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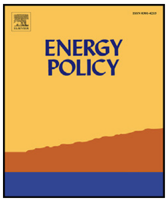

Research article

Empirical field evaluation of self-consumption promoting regulation of household battery energy storage systems

Leo Semmelmann [a,*], Marie Konermann [a], Daniel Dietze [b], Philipp Staudt [c]

[a] Karlsruhe Institute of Technology, Karlsruhe, Germany
[b] SENEC GmbH, Leipzig, Germany
[c] Carl von Ossietzky Universität, Oldenburg, Germany

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ABSTRACT

An increasing number of battery energy storage systems are installed in households globally. These systems are influenced by distinct regulatory frameworks. Internationally, a consolidated regulatory framework for household battery energy storage has yet to emerge. The widely proliferated self-consumption regulation promotes the utilization of battery storage systems to maximize the consumption of self-generated electricity from PV panels. Yet, a large-scale empirical field study evaluating the effect of such regulation is missing. To this end, we present an empirical evaluation of a unique dataset describing the operation of 947 household battery energy storage systems over one year, propose alternative regulatory regimes that we evaluate based on a simulation with the same battery profiles and a survey with 196 respondents evaluating household attitudes towards their battery storage. The results show that the self-consumption promoting regulation leads to almost no additional welfare for the system and even adds costs in some cases that are being socialized among energy consumers. Furthermore, minimal adjustments in the regulation might considerably increase the value of battery storage for households and the system and we find that trust in the supplier might suffice to have households adopt alternative battery storage profiles.

1. Introduction

The growing share of renewables in modern energy systems leads to an increasing need for flexibility on the demand side (Palensky and Dietrich, 2011; Strbac, 2008; Pedro et al., 2023). One promising technical solution for demand-side flexibility are battery energy storage systems (BESS) (Wu et al., 2015). The latest international statistics show that corresponding installations are on the rise: In Germany, the country from which we draw our data for this study, the total number of installed BESS was 320,000 in 2021, with a third added that year. Only 0.8% of those BESS were industrial-scale BESS with capacities over 30 kWh, while the remaining installations were household BESS capacity (Peper et al., 2022). However, this is an international trend: 227,477 BESS systems (ANIE, 2023) are installed in Italy, Australia has 180,000 installations (SunWiz, 2023) and Austria reports 17,111 installed BESS (Bundesverband Photovoltaic Austria, 2023) in 2022. In total, there were over 1 million households in Europe with Photovoltaic (PV)-BESS systems with an aggregated capacity of 9.3 GWh in 2021 (SolarPower Europe, 2022). Globally, BESS installation capacity was 43 GWh in 2022. It is assumed that by 2030, 400 GWh will be reached worldwide (Rystad Energy, 2023). However, the impact of regulation on household BESS and its subsequent effect on the wider energy system has yet to be empirically evaluated. The term "household storage regulation" refers to the policies and rules governing the use of household energy storage systems, including whether dynamic tariffs are encouraged, the allowance for batteries to be charged from the grid, and the structure of grid charges (Fett et al., 2019).

Many of the globally installed household BESS are embedded in a regulatory framework that promotes self-consumption of generated PV power (Mateo et al., 2018), even though, various studies indicate that the self-consumption-oriented regulatory pattern is counterproductive for the system overall (Green and Staffell, 2017; Moshövel et al., 2015; Aniello and Bertsch, 2023; Tidemann et al., 2018). The major caveat of these findings is that they are almost exclusively based on simulation studies or only feature very small sample sizes. These studies are based on the assumption that batteries are operated as permitted by regulation while households do not change their behavior once a BESS is installed. However, studies on the rebound effect seem to suggest that energy efficiency investments affect energy consumption behavior (Deng and Newton, 2017), even though other authors contest its generality (Brockway et al., 2021; Rajabi, 2022). It is therefore

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* Corresponding author.
E-mail addresses: leo.semmelmann@kit.edu (L. Semmelmann), philipp.staudt@uol.de (P. Staudt).

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necessary to evaluate the regulatory implications of BESS regulation to derive corresponding policy implications. To this end, we introduce and analyze the largest empirical dataset on BESS usage, with 947 BESS profiles from households measured over one year. We confirm that operating BESS for self-consumption can actually lead to welfare losses, i.e., costs that are socialized among energy consumers. Based on these results, we propose and evaluate the impact of alternative regulatory approaches based on simulation using the same data that are better suited to incentivize a system-friendly battery management system operation.

Another often neglected aspect in literature is the influence of regulation on preferences and behavior of the households in which BESS are embedded (Ambrosio-Albala et al., 2020). The charging and discharging behavior of households (i.e., the consumption behavior) determines the performance of the battery against the market, even in the absence of any market signals directly to consumers. On the other hand, households that choose to subscribe to a dynamic tariff might reap additional benefits from their BESS by shifting demand to low-price periods (Zakeri et al., 2021; Green and Staffell, 2017). Dynamic tariffs lead to time-varying consumer electricity prices according to signals from the power system instead of fixed electricity rates (Dutta and Mitra, 2017). Proliferated variants of dynamic tariffs include time-of-use pricing (varying prices on- and off-peak), critical peak pricing (higher prices during system peaks) and real-time pricing (prices reflect wholesale market prices) (Dutta and Mitra, 2017). We base our simulative evaluation of alternative regulatory schemes on real-time pricing, a rate design that is widely available in Europe (Tibber, 2023).

Although potentially being beneficial for the power system as a whole, such dynamic tariffs are not broadly popular (Schittekatte et al., 2023). It has been shown that this is partly caused by low energy literacy levels of households (Brounen et al., 2013; Reis et al., 2021).

Consequently, the interaction of households with their BESS has important implications for the market overall. It is, therefore, a valuable research direction to better understand how households perceive the effectiveness of their battery energy management systems. Beyond our empirical analysis of the impact of battery regulation and the proposal of alternative regulatory approaches, we further contribute to this question with an exploratory survey approach intended to explain the perceived effectiveness of BESS within a regulatory framework. We conducted a corresponding survey among 196 BESS owners. We find that perceived effectiveness is correlated with trust in the BESS management system and not correlated with any measures of perceived knowledge regarding energy consumption, the energy system or energy markets. This has implications for the impact of corresponding BESS regulation.

In summary, this paper makes the following three contributions based on three distinct methodological approaches (empirical analysis, simulation, survey):

- Based on the first-of-its-kind empirical sample of 947 households over one year, we show the observed effects of a self-consumption promoting regulation on the impact of BESS operation on energy markets and provide insights on the corresponding costs incurred by the system.
- Using the same sample, we use optimization modeling to show how opting for gradually more dynamic regulatory approaches improves the value of these BESS for the system and its owners.
- Using a different sample of battery owners, we use survey results to show the impact of various sociological constructs on the perceived effectiveness of battery energy management systems and find that trust is more influential than perceived knowledge on energy consumption, the energy system and energy markets, which has implications for the impact of corresponding regulation.

These contributions hold various implications. First, the impact of regulation applied to a large fleet of battery energy management systems shows the danger of regulating decentral energy resources that are not aligned with overall power system objectives. Second, small adjustments to the regulatory environment in alignment with overall system efficiency objectives can greatly increase the value of resources for the system. Finally, our results suggest that households judge the effectiveness of their battery energy storage based on trust in third parties rather than their own system understanding of the energy system. Regulators are, therefore, well-positioned to incentivize more system-beneficial choices that can also benefit them and their customers.

Our study is based on an extensive review of related studies and international regulation of household battery storage systems. The review serves as a basis for our three-part methodology. First, empirical data from storage systems operated under self-consumption-promoting policies is analyzed. Second, based on the presented sample, alternative policy options are investigated through an optimization-based simulation. Third, a survey is conducted to contribute a better understanding of customer attitudes towards their battery storage systems and energy management systems. Addressing the research questions at hand with three different methods enables a socio-technical perspective on the regulation of household storage systems.

2. Background

In this section, we review the relevant literature along a proposed framework shown in Fig. 1. The installation of household BESS in combination with PV systems has been widely discussed in the literature (Luthander et al., 2015). We use this variety of studies to build a framework that depicts the interaction of these systems and their socio-technical embedding within regulatory and market frameworks in Fig. 1. Zakeri et al. (2021) and Londo et al. (2020) show that the regulatory environment heavily influences household decisions to invest in PV-BESS systems. Besides regulation, the actual sizing decision is further influenced by consumer preferences and practical considerations (Agnew and Dargusch, 2017). The installed PV-BESS system is operated through a battery energy management system that schedules charging and discharging decisions of the BESS (Wu et al., 2022). The implementation of the energy management system again depends on the regulatory environment, the household's general preferences and the electricity tariff (Aniello and Bertsch, 2023; Wu et al., 2022; Zhou et al., 2018). The operation of PV-BESS systems impacts the energy spot market and power system as a whole (Fett et al., 2021). The described relationships are depicted in Fig. 1 and further discussed and substantiated in the following using related literature.

Impact of regulation on PV-BESS investment decisions: The initial decision whether to install a PV-BESS system depends on the existing regulatory environment (Avilés et al., 2019). For instance, net metering policies, where the electricity costs of a customer are calculated after deducting its generation from its consumption, make BESS investments economically unreasonable as the grid serves as a virtual battery to the PV prosumer (Abdin and Noussan, 2018; Londo et al., 2020). Self-consumption-focused regulation, in which self-generated energy is exempt from taxes and levies and excess production fed to the grid is remunerated by a feed-in-tariff (which is usually lower than the household tariff), promotes BESS (Castaneda et al., 2020; Zakeri et al., 2021). Consequently, it is economically reasonable for households to increase the self-consumption quota by installing a BESS (Aniello and Bertsch, 2023). For instance, self-generated electricity might be exempt from network charges, making BESS more attractive (Aniello and Bertsch, 2023). Dynamic tariffs paid by the grid operator for excess PV generation or BESS subsidies can further influence the sizing decision of PV and BESS systems from a regulatory perspective (Castaneda et al., 2020; Zakeri et al., 2021). In Section 3, we describe this in more detail and give an overview of international regulatory frameworks of household BESS.

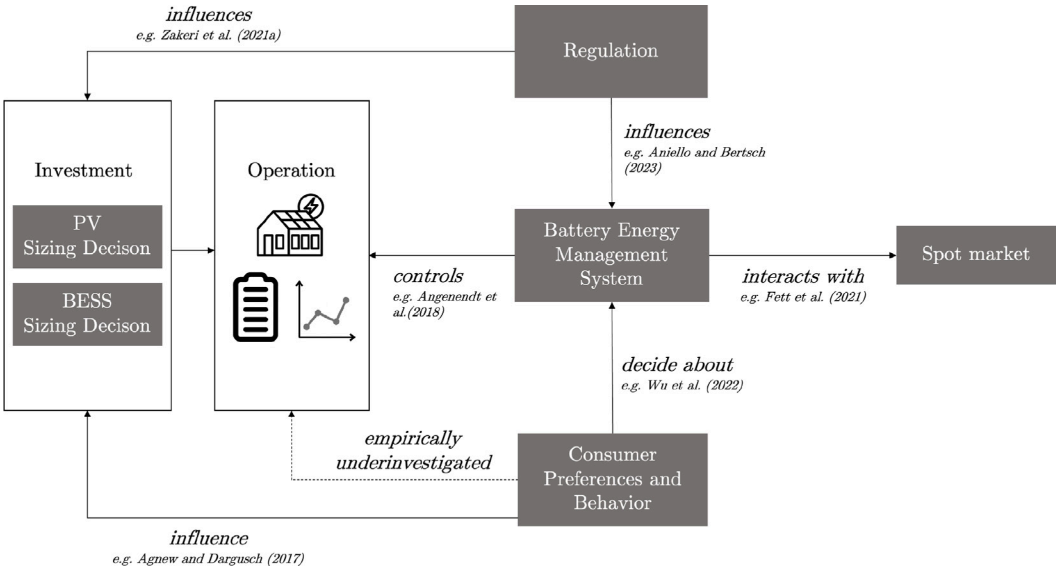


Fig. 1. Factors influencing battery installation decision and operation strategy.

Impact of consumer preferences on BESS investment decisions: While the regulatory environment mainly influences the profitability of different sizing options, the user makes the final decision incorporating factors like a desired safety from blackouts or maximizing self-sufficiency (Agnew and Dargusch, 2017). Further, the trust level in BESS technologies and the regulatory environment can be integral factors in the PV and BESS investment decision (Ambrosio-Albala et al., 2020). Consumer preferences can lead to a deviation from optimal economically induced PV and BESS sizes. Furthermore, the financial endowment and consumption behavior of households, such as ownership of an electric vehicle or roof area, can influence the PV and BESS sizing decision (Linssen et al., 2017; Wang et al., 2020).

Impact of battery energy management systems on BESS operation: After the installation of a PV-BESS system, the daily charging and discharging decisions of the BESS are implemented through a battery energy management system (Angenendt et al., 2018; Lokeshgupta and Sivasubramani, 2019). The system uses various inputs, such as the current PV generation and the household load, but might also include actual or expected price curves (Mishra et al., 2012) and regulatory conditions (Young et al., 2019), which are described in the following.

Impact of regulation on battery energy management system operation: The battery energy management system operates the BESS to optimize household utility given the regulatory environment (Zakeri et al., 2021). Important policy considerations that shape the way the battery management system is operated range from allowing or disallowing household BESS to charge from the grid (Bundesministerium der Justiz und für Verbraucherschutz, 2023), setting the remuneration for energy discharged from the BESS to the grid (Zakeri et al., 2021), exempting self-produced energy discharged from the BESS from taxes, fees and grid charges (Bundesnetzagentur, 2023b), to the promotion of dynamic tariff schemes (Parra and Patel, 2016). The impact of some of the aforementioned international regulatory approaches on operations of battery energy management systems is elaborated on in Section 3.

Impact of consumer preferences on battery energy management system operation: While regulation sets the boundaries in which a BESS can be operated and for its profitability, households control the selected tariff, pre-determining the way the battery energy management system schedules charging and discharging decisions (Zhou et al., 2018). Further, households are theoretically able to determine the operation schedule of a battery energy management system as they see fit. However, this requires technical capabilities and a market understanding that most households do not possess (Brounen et al., 2013). The decision for or against a dynamic tariff alters the scheduling of the battery energy management system (Zhou et al., 2018). The impact of consumer preferences and behavior on how their BESS is operated has not been investigated in detail yet.

Interaction of battery energy management systems with the spot market: Through the respective operation strategy, the BESS interacts with the spot market and has an impact on the overall power system (Fett et al., 2021). The share of households that operate their BESS with dynamic, price-responsive strategies influences the price level of the market and the power system as a whole. For instance, a responsive BESS fleet might reduce the curtailment of renewables (Fett et al., 2021) or change power system peak loads (Young et al., 2019). Household BESS can also influence wholesale prices for households without storage systems by impacting the dispatch of power plants (Say et al., 2020). An increased share of households with wholesale market-oriented tariffs can further relieve the grid by reducing PV feed-in peaks (Günther et al., 2021).

Behavioral influence of consumers on battery usage: First studies indicate that household electricity consumption might change after the installation of a PV-BESS system, thereby altering the discharging requirements of the BESS. For instance, a recent empirical study from Arizona has shown that after co-installing electric vehicles, PV systems and a BESS, consumers have changed their daily load profiles (Shen et al., 2023). Al Khafaf et al. (2022) find that the installation of PV and BESS leads to behavioral changes of consumers in a case study that analyzes smart meter data of Australian energy consumers. This finding should be taken into account when analyzing different policy or tariff options. However, existing simulation studies in the field of household PV-BESS operation strategies assume constant household load profiles, neglecting the potential impact of behavioral changes (Say et al., 2020; Linssen et al., 2017).

Due to a lack of empirically observed BESS load profiles, the studies mentioned in this section rely on various assumptions and corresponding optimization and simulation models (Angenendt et al., 2018; Linssen et al., 2017; Hesse et al., 2017; Naumann et al., 2015). This leads to certain shortcomings: First, the resulting BESS load profiles are dependent on the underlying household load profiles, which are often only available in a low number or derived from standard load profiles (Linssen et al., 2017). As a consequence, the outcomes are based on a small sample and less varied. Second, the BESS sizing decisions are often directly derived from an optimization model, neglecting that BESS might only be available in certain sizes or that the investment decision is based on personal preferences, beliefs or expectations (Schopfer et al., 2018). Third, the naive simulation of battery energy management systems based on household load profiles without any consideration of changes in household behavior and decisions, neglects the possible influence of user perception and actions on the resulting BESS operation strategy and contradicts first empirical studies showing behavioral change after PV-BESS installations (Al Khafaf et al., 2022).

Given the rising number of household storage systems in Europe and globally (SolarPower Europe, 2022), it is becoming increasingly important to give battery operations a regulatory framework to align them with the overarching goals of the power system. This requires researchers to evaluate possible regulatory designs for residential BESS to enable policymakers to make informed decisions, especially about the promotion of the widely proliferated self-consumption operation strategy of PV-BESS systems. Although there are various studies discussing the impact of policy and tariff options (Parra and Patel, 2016; Green and Staffell, 2017; Zakeri et al., 2021), a thorough analysis of empirical data and its implications is still missing. Past studies are hence calling for a consideration of socio-technical and non-monetary factors for investment decisions (Say et al., 2020; Schopfer et al., 2018) and an analysis of heterogeneous, real-world household load profiles (Aniello and Bertsch, 2023).

We are contributing to this research gap with the first study that analyzes a large-scale sample of residential BESS operation profiles and evaluates consumer attitudes towards BESS in their regulatory framework. The analysis of the empirically observed data allows us to draw conclusions about the market performance of PV-BESS systems operating in a self-consumption-promoting regulatory environment with fixed household tariffs as the observed systems have been operated in this environment. Based on these results, we can draw conclusions about the efficiency of current regulation without the limitations of neglecting consumer behavior. Furthermore, we can explore the impact of possible alternative tariff options with an optimization-based simulation. Finally, we contribute to the overall understanding of household perspectives on their BESS, thus addressing the socio-technical perspective on BESS through a survey amongst battery owners.

3. International regulation of household BESS

In this section, we portray various international BESS regulation approaches to describe the international regulatory context of BESS. The two fundamental types of national regulatory policies of BESS are self-consumption promoting and net metering or net billing policies (Fett et al., 2019).

Self-consumption: In self-consumption-promoting regulation, hou seholds are encouraged to increase the consumption of self-generated energy, typically from PV making household BESS an attractive option (Castaneda et al., 2020; Zakeri et al., 2021; Angenendt et al., 2018). This is promoted, for instance, by exemptions from taxes and levies or a gradual decrease of feed-in tariffs (Fett et al., 2019; Castaneda et al., 2020) making feed-in less attractive. In Germany, self-generated energy from PV installations under 30 kW is exempt from most taxes and levies (Bundesregierung, 2023; Fett et al., 2019). At the same time, feed-in tariffs are reduced (to 0.086 Euros in 2023, compared to an average household electricity price of 0.452 Euros) (Bundesnetzagentur, 2024, 2023a). In addition, charging the BESS through the grid leads to a loss of the previously listed benefits (Bundesministerium der Justiz und für Verbraucherschutz, 2023). A comparable regulatory framework is implemented in Austria, where self-generated energy up to 5000 kWh is exempt from taxes and levies, thereby encouraging the installation of storage systems (Unternehmensserviceportal (USP), 2024). Similarly, in Croatia, self-generated PV is exempted from fees and network charges (Croatian Parliament, 2021). The United Kingdom (UK) is also supportive of batteries used to increase self-consumption in households (Department for Business, Energy and Industrial Strategy, 2021), further promoted by a VAT relief for battery installations introduced in 2024 (HM Revenue and Customs, 2024). In the UK, energy exports to the grid are compensated by a “Smart Export Guarantee”, which replaced feed-in tariffs in 2019 (Department for Energy Security and Net Zero, 2020). Smart Export Guarantees are offered by a couple of utilities and can vary amongst them, in contrast to a nationwide uniform feed-in tariff. Contrary to Germany, the UK actively encourages households to charge their batteries from the grid and to be compensated for feed-in from batteries with the respective Smart Export Guarantee. Japan implements a self-consumption scheme with no additional costs for self-generated PV electricity (International Energy Agency, 2021). In Australia, the exemption from relatively high volumetric grid charges (Say et al., 2019) for self-generation, sets a strong incentive for installing BESS (SunWiz, 2023). In Italy, the government offered feed-in tariffs until 2013, which led to a mandatory opt-out from the net metering scheme, thereby encouraging self-consumption (Abdin and Noussan, 2018), which is still the most attractive option for BESS owners even in the absence of feed-in tariffs.

Net metering and net billing: The general idea of net metering regulation is that electricity can be sold to the grid at the price for consuming electricity at that point in time (Londo et al., 2020; Abdin and Noussan, 2018). The easiest way to understand this regulation is that in the presence of flat volumetric tariffs, the electricity meter runs backward when electricity is provided to the grid. This makes the grid a virtual battery for prosumers. A more detailed classification of the regulatory framework depends on the way the PV feed-in is compensated. The policy scheme is then either called net metering (compensation at retail rates including taxes and levies) or net billing (compensation only at current wholesale prices). Italy introduced an optional net billing scheme in 2008, which is seen as the main driver of PV installations in the country after the end of feed-in tariffs (Autorità di Regolazione per Energia Reti e Ambiente (ARERA), 2008; Abdin and Noussan, 2018). The scheme values PV feed-in weighted at the national market price, which is then deducted from the customer’s electricity bill. In the United States, net metering and net billing policies are implemented on a state level in various states (Gregoire-Zawilski and Siddiki, 2023). Policy elements vary from state to state. For instance, in Texas, Oregon and Maine, the policy design is rather utility-favoring and implements a net billing scheme, including a valuation of feed-in at market prices rather than retail rates and no possibility to rollover credits to upcoming periods (e.g., months or years). On the other hand, Florida, New York and New Mexico, pursue a customer-favoring design that resembles net metering with a valuation of excess generation at retail rates and a compensation for remaining credits at the end of the year (Gregoire-Zawilski and Siddiki, 2023). In Spain, a net billing scheme was introduced in 2018, which is based on a monthly balance of electricity consumption drawn from the grid and PV feed-in, whereas the feed-in is valued by a rate set by the system operator, which is marginally lower than the wholesale price (Ordóñez et al., 2022). Since negative balances are not rewarded, the regulatory framework encourages proper sizing of the PV installation. Ecuador implements a net metering scheme with rather long credit transfer periods (Ordóñez et al., 2022). Negative balances can be used as rolling credits up to two years after being generated. Although the presented regulatory net metering policies incorporate different features, they all take away incentives to install household BESS as the grid serves as a virtual battery (Abdin and Noussan, 2018; Ordóñez et al., 2022). However, there are endeavors to incentivize household storage installations, even in regions with net metering or net billing policies in place. California, a state with a plain-vanilla net billing policy, moved away from fixed feed-in compensation to a new model called “NEM 3.0”, which implements a time-variable compensation. This should encourage homeowners to install battery systems alongside their PV installation and to shift their feed-in away from peak feed-in periods (California Public Utilities Commission, 2023).

The different regulatory frameworks and the wide range of individually implemented policy features for BESS regulation show that a best practice for storage regulation has yet to emerge. This may be due to a lack of experience with large market penetration of battery storage

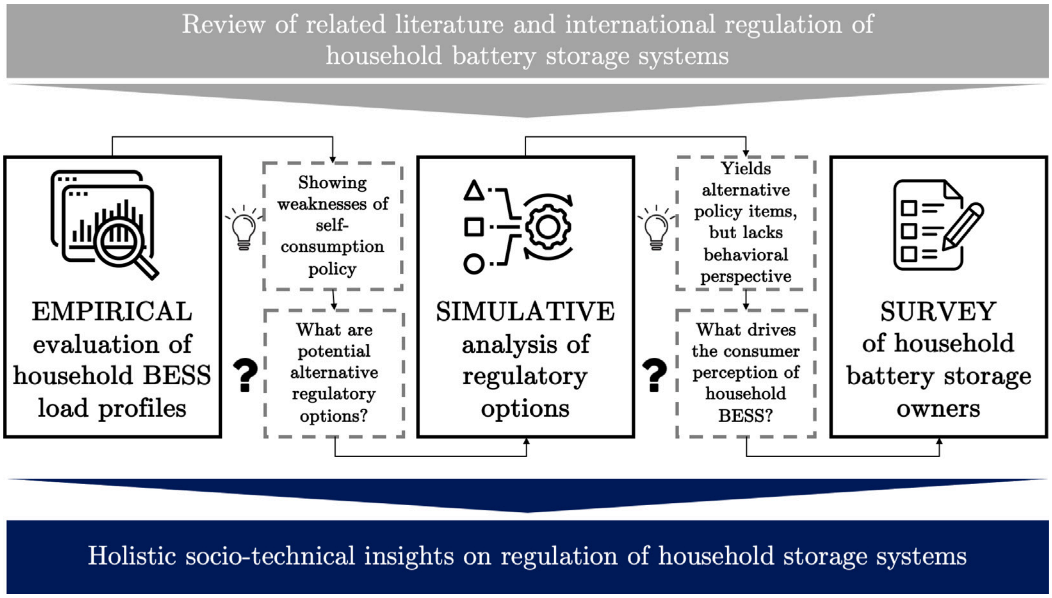


Fig. 2. Paper structure and methodological overview.

or because of different national electricity market designs. In any case, our results can provide some guidance for making corresponding policy decisions. Our study is an important contribution to this policy discussion since we are the first to evaluate a large empirical dataset from a region promoting self-consumption to describe the impacts of the regulation framework. Furthermore, the study also allows us to evaluate alternative regulatory strategies.

4. Methodology

The review underlines the need for an empirical analysis of household battery storage systems operated in a self-consumption-focused regulatory setting. We tackle the identified research gap with an approach divided into three parts, as depicted in Fig. 2.

First, we analyze spot market profits of an empirical year-long sample of 947 household battery storage system profiles. This analysis fills a research gap addressing the potential effects of customer behavior on the market performance of battery storage systems. We find that the system benefits of household BESS are currently markedly low. We therefore evaluate alternative regulation.

We thus extend our empirical perspective with an analysis of alternative policy options, derived from our review of international regulation and related work. While the empirical characteristics of the 947 systems at hand set the boundaries for the analysis of alternative regulatory options, the resulting charging and discharging profiles are obtained using optimization. The results of the simulation allow for a comparison of the empirical analysis with policy options, such as the promotion of dynamic tariffs or allowing household storage systems to charge from the grid. Given that households need to adapt to this changing regulation, we further analyzed the attitudes of households towards their BESS to better understand antecedents for household behavior.

We, therefore, conduct a survey amongst battery owners. Thereby, we also provide a behavioral perspective on the problem at hand, which is often neglected in related studies.

Overall, our three-part approach allows us to analyze household battery storage systems operated in a self-consumption regulatory framework as a socio-technical policy problem, rather than from a purely techno-economic perspective.

4.1. Evaluating empirical BESS operation

First, we evaluate the effectiveness of the self-consumption-promoting regulatory framework through an empirical dataset from Germany. Germany implements a self-consumption promoting regulation that makes it financially attractive to consume self-generated energy. This evaluation is unique as it is the first to evaluate the empirical consumption behavior of households that own a BESS. This differentiates the results from simulation results that assume no change in behavior or optimal response to signals (Angenendt et al., 2018; Naumann et al., 2015; Aniello and Bertsch, 2023). We can calculate the effectiveness of household BESS by evaluating the hypothetical market performance on the spot market. This indicator is representative of the overall value the BESS is adding to the system. To do that, we multiply charging and discharging actions aggregated over an hour with the spot market price in the respective time interval on the day-ahead market. The underlying economic rationale is that high spot market profits for household BESS operation indicate a high overall power system utility generated from shifting loads from periods with high demand and costly generation (and high prices) to periods with lower demand and cheap generation (and correspondingly low prices) (Zafirakis et al., 2016; Lamp and Samano, 2022). We underline this point with a complementary analysis in the Appendix, showing that German day-ahead market prices are strongly positively correlated with balancing energy costs, fossil fuel-powered conventional production and residual load.

To analyze the profitability of the BESS charging and discharging decisions on the European EPEX spot day-ahead market within the German market zone (EPEX Spot, 2023), we aggregate the battery load profiles to an hourly resolution matching the day-ahead market contract duration (Märkle-Hußet al., 2018). We model the BESS as price takers, thereby having no impact on market prices and always finding a counterparty for possible trades. We assume that every sell- and buy-order could be conducted at market prices, which is a reasonable assumption given the liquidity of the market in question and the current capacity of market-oriented BESS operation strategies (Naseri et al., 2023; Wankmüller et al., 2017).

We evaluate the spot market profits (denominated as Π) of household BESS operation using Eq. (1), which is similar to objective functions used in simulation studies of market-focused battery operation (Schneider et al., 2020; Krishnamurthy et al., 2017). The same objective function is used in the following section to evaluate alternative tariff structures. In the evaluation of the empirical case, we ignore the inverter efficiency losses η_{inv} because the observed values already incorporate these losses.

$$\Pi = \sum_{t \in T} \quad (\eta_{inv} p_t P_t^d \tau - \frac{1}{\eta_{inv}} p_t P_t^c \tau) \tag{1}$$

When the BESS is charged with power P_t^c over a period τ, costs at the current market price p_t occur. This is irrespective of whether the battery is actually charged from the grid or from self-generation, as self-generation could be sold on the market, which, therefore, leads to opportunity costs. We proceed correspondingly for discharging of the BESS with power P_t^d, which leads to revenues either as market income or as foregone costs. The charge and discharge operations correspond to the empirically observed operations $P_t^{d,real}$ and $P_t^{c,real}$. We use this definition of BESS energy flows to the empirically observed behavior further in the following section to differentiate the empirical case from hypothetical alternative regulation approaches and dynamic tariff options.

$$P_t^d = P_t^{d,real}, \quad P_t^c = P_t^{c,real} \quad \forall t \in T. \tag{2}$$

4.2. Simulative analysis of regulatory alternatives

Second, given that our empirical analysis confirms the assumption that a BESS operation schedule prioritizing self-consumption does not necessarily align with the power system's needs (Green and Staffell, 2017), we propose several alternative approaches by building on more dynamic regulatory policies. We gradually increase the degrees of freedom with the following suggestions. We consider four different variations of the baseline optimization problem, varying from the actual, empirically observed BESS operation to a completely market-oriented operation. Through the cases, we explore different regulatory options for BESS and their influence on market profits on the day-ahead market. The cases increasingly deviate from the known, self-consumption-promoting empirically observed profile. Comparing different possible operation strategies to the empirical profiles allows us to draw conclusions about the economics of current BESS operations. This perspective is again simulation-based, which we further discuss in Section 8.

Various constraints are accommodated to analyze different operation strategies derived from the empirical profiles. First, the maximum charge and discharge power P^{max} of the BESS P^{max} must never be exceeded for P_t^c and P_t^d (Eq. 3b). Second, the SOC of the BESS is connected to the previous SOC and the current charging or discharging operation, as denoted in Eq. 3c. Finally, the SOC_t has to be kept within the boundaries of the minimum SOC^{min} and maximum SOC^{max}, as in Eq. 3d (Krishnamurthy et al., 2017). To realistically consider efficiency losses, the marketable discharge power has to be multiplied by the DC-AC inverter efficiency η_{inv} and the charging power has to be divided by it. A round-trip inverter efficiency of 90% is assumed, based on Soini et al. (2020). Since efficiency losses are considered for charging and discharging the BESS, η_{inv} is set at $\sqrt{90\%}$. Since the empirical SOC measurements and the charging power derived from it already include charging efficiency losses, we divide the charged energy by the efficiency rate of $\sqrt{90\%}$. Thereby, we prevent a double consideration of efficiency losses, which would potentially distort the comparison of the empirical case with alternative approaches.

$$\max \sum_{t \in T} \quad (\eta_{inv} p_t P_t^d \tau - \frac{1}{\eta_{inv}} p_t P_t^c \tau) \tag{3a}$$

$$\text{s.t.} \quad P^{max} \geq P_t^c, \quad P^{max} \geq P_t^d, \quad \forall t \in T, \tag{3b}$$

$$SOC_t = SOC_{t-1} + \tau(P_t^c - P_t^d), \quad \forall t \in T, \tag{3c}$$

$$SOC^{min} \leq SOC_t \leq SOC^{max}, \quad \forall t \in T \tag{3d}$$

Using this basic optimization problem and the notation of restricted charging and discharging powers in Eq. (2), we can formulate alternative regulatory options and tariff designs mathematically. We establish the following alternative regulatory options based on our review of existing policies and studies from Section 3.

Case 1: Flexible Discharging We begin by only slightly deviating from the self-consumption promoting regulation by only allowing battery charging from self-generated energy while subscribing the household to a real-time pricing tariff that sets the price for buying and selling energy to or from the grid. We model this mathematically by limiting the charging power P_t^c at time t to the respective empirical observation $P_t^{c,real}$, while P_t^d can be freely chosen within the given battery constraints.

$$P_t^c \leq P_t^{c,real} \quad \forall t \in T. \tag{4}$$

By replacing Constraint (2), which limits BESS operations to the underlying empirical observations, with the new Constraint (4), we ensure that the battery is only charged with available excess PV power of the household (Parra and Patel, 2016). Since only the upper bound for BESS charging is set, it is now possible to suspend charging operations at periods of high market prices and sell electricity to the grid, thereby reducing opportunity costs. It is now also possible to discharge the BESS to provide energy to the grid at the current market price. This operation strategy incorporates dynamic tariff elements (Parra and Patel, 2016), as well as a time-variable feed-in compensation component, comparable to the newly introduced variable "NEM 3.0" policy in California (California Public Utilities Commission, 2023).

Case 2: Calendaric limits *Case 1* offers more potential to react to market signals than the empirical self-consumption, but is still similar due to Constraint (4), which limits charging to the empirical observations. To enable a higher degree of market price exploitation, we replace Constraint (4) with Constraint (4.1), which only limits the sum of all charging operations P_t^c to the sum of all empirically observed charging operations $P_t^{c,real}$. By employing Constraint (4.1), we enforce that the battery is not discharged more than in the actual empirically observed case. *Case 2* can therefore be thought of as a compromise between real-time pricing with grid charges and net billing similar to the Texan regulatory approach (Gregoire-Zawilski and Siddiki, 2023). Under a net metering regime, the grid essentially serves as a BESS for prosumers with PV generation. Using the proposed approach, households are forgiven grid charges for the energy they provide to the system through their BESS. This incentivizes further flexibilization as households can provide energy when it is expensive in the system and buy it back later as incentivized through real-time pricing without having to pay additional grid charges or levies. This right of buying back provided energy is temporally restricted to avoid the usage of the grid as long-term storage. For instance, one might want to avoid households providing energy during the summer to buy it back in the winter. We, therefore, differentiate between *Case 2Y*, *Case 2M* and *Case 2W*, where the limiting sum of charging operations is applied either for the whole year or within every month m or for every week w, for the set of all months M and respectively all weeks W, as depicted in Constraints (4.2) and (4.3).

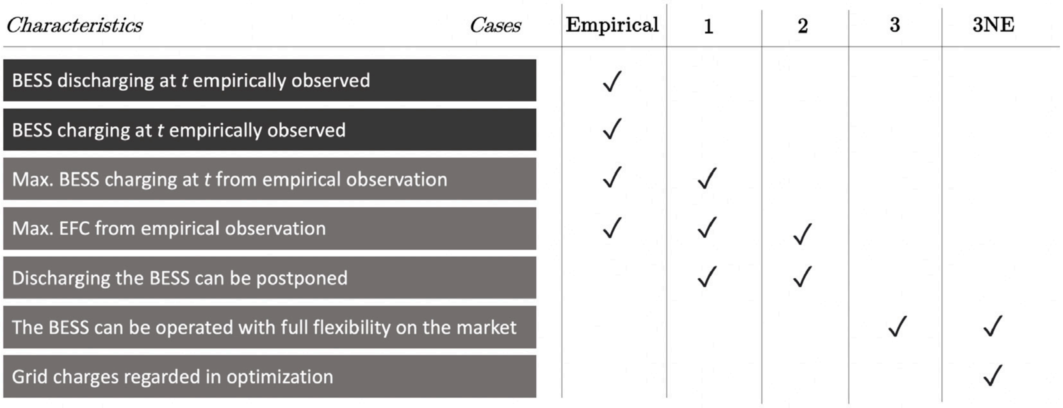
$$\sum_{t \in T} P_t^{c,real} \quad \geq \quad \sum_{t \in T} P_t^c. \tag{4.1}$$

Since by omitting Constraint (4), the BESS can also be charged in times without PV excess power ($P_t^c \geq P_t^{c,real}$), potential differences in market prices can be exploited more flexibly.

$$\sum_{t \in T,m} P_t^{c,real} \quad \geq \quad \sum_{t \in T,m} P_t^c. \quad \forall \quad m \in M. \tag{4.2}$$

$$\sum_{t \in T,w} P_t^{c,real} \quad \geq \quad \sum_{t \in T,w} P_t^c. \quad \forall \quad w \in W. \tag{4.3}$$

Case 3: Market responsive Finally, in *Case 3*, all constraints on charging and discharging based on the empirically observed data are



Characteristics *Cases*	Empirical	1	2	3	3NE
BESS discharging at *t* empirically observed	✓				
BESS charging at *t* empirically observed	✓				
Max. BESS charging at *t* from empirical observation	✓	✓			
Max. EFC from empirical observation	✓	✓	✓		
Discharging the BESS can be postponed		✓	✓		
The BESS can be operated with full flexibility on the market				✓	✓
Grid charges regarded in optimization					✓

Fig. 3. Properties of investigated cases.

dropped. This enables a fully flexible BESS operation based on market prices and represents a pure real-time pricing tariff. *Case 3* resembles the optimization case from Schneider et al. (2020), but without considering battery degradation in the optimization problem. From a policy perspective, the implementation of *Case 3* requires allowing household battery charging from the grid, which is, for instance, in Germany, penalized by the loss of self-consumption tax and levy exemptions (Bundesministerium der Justiz und für Verbraucherschutz, 2023).

We further differentiate between *Case 3*, where BESS are assumed to be exempt from grid charges, and *Case 3NE*, in which charging the BESS from the grid causes additional charges p^{grid}. We add the grid charges p^{grid} to the current market price p_t in time steps where the charging power P_t^c exceeds the empirically observed value $P_t^{c,real}$ as this indicates charging the BESS from the grid. We use hypothetical grid charges p^{grid} in the amount of 0.0735 Euros per kWh in our optimization model based on the actual charges of a Southern German distribution grid operator (Netze BW, 2021). While seemingly very different from the empirical case, *Case 3NE* represents households that subscribe to a real-time tariff within the context of self-consumption promoting regulation.

$$p_t' = \begin{cases} p_t + p^{grid} & P_t^c > P_t^{c,real} \\ p_t & P_t^c \leq P_t^{c,real} \end{cases} \tag{5}$$

Fig. 3 provides a graphical overview of the presented cases. The cases represent an increasing degree of market flexibility, but also decreasing similarity to the original operation strategy from the *Empirical Case*.

4.3. Survey of household storage owners

The results of our analysis and our proposed regulatory adjustments show the importance of the interaction between regulation and system. Besides regulation, the interaction of BESS and the energy spot market is also governed by personal preferences and behavior. For instance, households that decide to subscribe to a real-time pricing tariff already have an incentive to operate their BESS in a more system-friendly way as they are exposed to temporally differentiated external price signals. However, few consumers choose to do so. The reasons for this lack of engagement with more dynamic tariff designs are unclear. Recent research has shown that consumers with a higher energy literacy are more likely to adopt time-of-use pricing (Reis et al., 2021). We, therefore, acquired additional sample data from a survey conducted by Bilendi[1] to better understand the attitude of household BESS owners towards their battery energy management systems. Due to data privacy regulation, we were unable to directly contact the consumers from the described empirical sample. We, therefore, acquired an additional sample to conduct the survey with.

We focus our analysis on understanding the determinants of the perceived effectiveness of household BESS. We choose this as our dependent construct as we aim to better understand how households perceive the interaction of their BESS with the external energy spot market. Perceived effectiveness is instrumentalized using the scales proposed by Luo et al. (2008). As potential determinants of perceived effectiveness, we choose trust in the system (Gefen et al., 2003), the perceived behavioral control (Sheeran and Orbell, 1999), the importance of financial profitability and the sustainability of BESS (Bucher et al., 2016), the overall satisfaction with the BESS (Liao and Chuang, 2004) and several indicators to measure the perceived self-rated individual knowledge on personal energy consumption, the energy system and the energy market (Schlösser et al., 2013). We use an Ordinary Least Squares (OLS) regression, a statistical method that estimates the relationship between independent variables and a dependent variable by minimizing the sum of the squared differences between observed and predicted values, to determine the impact of these variables on perceived effectiveness (Craven and Islam, 2011; Jia et al., 2021).

5. The dataset: Empirical BESS load profiles

We begin by introducing the empirical dataset of 947 battery load profiles. The BESS profiles were measured over the course of the year 2021 and include state of charge (SOC) measurements with a one-minute resolution. The profiles come from regionally distributed German households and were anonymized before being provided to us for this study. All the residential BESS within the study are installed with corresponding PV systems. They have an energy capacity of 2.5 kWh (6.7%), 5 kWh (37.2%), 7.5 kWh (31.5%), or 10 kWh (24.6%). The BESS' maximum discharge power P^{max} is either 1.25 kW (6.7%), 2.5 kW (68.7%) or 3.75 kW (24.6%). On average, the Power-to-Energy ratio, which is often used to set the power rating in relation to the energy capacity, lies at 0.41. These figures provide important insights into the current distribution of household BESS in Germany.

The provider of the BESS guarantees the nameplate energy capacities for ten years by oversizing the systems to account for degradation. It operates a dedicated battery management system that ensures the nameplate capacity even as the total (oversized) capacity diminishes (SENEC GmbH, 2024). As a result, the BESS is operated with the guaranteed nameplate capacity throughout the observed period.

The empirically observed battery charging or discharging power P_t^{real} is based on the SOC change between two time steps SOC_{t+1} and SOC_t, divided by the time resolution τ, as in Eq. (6). We aggregate

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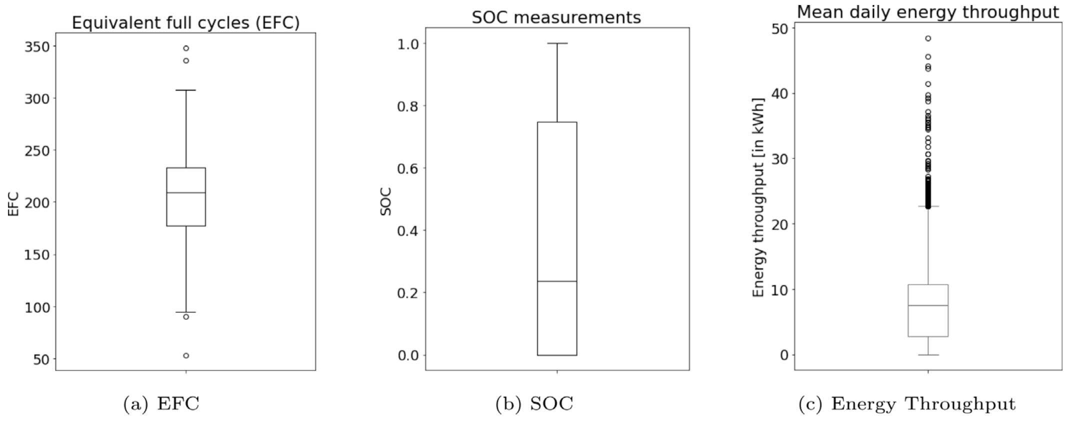
[1] https://www.bilendi.de



(a) EFC (b) SOC (c) Energy Throughput

Fig. 4. Descriptive statistics of empirically observed BESS usage.

the values to an hourly time resolution to link the data to the contract duration of the European EPEX spot market (Märkle-Hußet al., 2018).

$$P_t^{real} = \frac{SOC_{t+1} - SOC_t}{\tau} \tag{6}$$

As battery cycling influences the battery degradation and, therefore, the battery's lifetime (Kucevic et al., 2020), we also analyze the BESS usage throughout this study. We, therefore, determine the number of Equivalent Full Cycles (EFC), which set the Energy Throughput (E^{tp}) of the BESS in relation to its nominal capacity. The energy throughput E^{tp} is the sum of the absolute charging (P_t^c) and discharging power (P_t^d) of the BESS over time T measured in steps of the time resolution τ, as formulated in Eq. (7) (Koltermann et al., 2023).

$$E^{tp} = \sum_{t=0}^{T} |(P_t^c + P_t^d)\tau| \tag{7}$$

The energy throughput of one entire charging and discharging cycle in the amount of the nominal BESS energy capacity E^{BESS} represents one EFC. Hence, we divide E^{tp} by two times E^{BESS} to calculate the resulting EFC (Kucevic et al., 2020; Maheshwari et al., 2020):

$$EFC = \frac{E^{tp}}{2E^{BESS}} \tag{8}$$

Cycle depth is also commonly mentioned as a source of battery degradation. Deep cycles lead to faster BESS degradation (Schimpe et al., 2018). We are neglecting an analysis of the cycle depth and focusing instead on EFC. We do so because the empirically observed self-consumption-oriented BESS operation strategy – charging until the battery is full, discharging until it is empty – already leads to the highest possible cycle depths. Hence, any alternative operation strategies could even lead to comparable or even lower cycle depths.

Fig. 4 presents the introduced measures for the empirical sample. Most household BESS exhibit 198 EFC on average, with few outliers. The SOC measurements are distributed between 0 and 1 as the share of charged total capacity, with most measurements lower than 0.5, indicating that the BESS is more frequently empty than fully charged. The 75th percentile of the mean daily energy throughput of the individual BESS is below 10.7 kWh, while there are again a couple of outliers. Some of them are caused by the BESS still being charged from the day before, and then being discharged during the beginning of the day. Others are caused by multiple charging and discharging cycles per day. These patterns are only observed in a few households.

6. Results

In this section, we apply the first two steps of our methodology – an empirical analysis of BESS load profiles and the simulative analysis of alternative regulatory options – to the underlying dataset.

In Fig. 5, we depict the cumulated empirical annual profits per individual household. The average profit per installed BESS is 5.0 Euros. This means that every installed BESS only contributes 5.0 Euros to the overall system welfare per year. In total, 23.02% of households operating a BESS exhibit negative spot market returns as depicted in Fig. 5. This means that this BESS operation leads to additional costs for the system overall. More expensive power stations have to be operated because these BESS are operated within the system. This finding strongly calls into question the effectiveness of the corresponding regulation.

In the following, we compare the market results from the empirically observed BESS operation in a regulatory environment that promotes self-consumption with the introduced alternative regulatory policies. To do that, we assume perfect foresight for market prices and load values, which is common in studies focusing on BESS profitability (Olk et al., 2019; Wankmüller et al., 2017; Sioshansi et al., 2009). Sioshansi et al. (2009) observe in a study about battery trading profitability on the PJM market that the perfect foresight assumption overestimates battery trading revenues by 10%–15% compared to a backtesting-based trading strategy. In addition, we evaluate the efficiency of the respective BESS operation strategies in different regulatory environments by considering EFCs. We also relate the EFCs to the economic performance Π by calculating the Profit per Cycle (PPC), as in Eq. (9). Assessing the efficiency of BESS operations is especially important in light of the scarce resources used to build lithium-ion BESS (Costa et al., 2021).

$$PPC = \frac{\Pi}{EFC} \tag{9}$$

To better understand the BESS charging and discharging operations induced by the presented strategies, we depict the BESS SOC of an exemplary household over a day in Fig. 6. The y-axis represents the SOC and the x-axis shows the time of day. The lines represent the progression of the SOC over the day for the empirical case and for the simulated alternative regulatory approaches, while the green dots depict the hourly day-ahead spot market prices. We note that we only discuss an exemplary profile for the sake of comprehensibility. However, in the Appendix, we plot the SOC curves of all households and all cases, underlining that the exemplary Fig. 6 is representative of the whole sample, exhibiting comparable patterns. Furthermore, we depict all diurnal day-ahead price curves and their average over the year in the Appendix, illustrating their resemblance with the price curve from Fig. 6.

The empirically observed operations follow the expected self-consumption pattern. The BESS is charged in the morning until midday, when it is completely charged. In the afternoon and evening, the BESS is discharged. Our results are specifically important in light of the solar duck curve (California Independent System Operator, 2015). When prices are very low during the afternoon in spring or summer, battery storage are

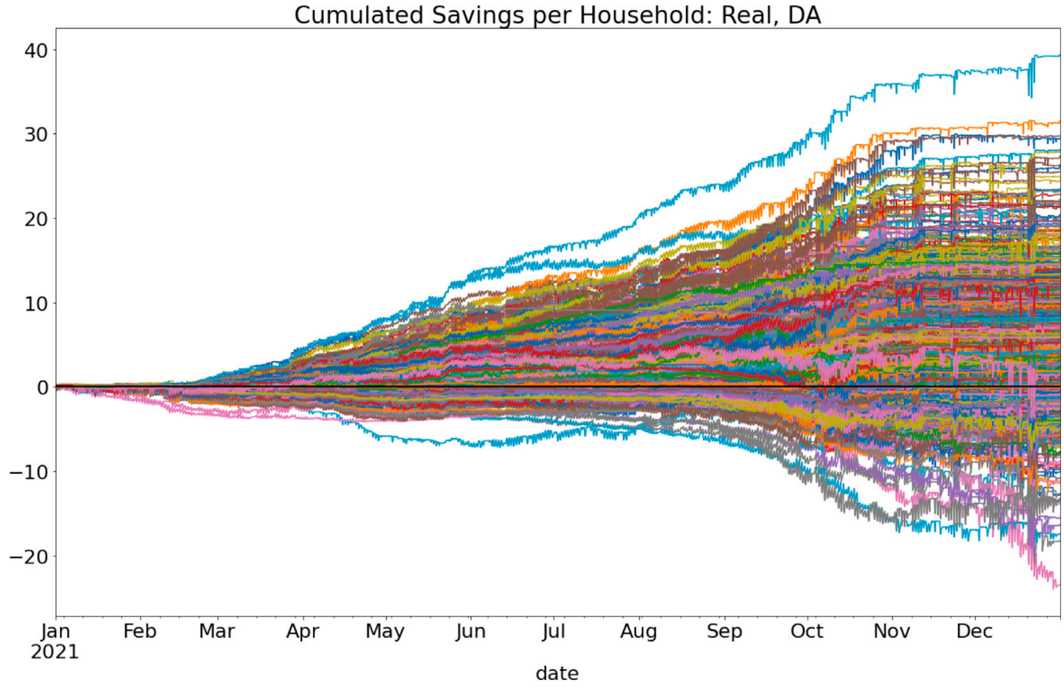
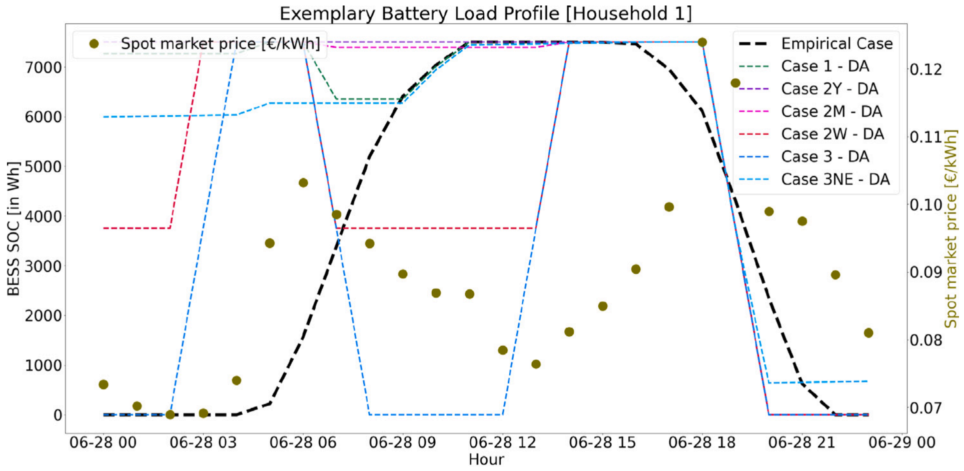


Fig. 5. Cumulated empirical profits.



(a)

Fig. 6. BESS SOC of exemplary household and spot market price for different operation strategies over one day.

often already fully charged and cannot absorb energy during times of negative wholesale prices (Denholm et al., 2015). We can observe a deviation from the empirical profiles when we analyze the resulting alternative regulatory options. Two peak price hours in the evening are used to discharge the BESS. In *Cases 1, 2 W and 3*, the battery energy management system also discharges the BESS during a morning price peak at 6 AM. Most observed battery energy management strategies under alternative tariff designs directly feed morning PV generation into the grid due to a relatively high price level rather than using it to charge the BESS on this exemplary day. *Cases 2 W and 3*'s midday charging decision at 1 PM coincides with the lowest daily electricity price of 0.08EUR/kWh. Thereby, we illustrate a general outcome of the more flexible operation strategies: The alternative BESS operations follow the overall market signals of the power system.

Case 2Y, 2M, 2W allow flexible BESS operation but restrict the maximum amount of EFC to the empirically observed values. By restricting battery cycles yearly, *Case 2Y* shifts most grid charging to the more lucrative winter months. In contrast, *Cases 2M and 2W* keep the cycle amount at the monthly and weekly level of the empirically observed values. From a household perspective, this might lead to months, weeks, or days without BESS usage, representing a significant difference to the empirically observed status-quo operation profiles from the *Empirical Case*.

Case 3 differs from *Case 3NE* because the latter incorporates grid charges in the optimization problem when the BESS is charged through the grid. Apart from that, both cases allow fully flexible BESS operations. As a result, in *Case 3*, the BESS is used most, but at the cost of a higher amount of cycles, whereas *Case 3NE* even reduces the number of cycles by weighing up grid charges against possible profits while considering direct feed-in of PV instead of charging from self-generation.

Table 1 provides an overview of market results and EFC for the considered regulatory and tariff cases and a comparison to the analysis of the empirical data. In the scope of the alternative tariff options, the

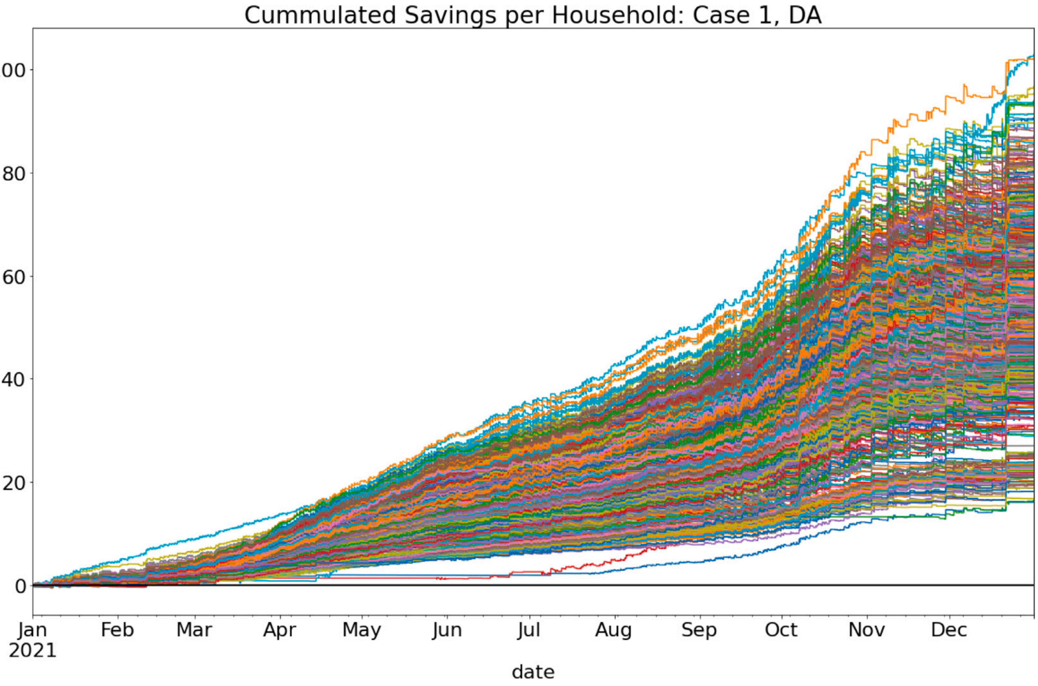


Fig. 7. Cumulated profits in Case 1 (Flexible Discharging).

Table 1
Average annual results per household on the day-ahead market.

Case	Profit [EUR]	Equivalent Full Cycles	Profit per Cycle [EUR/EFC]
Empirical case	5.0	198	0.03
Case 1	54.7	141	0.39
Case 2Y	159.5	208	0.76
Case 2M	118.0	208	0.57
Case 2 W	113.7	208	0.55
Case 3	225.2	640	0.35
Case 3NE	44.7	87	0.51

market profits and hence, the added value to the power system from storage operation, increase significantly, compared to the empirical case. Even moderate changes to the regulatory environment as *Case 1 (flexible discharging)* would lead to a ten-fold increase of average welfare gain per storage system. *Case 1* even leads to less EFC. This means a Pareto improvement under such a regulatory regime as system benefits increase, while costs for the individual are decreased. In *Case 2 (calendric limits)*, system welfare can be further increased, also leading to the highest profits per cycle, indicating the most efficient use of the systems from an economic point of view. In *Case 3 (market responsive)*, the high flexibility and highest returns come at the price of the highest amount of EFC, possibly leading to faster degradation of the BESS (Schimpe et al., 2018; Kucevic et al., 2020). Implementing grid charges for charging the BESS from the grid as in *Case 3NE (market responsive with grid charges for grid charging)* leads to the lowest EFC. When we compare the actual implementation of the operation strategies in Fig. 6, we can observe that *Case 3NE* resembles *Case 1*. Looking at profits per cycle in Table 1, we can see that the current operation leads to the worst efficiency. Given the scarcity of the materials used in lithium-ion batteries (Costa et al., 2021), these systems should be used more effectively and efficiently.

Fig. 7 shows the cumulated annual profits per individual household for *Case 1 (flexible discharging)*. In contrast to the empirical case, the relatively constrained regulatory option of *Case 1* leads to consistently positive returns for every household in the dataset. This result shows that instead of mandating or clearly incentivizing specific behavior, regulators should focus on system objectives and provide guardrails to be respected that lead to those ends. However, in order to do that, a detailed understanding of household attitudes towards their BESS and its antecedents is necessary.

7. Consumer preferences and attitudes

The survey sample for this analysis was provided by Bilendi, a European sample provider and included 333 data points. In their internal characterization of participants, Bilendi keeps a flag for “owning a PV installation”, which is unique and useful for our purposes since the installation of PV is an indicator for the installation of a BESS (Figgener et al., 2021). In addition to the final sample, 111 participants started the survey but failed an attention check and were, therefore, immediately screened out. Of the 333 valid completions, 79 participants were removed because they failed a comprehension check. Finally, another 59 participants were screened out because their answers to the questions about what BESS they used were incomprehensible or the provider did not exist. This led to a final cleaned sample of 195 BESS owners. 33% of those respondents are female, 79% stated a household income of more than 3000 Euro per month, 72% are older than 40 years and 99% have some form of advanced education. This shows that the sample consists of a group with high socio-economic advantage, which can be expected as investing in household BESS requires substantial financial resources.

Table 2 provides an overview of the used constructs, including the number of items, original reference, and Cronbach’s alpha based on the resulting responses. All Cronbach’s alpha values are in the acceptable range except for self-rated knowledge on energy consumption. In the following regression, the items of this construct are, therefore, used individually, while the other constructs are based on the average of the corresponding items.

The results of regressing the perceived effectiveness against the other discussed constructs are presented in Table 3. The adjusted R^2 value of 0.74 signals a reasonable explanatory power of the corresponding model.

The individual coefficients and p-values show a strong correlation between trust in the battery energy management system and its perceived effectiveness. Interestingly, self-rated knowledge is not

Table 2
Evaluation of constructs.

Construct	Reference	Items	Cronbach's α
Perceived effectiveness	Luo et al. (2008)	4	0.81
Trust in system	Gefen et al. (2003)	6	0.94
Perceived behavioral control	Sheeran and Orbell (1999)	4	0.84
Importance financial profitability	Bucher et al. (2016)	5	0.93
Importance sustainability	Bucher et al. (2016)	4	0.89
Satisfaction	Liao and Chuang (2004)	3	0.92
Knowledge energy consumption	Schlösser et al. (2013)	2	0.55
Knowledge energy market	Schlösser et al. (2013)	2	0.72
Knowledge energy system	Schlösser et al. (2013)	2	0.72

Table 3
Regression on Perceived Effectiveness.

Residuals: Min	Q1	Med	Q3	Max
−2.16	−0.28	0.01	0.31	1.27
Residual standard error:	0.47			
Degrees of freedom:	185			
Adjusted R^2	0.74			
F-statistic:	60.9			
Coefficients	Estimate	Std.Error	*t*-value	*p*-value
(Intercept)	0.57	0.28	2.03	0.043*
Energy Knowledge Consumption 1	−0.04	0.04	−1.03	0.306
Energy Knowledge Consumption 2	−0.01	0.03	−0.27	0.790
Energy Knowledge System	0.02	0.05	0.43	0.666
Energy Knowledge Market	0.08	0.04	1.77	0.079
Perceived Behavioral Control	0.06	0.03	2.06	0.041*
Satisfaction with System	0.04	0.04	0.86	0.393
Trust in System	0.56	0.04	12.70	0.000***
Financial Importance	0.11	0.04	3.00	0.003**
Sustainability Importance	0.08	0.04	2.36	0.020*

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

correlated to perceived effectiveness across all constructs and items capturing this concept. This means that perceived effectiveness increases with trust but not with increasing or decreasing self-perceived knowledge of energy consumption, the energy system, or the energy market. Additionally, perceived behavioral control positively affects perceived effectiveness. Similarly, the importance of financial performance and the importance of a sustainable operation of the BESS positively influence the perceived effectiveness. Interestingly, satisfaction with the energy system does not correlate with perceived effectiveness. The implications of this model are further discussed in the following discussion section.

8. Discussion

With this study, we contribute to an improved integration of household BESS into the energy system and a socio-technical understanding of the phenomenon BESS usage. To this end, we use empirical data to show the effect of regulation and corresponding consumption behavior on the effect of market integration.

Our results show that under the regulatory policy of self-consumption promotion and the resulting household behavior, the average welfare gain per BESS is virtually zero. In other words, the installed BESS do, on average, not lead to any balancing benefit for the power system. This is not to say that they do not benefit the individual, but based on their operation and the corresponding household behavior, they do not lead to a benefit for the other market participants. In specific cases, they even add costs for other energy consumers. It is advisable that incentives would be designed so that individual benefits also lead to a global welfare gain. One might argue that the use of local renewable generation is a value in itself. However, this energy would be consumed in any case.

Our study has a few limitations. We are limited to the observations we report. We cannot say whether the absence of BESS would impact the price such that the outcome could be different. However, the results still show that the coordinated behavior of all household BESS is not beneficial or even detrimental to the energy system as a whole. Our sample might still be categorized as early adopters with corresponding biases in their behavior. We have no specifics on the households as the sample is anonymous. However, given the already considerable market penetration of BESS, it is unlikely that the demographics of battery owners will shift beyond single-family homes as of now. In any case, based on the data, households seem to behave according to the incentives given by the regulation and charge their storage fully during the day before depleting it in the early evening. These results show that uniform and homogeneous regulation of BESS without specific economic signals is likely to yield suboptimal results.

We only analyze empirical BESS load profiles without considering connected PV and household load profiles, as this data was not available due to privacy reasons. Although this does not change the overall direction of our results, since the BESS load profiles are directly connected to household loads and PV generation, we see potential for more granular analyses in future studies that also have access to the corresponding data.

Given that current regulation leads to seemingly suboptimal results, we propose alternative regulation and tariff structures utilizing price signals with a higher resolution derived from existing designs. This approach is, of course, based on the simulation of behavior, which, as we argue throughout this paper, does not necessarily represent empirical behavior. However, the simulation results in this study represent behavior based on empirical data of battery-owning households that would not be impacted. Therefore, there is no reason to believe that they would change their behavior only because their batteries are operated differently. Corresponding battery energy management systems could redirect power flows without any effect on comfort or change in the behavior of households, leading to lower cycle numbers and more income as in Cases 1 and 3NE. The alternative regulation is, therefore, a Pareto improvement compared to the current regulation.

Although our study was solely conducted with a sample of German households, it yields important insights for lawmakers internationally. As described in Section 3, various countries, such as the UK, Australia or Japan, are also promoting battery installations to increase self-consumption of household PV generation in a comparable way. Hence, we argue that the results of our study can be generalized to some extent to other countries. Nonetheless, we call for a comparable empirical investigation in other countries under self-consumption-promoting regulation.

To round off our research on household behavior and BESS, we conduct a survey to better understand the perception of battery owners of their BESS effectiveness. We conducted this study with a sample different from that used for the empirical BESS usage evaluation. This was necessary because this sample is anonymous to us due to data privacy reasons. Again, the survey sample is not representative of the general population, but we are unaware of any study that describes the representative demographics of a battery owner. This survey should be understood as an exploratory study that can only provide some indication in regard to the relationship of the perceived effectiveness of BESS with other constructs. Yet, the results are interesting and open avenues for further research. They seem to indicate that trust in the system supplier is linked to perceived effectiveness, while different types of self-perceived knowledge are not. This suggests that the perception of effectiveness currently is independent of the perception of knowing what is effective but rather linked to a general positive feeling towards the BESS. It is also noteworthy that having an objective that is pursued with the BESS (be it financial or sustainable) positively influences perceived effectiveness. This seems reasonable as judging effectiveness is easier when it is clearly understood to what end one expects the system to be effective. Interestingly, satisfaction is not correlated with perceived effectiveness, while perceived behavioral control over personal energy consumption is. This might be caused by the fact that those who feel that they would have an idea of how to act in the absence of the storage feel that the storage does what they would otherwise do. These results highlight the importance of proper regulation as households trust their supplier who will adapt operation to the corresponding regulatory policies.

The results indicate the need for further research. For instance, it is unclear how potential additional market profits should be optimally distributed between the aggregator and BESS owner to incentivize market-friendly behavior or to maximize perceived fairness. Furthermore, we only considered the participation of BESS in energy spot markets. We, therefore, ignored the potential of residential BESS to participate in reserve markets. This could further increase the revenue potential of market-oriented BESS operation strategies (Naseri et al., 2023). Finally, our findings on the perceived effectiveness of battery energy management systems lead to further questions in regard to the perception of information systems in household appliances.

9. Conclusion and policy implications

Distributed battery energy storage systems are an important asset for future energy systems that will continuously rely more on intermittent renewable generation. Therefore, the regulation and resulting battery energy storage system operation are highly relevant. However, there is currently no international consensus on an optimal regulatory framework, as shown by the variety of international policies. One widely proliferated regulatory framework incentivizes households to increase the self-consumption of electricity generated by their PV installations. Although previous research questions the benefits of self-consumption promoting regulation, this has never been analyzed empirically. To this end, we analyze an empirical sample of 947 year-long load profiles of household battery energy storage systems. We find that a self-consumption promoting regulation causes an operation of battery energy storage systems that leads to virtually no additional welfare for the energy system overall, while it does benefit battery owners. In individual cases, this regulation even leads to additional costs for the system that are socialized among energy consumers. These results hold important implications for policymakers worldwide. Given our results based on empirical field behavior, we show that self-consumption regulation needs to be carefully designed in order to contribute to the overall optimization of the energy system.

We, therefore, move on to simulate alternative regulatory approaches and tariff designs and show that these may lead to a Pareto improvement. This highlights the positive impact of slightly adjusting regulatory policies. We propose only slight adjustments to a self-consumption promoting regulation such as delayed feed-in, time-varying feed-in compensation, dynamic tariffs and structures from net billing. Our analysis shows that these adjustments lead to universally system-beneficial household battery energy storage systems. The paper is, therefore, a valuable point of reference for energy regulators and academics in the field.

Furthermore, we present a framework to describe the relationships between household battery regulation, battery energy management systems, household preferences, and the energy market, contributing to the understanding of these systems. We find that household preferences and behavior are often neglected when analyzing regulatory options. To contribute to this research gap, we complete the research with a third methodological approach with an exploratory perspective on the perceived effectiveness of battery energy storage systems. To this end, we conduct a survey among battery owners. The results indicate that trust in the system operator rather than self-perceived competency correlates with perceived effectiveness. This shows the important role of regulation in the operation of household battery energy storage systems as it shapes behavior. In conclusion, our study suggests that regulatory approaches towards household BESS operation should employ carefully designed and temporally differentiated signals to be more aligned with overall energy policy objectives.

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CRediT authorship contribution statement

Leo Semmelmann: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marie Konermann:** Software, Data curation. **Daniel Dietze:** Validation, Supervision. **Philipp Staudt:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization, Data curation, Formal analysis, Validation, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Appendix

Diurnal price curves over the year

See Fig. 8.

Correlation of day-ahead market prices

See Fig. 9.

Battery SOC profiles over all cases and households

See Fig. 10.

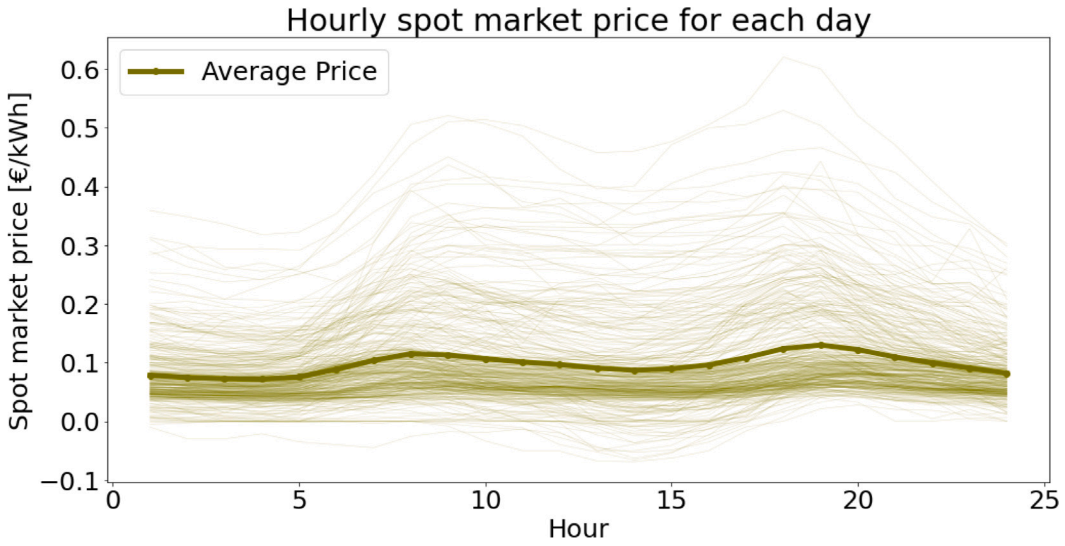


Fig. 8. Diurnal price curves over the year 2021.

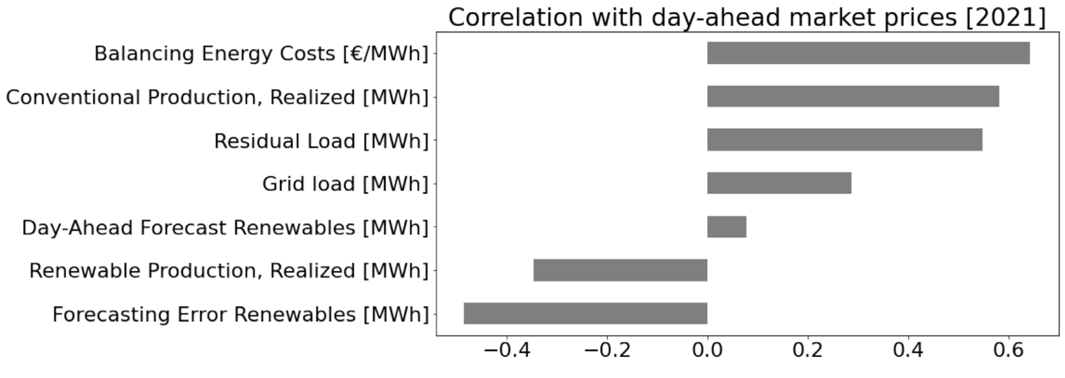
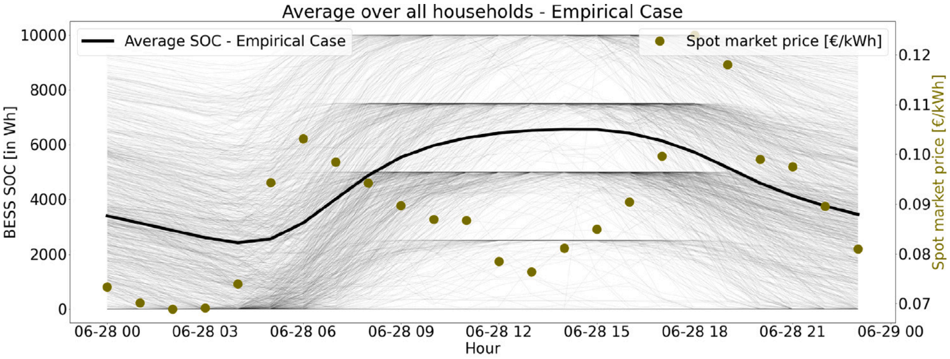
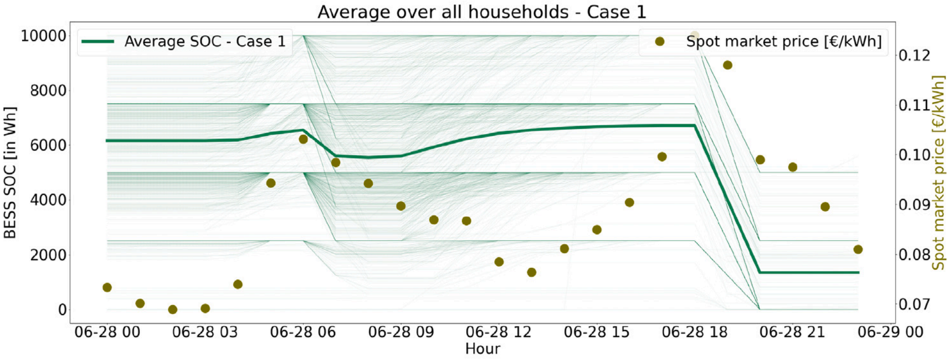


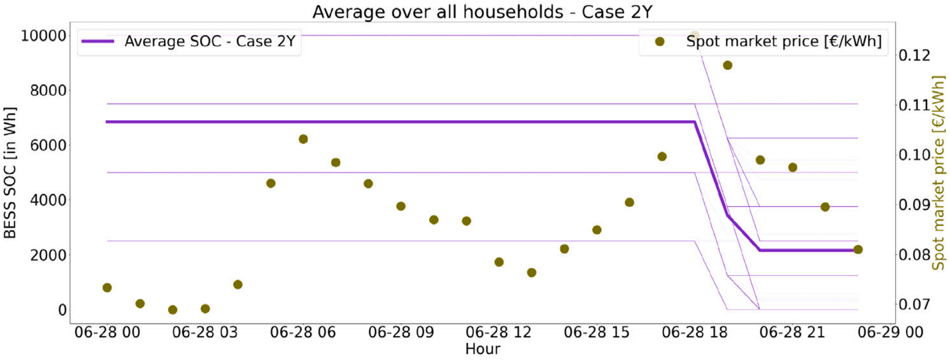
Fig. 9. Correlation of German power market metrics with day-ahead market prices for the year 2021.



(a) Battery SOC profiles for the empirical case

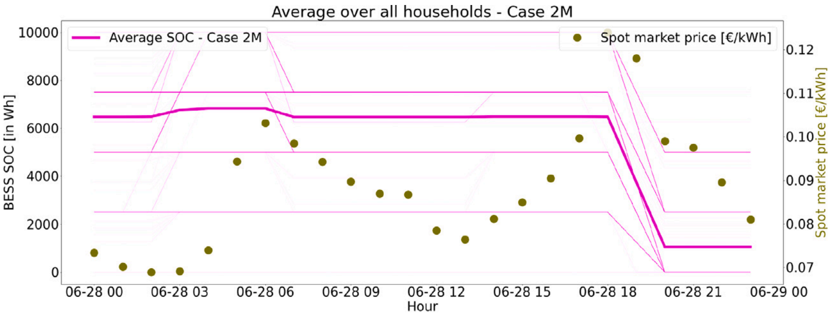


(b) Battery SOC profiles for Case 1

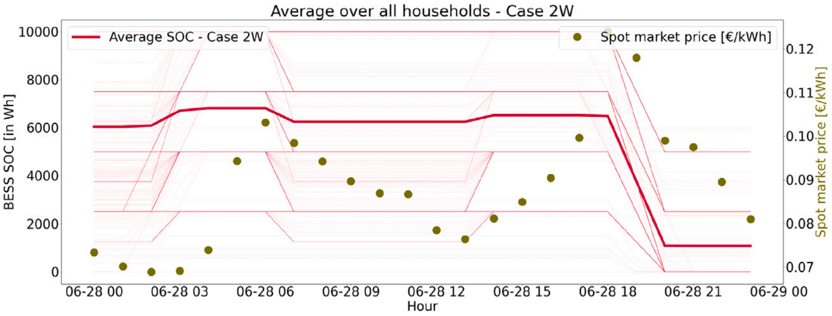


(c) Battery SOC profiles for Case 2Y

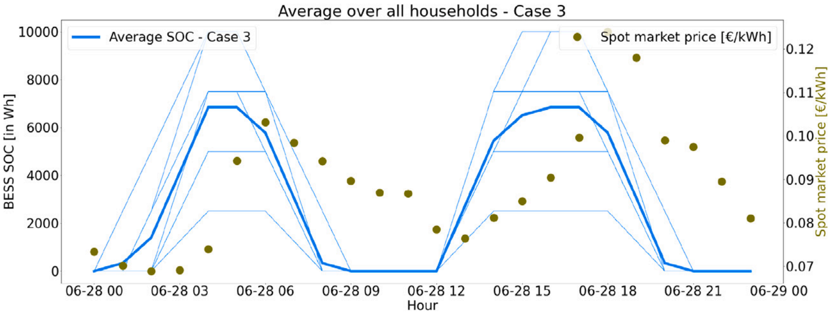
Fig. 10. Battery SOC profiles over all cases and households.



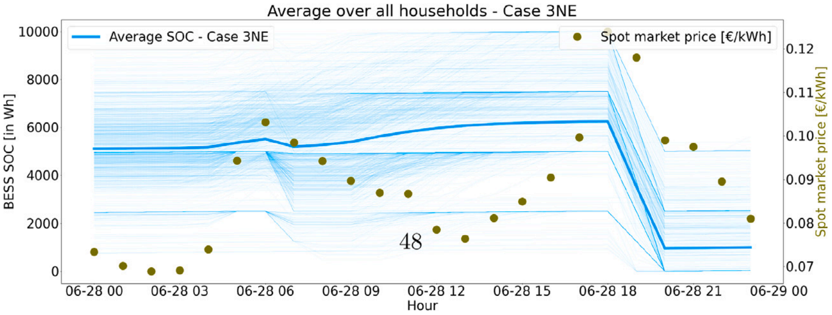
(d) Battery SOC profiles for Case 2M



(e) Battery SOC profiles for Case 2W



(f) Battery SOC profiles for Case 3



(g) Battery SOC profiles for Case 3NE

Fig. 10. (*continued*).

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