment decisions and their interplay with the energy market.

Figure 2 illustrates that in the absence of any distortions, the prosumer household do neither invest in PV systems nor in storage. In the other extreme scenario, which reflects the currently predominating incentive structure in Germany, we yet observe almost 83 GW investment in residential PV and 24 GWh investment in BSS. Among the single distortions, the support payments for solar infeed (scenario *FRWS*) have the strongest individual effect on PV investments, while the surcharges included in retail prices (scenario *RPWS*) turn out to be the main driver for BSS investments. Yet in the absence of support payments for solar feed-in, the PV installations in the scenario *RPWS* are less than a third of those observed in the scenario *FRWS*. Applying only time-independent retail pricing (scenario *TIRP*), already induces some solar investments in the order of 5 GW, while the flattening of feed-in remunerations (scenario *TIFR*) does not provide any incentive to invest.

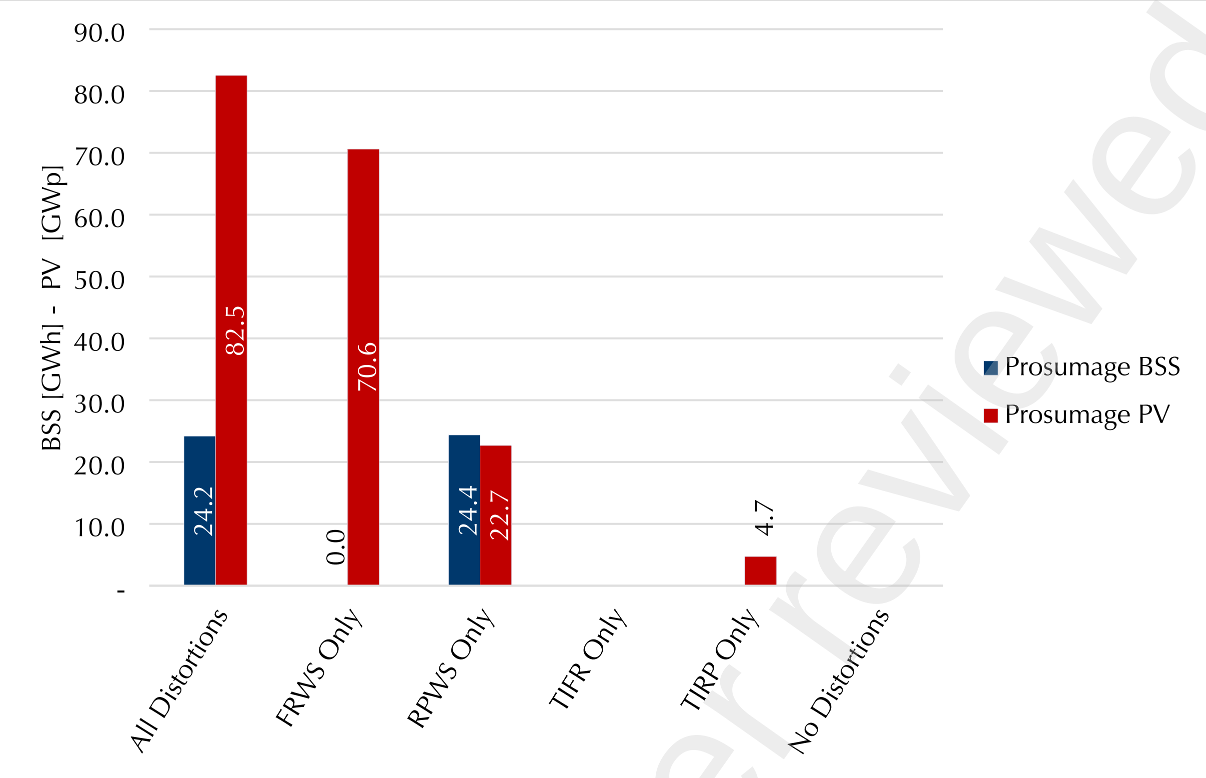

Figure 2: Investment Decisions of Prosumage Households in the different scenarios.

In the scenario TIRP with time-independent retail tariffs, a major benefit of PV installations is that electricity purchased from the market at a fixed rate may be substituted by self-produced PV power which comes at zero marginal costs. Correspondingly, the rate of self-consumption (RSC) is rather high (65%), cf.

Figure 3. Yet given the low level of realized PV investments, the share of electricity consumption that prosumage households cover from their own solar generation remains relatively low, the rate of self-sufficiency (RSS) reaching only 12%. (cf.

Figure 3).

Considering the isolated case of a retail price with surcharges (scenario *RPWS*), the effect is primarily a decrease in prosumage households' demand for grid electricity which comes with a rather high rate of self-sufficiency (59%) among prosumage households. At the same time, the rate of self-consumption is also high (64%), indicating that the main benefit from PV is the avoidance of high retail surcharges.

On the feed-in side, in contrast, the scenario *FRWS* with infeed subsidies induces a strong incentive to feed electricity into the grid, so that prosumage households prioritize sales over self-consumption or storage. In this case, virtually none of the generated electricity is used on-site or stored; instead, it is entirely directed towards the grid to maximize financial return.

When all distortions are combined, prosumage households generate significantly larger quantities of electricity. This leads to a rather low rate of self-consumption (22%), which seems paradoxical at first sight. Yet the high generation level exceeds by far own consumption, notably in summer, which implies that a substantial surplus is produced which may only be partly absorbed by storage for consumption during nighttime. Accordingly. much of the surplus is fed into the grid, even though the prosumers realize a rate of self-sufficiency of 75%. This scenario highlights how multiple overlapping policies can drive behavior towards extensive generation while reducing the emphasis on self-consumption, causing prosumage households to act more as producers than as flexible self-suppliers.

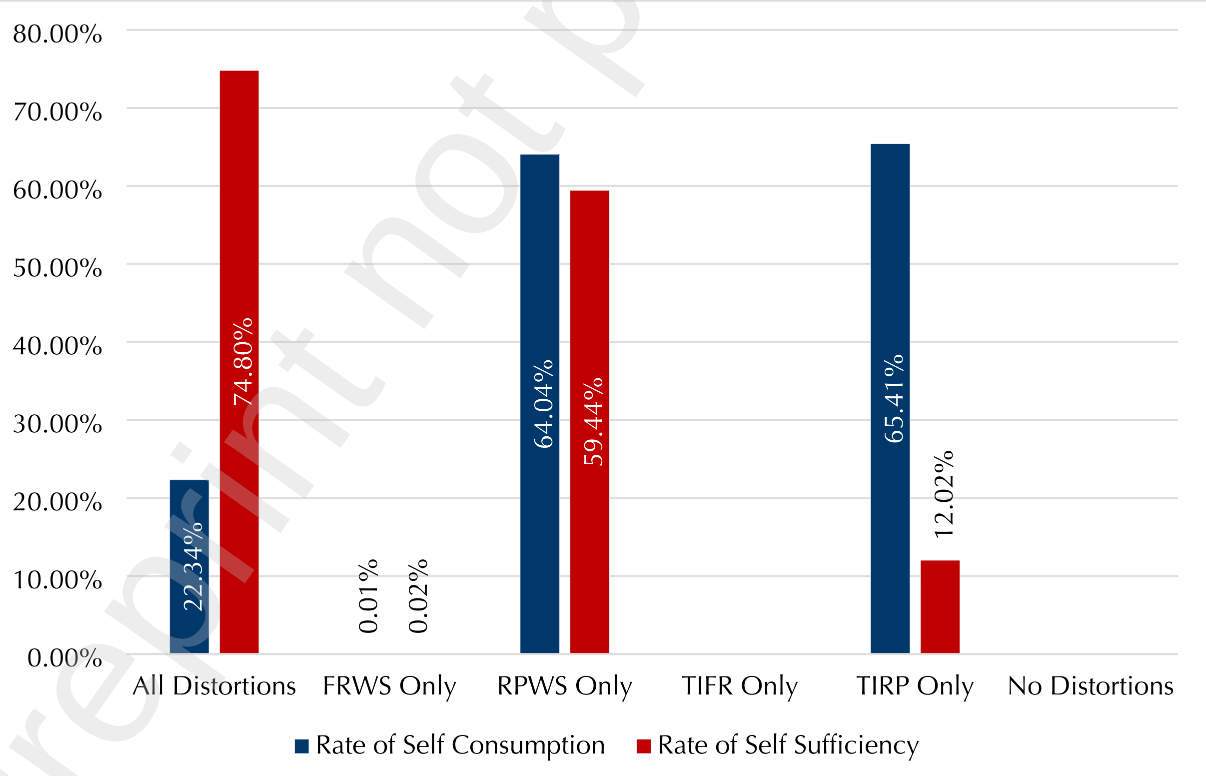

Figure 3: Rate of self-consumption and rate of self-sufficiency for prosumage households.

5.2 Wholesale level

At wholesale level, we observe distinct investment decisions , induced by the different tariffication schemes (cf. Figure 4). The baseline (*No Distortions*) shows highest PV level as households are not incentivized via cost-reflective pricing. *TIRP* encourage utilities to similar decisions in the long run as the retail price is time-independent and the feedback effect from prosumage households does not allow for cost-efficient capacity reduction. The *TIFR* appears to trigger similar investment decisions as in the base scenario. Thus, a fixed feed-in tariff based on solar market value does not incentivize prosumage households, corresponding to no feedback effects in the long run at wholesale level.

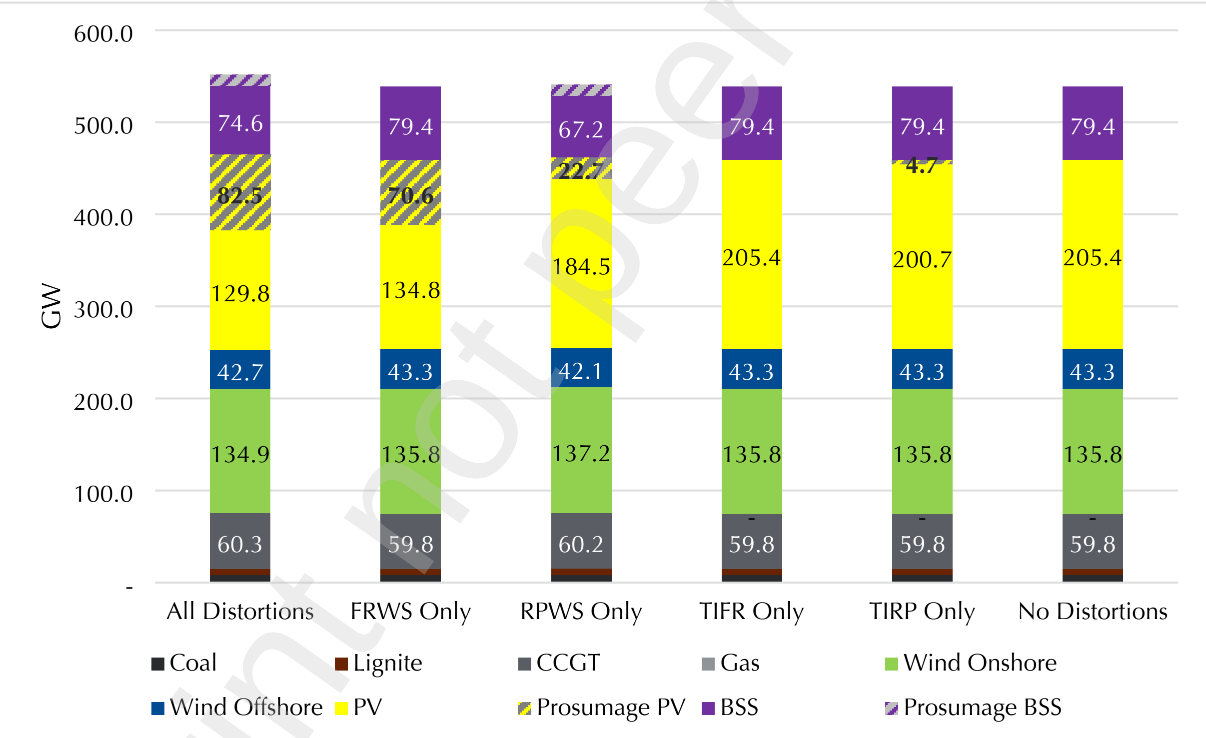

Figure 4: Investment Decision at Wholesale level (incl. Prosumage level [hatched]).

In contrast, scenario *RPWS* incentives to reduce PV investment and investment in BSS. This reaction is due to the increased cost of electricity tariffs to households, making self-generation and storage more economically attractive.

In the *FRWS* scenario, we observe a further decline in PV capacity while storage utilities invest in more capacities. This feedback effect is due to the household decision to invest heavily in solar capacity, while neglecting to invest in storage solutions. Thus, it is profitable at wholesale level to provide flexibility solutions. This indicates that strong positive monetary distortions in feed-in premiums lead to households acting primarily as producers.

Under the combination of all distortions, the role of utilities at the wholesale level is similar. The results reveal substantial shifts in production and storage capacity from wholesale to prosumage level.

In addition to influencing investment decisions, adjustments to the retail price alter the feed-in behavior and grid consumption patterns of prosumage households. Despite the significant number of prosumage households and their potential impact on the wholesale market, the resulting changes in wholesale prices are minimal. In the scenario *RTWS*, prices increase by an average of 0.5% compared to the scenario *No Distortions* while in *All Distortions*, we observe a marginal decrease of less than 0.1% on average.

The renewable production volumes slightly differ between the scenarios *No Distortions*, *TIRP*, *TIFR* and *RPWS* (cf. Table 2). In the *FRWS* and *All Distortions* scenarios, PV production drops by 86 TWh and 91 TWh, respectively, compared to the baseline. These results are a consequence of the sharp increase in prosumage PV capacity and indicate that prosumage households act as substitutes rather than complements.

Storage full charging cycles (FCC) refer to the number of complete charge and discharge cycles a BSS undergoes and serves as a metric to track the usage and integration into the energy system (cf. Table 2). Interestingly, compared to the *No distortions* scenario, the FCC of large-scale battery storage systems declines by 8% in the *All Distortions* scenario. Under the scenario *RPWS*, this effect also appears, albeit somewhat dampened due to lower investments in storage capacity at the wholesale level. Hence, when no distortions are applied, the results reveal the lowest flexibility demand at wholesale level.

Table 4: Renewable Production Volumes and Full Charging Cycles.

		All Distortions	*FRWS Only*	*RPWS Only*	*TIFR Only*	*TIRP Only*	*No Distortions*
Wholesale	**Wind Onshore (TWh)**	263	265	268	265	265	265
	Wind Offshore (TWh)	108	110	107	110	110	110
	Solar (TWh)	159	165	226	251	246	251
	Curtailment (TWh)	135	131	133	131	131	131
	Storage Discharge / Charge (TWh)	34 / 38	40 / 45	32 / 36	40 / 45	40 / 45	40 / 45
	Full Charging Cycles	249	249	249	236	250	229
Prosume	**Solar (TWh)**	101	86	28	-	6	-
	Storage Discharge / Charge (TWh)	8 / 9	-	7 / 8	-	-	-

5.3 Welfare effects

The economic and environmental impacts of tariff distortions are evident when analyzing the total system costs and CO_2 pricing. The scenario without any distortions results in the lowest total system costs, demonstrating that a pure market environment leads to the most cost-efficient outcome (cf. Figure 5). Conversely, when all distortions are applied simultaneously, system costs increase by around 5 billion € or more than 10 %. This indicates that the combined impact of multiple tariff distortions leads to inefficiencies.

The introduction of time-invariant feed-in remuneration (scenario *TIFR*) does not influence investment behavior on wholesale nor prosumage level and, consequently, has no effect on the system costs. The reason is that a remuneration based on the solar market value (infeed-weighted wholesale prices) does not change the overall remuneration level – which is the key driver for investment decisions.

In the scenarios *RPWS, FRWS* and *All Distortions*, the increasing shares of residential PV and storage, which mostly substitute cheaper utility-scale installations at wholesale level, lead to an increase in overall system costs.

Yet only minor differences in the scenarios endogenous CO_2 price are observable. Thus, different tariff structures have no significant impact under the given system setup.

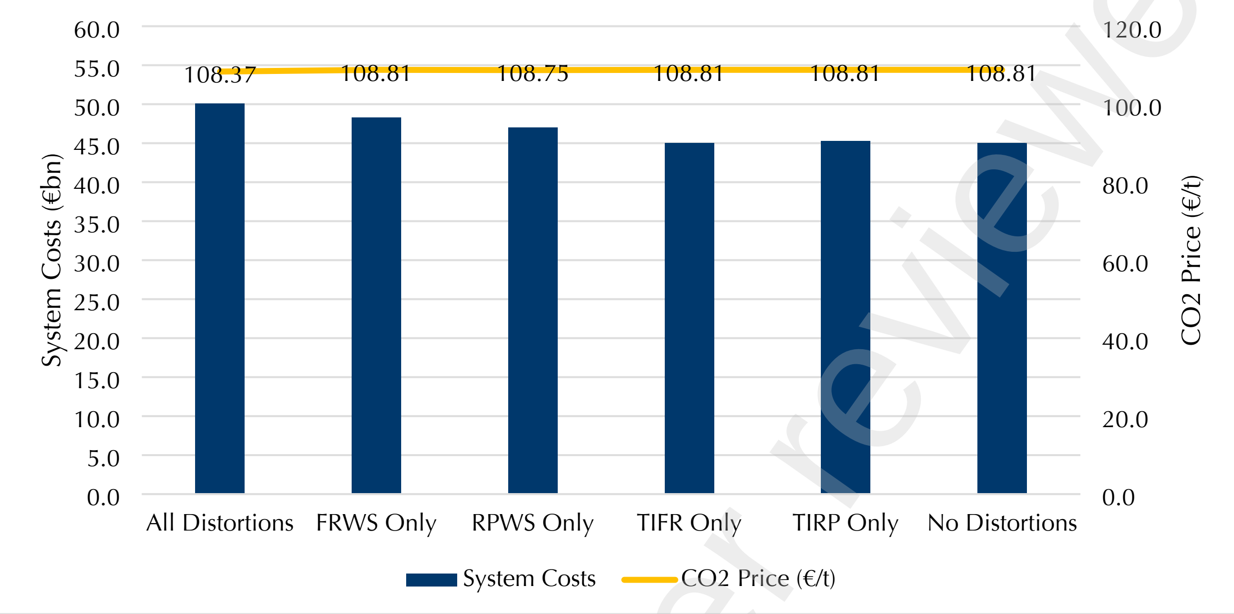

Figure 5: System Costs and CO_2 Price

The producer surplus is zero for all renewable technologies where the capacity constraint is not binding, in line with the findings of Finke et al. (2024). The same holds for technologies without any initial capacity, as in the case of CCGT in our model. In contrast, technologies with pre-existing capacities exhibit a positive capacity rent.

If we consider the prosumage households' surplus as the combination of consumer and producer surplus for prosumage households, we see that the delta compared to the *No Distortions* scenario may be negative or positive depending on the considered scenarios (cf. Figure 6). In *FRWS Only*, the increase in prosumer surplus reflects the support payments received for the PV installations. In the *TIRP Only* scenario, it is rather the substitution of relatively expensive electricity purchases around noon by cheaper self-produced PV power that raises the prosumer surplus. In contrast, the particularly negative outcome in *RPWS Only* is driven by the introduction of (grid and other) surcharges. The resulting cost increase for prosumers is only to a very limited extent compensated by cost savings through combined PV-BESS investments. Also for the *All Distortions* case, the impact of consumption surcharges exceeds the benefits of infeed support payments. But this prosumer perspective has to be complemented by the government and grid operator perspective, where the surcharges paid constitute a source of revenue.

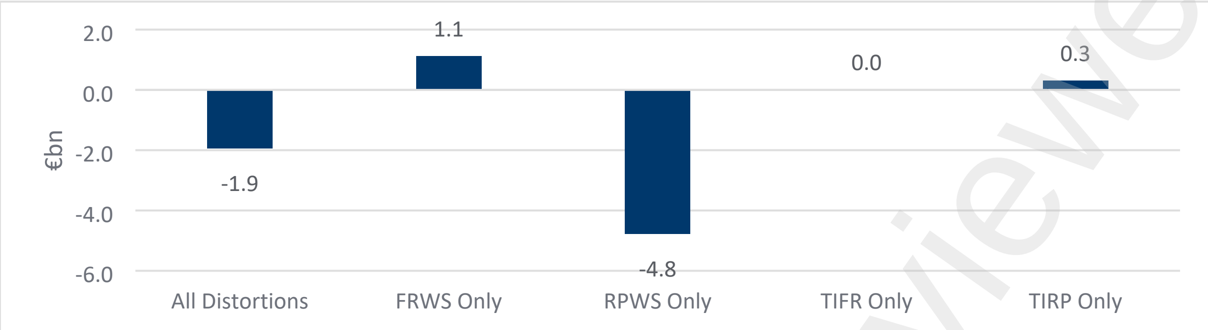

Figure 6: Prosumage households Surplus change compared to No Distortions Scenario.

6 Conclusions

Incentivizing increased installations of PV and storage systems is a key policy priority for the transition to a carbon neutral future. Yet our analysis highlights that various measures put in place in terms of retail pricing and PV support mechanisms have distortionary effects on prices and contribute to increasing overall system costs. This work assessed the effects of time-invariant retail prices on prosumage households' behavior and the reflection of market conditions into prosumage models and long-term system-wide effects of prosumage incentives. We showed on three scopes (prosumage household level, wholesale level and system level) how distortionary tariffs and feed-in schemes impact long-term equilibria.

In conclusion, the design of retail pricing schemes has a very substantial impact on prosumage household investment behavior and the resulting operational energy management. Time-Independent Retail Prices (scenario *TIRP*) increase the returns on household PV investments as PV production substitutes for purchased electricity during sunny hours. The household saves costs based on average wholesale market prices, while the actual cost savings at system level are lower – in line with low market prices during periods with high solar infeed.

Time-independent feed-in remunerations (scenario *TIFR*), in contrast, do not induce higher PV investments by themselves. When the solar-market value provides the basis for the remuneration level, the overall profitability level is not altered – so no additional investment incentive is provided.

On the other hand, surcharges on retail prices (scenario *RPWS*) imply that PV generation and battery systems lead to higher savings in electricity procurement, which makes them more attractive. Yet compared to the status quo, the reduction or abolishment of retail surcharges would imply that expenses for the grid infrastructure or alike have to be covered from other means such as taxes.

Finally direct support payments for renewable production provide immediate incentives for investment, yet again the resources for the funding must come from other sources.

The combination of all these design elements results in even higher investments in solar and some storage by prosumage households, indicating that the interplay of these distorting price elements can significantly shift household electricity usage towards more renewable generation and storage integration.

In terms of overall welfare, a distortion-free scenario yields the lowest system costs, in line with standard economic results on the efficiency of a pure market. Conversely, when all distortions are in place, system costs rise sharply due to overlapping policies inducing strong investments in expensive technologies. Regarding CO_2 abatement, the emission cap is met in all investigated scenarios, and the resulting (shadow) price of CO_2 is rather stable. Only the retail surcharges in the scenario *RTWS* lead to a 3% higher CO_2 price, indicating that this standard retail pricing component implies that utility-scale PV investments become less attractive while thermal units like CCGT face better incentives – which have to be counterbalanced- by somewhat higher carbon prices.

This underscores the complexity of pricing impacts on both, economic and environmental aspects of energy systems. Overall, the diverse pricing schemes profoundly shape prosumage households' behavior, influencing investment and consumption patterns, with each pricing scheme having specific implications.

In turn, the household decisions, influenced by distortions in pricing schemes, affect the agents in the wholesale market. Their investments in PV and storage capacity vary substantially depending on the retail pricing scheme in place. Notably, the scenarios *FRWS* and *All Distortions* lead to substantially lower production and storage investments in the wholesale market.

Finally, prosumage surplus is lower in all scenarios compared to No Distortions, except in *FRWS Only* where support payments are retained. In RPWS, the combination of higher purchase prices and missing feed-in remuneration leads to the strongest decline.

This analysis relies on a simplified representation of prosumage and wholesale market agents, allowing for a clear assessment of structural effects. However, it does not account for emerging flexible loads such as heat pumps and EV charging, whose system integration and regulatory implications merit further investigation.

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Nomenclature

Indices and Sets:

h	Households
i	Dispatchable generation technologies
j	Non-Dispatchable generation technologies
k	Storage technologies
T, t	Hour

Parameters:

C^{invPV}, $C^{invBatK}$	Ann. capacity investment costs for PV and storage
$Q^{con}_{h,t}$	Given demand of household h
K^{PV}_h,K^{Bat}_h	Exogen. given start capacity for PV and storage
$\varphi_{h,t}$	Capacity factor at time step t
ρ	Infeed constraint for household
θ	Self-discharge
η_h	Storage load efficiency
ψ_h	Storage Volume Factor
K^{PVmax}_h,K^{Batmax}_h	Capacity investment limits for PV and storage
p^{VOLL}	Value of lost load
$c^{var}_{i,j,k}$	Variable costs of technology i, j, or k
$c^{inv}_{i,j,k}$	Investment costs of technology i, j, or k
$pen^{penalty}_j$	Penalty for curtailment
$\omega^{ret,fit}$	Markup on retail and feed-in tariff
$CO2^{Bound}$	Emission limit
f^{CO2}_i	Emission factor of technology i

Variables:

p^{fit}_t, p^{fit}_{fix}	Time variant and fixed feed-in tariff
p^{ret}_t,p^{ret}_{fix}	Time variant and fixed retail tariff
$q^{gridin}_{h,t}$	Quantity fed into the grid
$q^{gridout}_{h,t}$	Quantity drawn from the grid
k^{PV}_h,k^{bat}_h	Capacity investment in PV and storage
$s^{-}_{h,t}$	Discharging at time step t
$s^{+}_{h,t}$	Charging at time step t
$bl_{h,t}$	Battery storage level at time step t
$q^{conv}_{t,i}$	Produced electricity by conventional technology i at time step t
$cap^{new}_{i,j,k}$	Capacity investment in technology i, j and k
$curt^{res}_{t,j}$	Curtailed renewable production in time step t
$q^{res}_{t,j}$	Produced electricity by renewable technology j at time step t
$q^{sto\|out}_{t,k}$	Wholesale storage discharging at time step t
$q^{sto\|in}_{t,k}$	Wholesale storage charging at time step t
$q^{ret\|dem}_t$	Retail demand and time step t

p_t^{who}	Wholesale price (Dual variable on wholesale market clearing)
C^{sys}	Total system costs
C^{opr}	Total operational costs
C^{inv}	Total investment costs

Abbreviations:

CCGT	Combined Cycle Gas Turbine
CO_2	Carbon dioxide
EU	European Union
RES	*Renewable energy source*
TYNDP	*Ten Year Network Development Plan*

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Declaration of generative AI and AI-assisted technologies in the writing process.

During the preparation of this work the authors used ChatGPT and DeepL in order to increase readability and language of the work. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Felix Meurer: Conceptualization, Methodology, Investigation, Formal analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization.

Marco Breder: Conceptualization, Methodology, Investigation, Formal analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization.

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