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THE ROLE AND VALUE OF SERVICE ORCHESTRATION IN SMART GRID PROSUMER SERVICE SYSTEMS

Research Paper

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Abstract

The implementation of smart grid infrastructure as well as the rise of eco-conscious prosumers in the energy markets are leading to a paradigm shift in the energy sector. Residential households can no longer be viewed as passive market entities, but have to be considered as actors participating in value creation. In this work, we present the co-creation of value in energy markets through the lens of service dominant logic, and highlight the importance of service orchestrators for deriving both design decisions and operational decisions for complex energy systems. For the example of a real-time energy trading service, we assess the value of service orchestration by means of a simulation study. Thereby, we highlight the importance of service orchestration for creating valuable business opportunities, and we provide a transdisciplinary approach that combines service science and service operations research.

Keywords: Service Orchestrator, Prosumer, Value Co-Creation, Electric Vehicle.

1 Introduction

The energy sector currently undergoes drastic changes towards a low carbon energy system with many distributed generation units. More households are being equipped with small generation units (e.g., solar panels) and storage devices (e.g., power walls or electric vehicle batteries). By the ability to produce and store energy, these households become prosumers (Chandler and Chen, 2015) in the energy markets. Advances in technology (e.g., smart grid infrastructure including information and communication technology) enable previously passive residential energy consumers to become active players in the energy grid. The effective and efficient integration of these prosumers into energy markets poses a significant challenge (Parag and Sovacool, 2016). Breaking the traditional energy market structure by establishing a network of independent prosumers, implies a paradigm shift of how we view value creation in energy markets. Service-dominant logic (Vargo and Lusch, 2016) provides a framework for describing this shift. Considering value creation in energy markets as service provides a holistic view in which prosumers are entities that co-create value.

The changes in the energy markets provide opportunities for beneficial resource integration. However, operational energy management and identification of the right prosumer setup (e.g., charging infrastructure, generation and storage capacities) is challenging for individuals that are typically not energy management experts (Burger et al., 2017; Brown et al., 2019). Therefore, service orchestrators are required to guide individual prosumers towards participating in beneficial energy services.

In this paper, we describe the role and value of service orchestration in smart grid prosumer service systems. In Section 2, we apply service-dominant logic to prosumer driven energy markets, we highlight the need for service orchestrators in the prosumer era, and we subsequently elaborate on how service science and service operations research form a synergetic relationship for transdisciplinary service orchestration analysis. In Section 3, we provide a simulation study for analyzing service orchestration for a residential prosumer that participates in a smart grid service featuring real-time energy trading, solar energy generation, stationary energy storage and an electric vehicle (e-vehicle). Subsequently, Section 4 provides a discussion of the results obtained from the simulation study, and highlights opportunities for transdisciplinary research on service orchestration. Section 5, concludes our work with an outlook on future research directions that result from our research.

2 Energy Markets Through the Lens of Service-Dominant Logic

The transition towards a sustainable and efficient energy system with a high share of renewable energy is expected to result in dramatic changes for energy markets (see, e.g., Abrishambaf et al. (2019), Howell et al. (2017)). In Section 2.1, we elaborate on the change in energy markets and discuss the associated necessary shift towards a more service-centric perspective. In Section 2.2., we identify the need for service orchestrators in energy markets, and highlight the transdisciplinary nature of this research topic by discussing the synergetic relationship of service science and service operations research for analyzing and assessing the value of these new service orchestrators.

2.1 A Paradigm Shift in Energy Markets

The eco-consciousness of individuals and of society as a whole lead to a transformation of the energy sector. As more consumers demand energy that is both green and affordable, the energy system undergoes a process of decarbonization (Danne et al., 2021; Moon, 2018) creating the need for increased economic efficiency. The decarbonization includes the deactivation of well-controllable oil- and coal-fired power plants, and the construction of intermittent renewable energy power plants (e.g., wind and solar). The growing number of such power plants poses a threat to grid stability as it leads to higher fluctuations in energy supply. At the same time, the decarbonization of the energy system also leads to more volatile energy demand due to, e.g., the uncontrolled charging behavior of e-vehicle owners. As a consequence, energy market actors are looking for business models that allow for both environmental sustainability and economic sustainability of the energy system.

Until recently, energy provider and energy consumer have been two distinct roles in the energy system. As a consequence, the energy sector has been defined by a goods-dominant logic perspective, where the energy provider is the creator of value, which is transferred to the consumer who exploits this value and pays a compensation to the energy provider. However, this view of value creation does not fit the more recent energy market reality (Sadjadi, 2020). Driven by both economic and ecological concerns, traditional energy consumers are beginning to take more active roles by engaging in demand response programs (Parrish et al., 2020) or by becoming prosumers (Zakeri et al., 2021). Alongside commercial renewable power plants, the number of residential prosumers operating small renewable energy generation units is on the rise. With the integration of these independent prosumers into energy markets, the boundaries between energy provider and consumer are blurred (Ekman et al., 2019).

The perceived value no longer only corresponds to the mere provision of energy, but also includes an environmental component that has to be accounted for in value propositions on the market. This change in energy markets requires a paradigm shift with respect to the strategic logic by which we view the markets. Service-dominant logic (Vargo and Lusch, 2016) provides a holistic view of value generation in energy markets, and emphasizes the importance of service. Adopting this logic, traditional energy providers (e.g., utilities) as well as new energy prosumers, do not create value on their own, but rather offer value propositions to other market entities, who become co-creators of value.

The disruptive eco-consciousness of individuals paired with disruptive technology developments, cause the creation of new service types in energy markets. These services rely on the roll-out of smart grid infrastructure, especially smart meters (e.g., Gonçalves et al. (2020), Sadjadi (2020b), Shomali and Pinske (2016)). Moreover, such services can leverage time-dependent energy tariffs (e.g., static time-of-use tariffs (Yang et al., 2013) or dynamic real-time prices (Faria and Vale, 2011)) that are offered increasingly by utilities. As energy prices reflect the current energy supply and demand in the grid, individual households are able to perform grid support by demand response, i.e., the households increase grid stability. Furthermore, the new smart grid services may leverage the recent technological advances in the areas of small-scale renewable energy generation systems (Tazvinga et al., 2017), stationary batteries (Barbour and Gonzaléz, 2018), and e-vehicles (Andwari et al., 2017). In these services information and communication technology (ICT) enables the collaboration between the different energy market actors. Thus, ICT supports economic and sustainable energy provision (Loock et al., 2013; Moreno-Munoz et al., 2016), and is crucial for value co-creation (Blaschke et al., 2019; Breidbach and Maglio, 2016).

2.2 The Need for Service Orchestration in Energy Markets

Navigating in these new energy markets can be challenging for companies (Markard, 2018; Shomali and Pinske, 2016), and, especially, for residential energy prosumers, that do typically neither have detailed knowledge about energy technology and energy trading, nor the time required for performing advanced energy management (Ito, 2014; Layer et al., 2017). Therefore, the prosumer's ability to act as the leading resource integrator is often limited. For solving the multiobjective task of designing and operating smart grid prosumer services, the need for service orchestration arises. Service orchestrators act as intermediaries between residential prosumers and the energy market by deciding about service design (e.g., technological setup and energy tariff) as well as about service operation management (e.g., managing energy flows). The prosumer defines service objectives for the service orchestrator, typically including energy cost minimization and renewable energy usage maximization.

The general concept of service orchestration is well-known. Service orchestrators are defined as *dedicated firm-centric actors who facilitate and orchestrate resource integration, and thereby value cocreation, between other independent actors [...] in complex [service systems]* (Breidbach et al., 2016). The need for service orchestration has been identified in various sectors, such as retailing (Bradford and Sherry, 2013), real estate (Nätti et al., 2014), consulting (Breidbach and Maglio, 2016) and health care (Breidbach et al., 2016). In the energy markets, a service orchestrator acts as a knowledge broker (Truong et al., 2012) that provides expertise ranging from energy technology, to energy markets, and to energy management. Such an orchestrator is therefore ideally implemented by 'T-shaped' professionals (Demirkan and Spohrer, 2018). The environment of a service orchestrator in the energy market is a complex sociotechnical system that features disruptive technological advances (e.g., smart grid infrastructure), disruptive market developments (e.g., market liberalization), and disruptive shifts in value perception (e.g., growing eco-consciousness). Therefore, service orchestration in the context of energy markets must be supported by transdisciplinary research that crosses traditional disciplinary boundaries. With the increasing scale and complexity of energy systems and markets, drastic changes in the mindset of energy service researchers are becoming inevitable, and transdisciplinary systems engineering (Madni, 2018) is required in order to solve the problems emerging from the complex sociotechnical system at hand. These problems are intractable when viewed solely through the lens of engineering or solely through the lens of economics. On a general level, Mariotti (2021) reveals the ongoing transdisciplinary evolution of the two disciplines engineering and economics, and shows the synergies that exists between both. Within the information systems community, transdisciplinary research agendas are called for in order to study the topic of smart cities (e.g., Becker et al. (2021)).

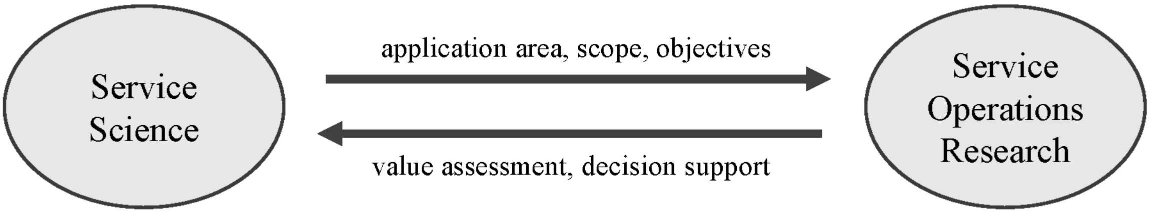


Figure 1. Synergies of service science and service operations research.

We perform transdisciplinary research on service orchestration by exploiting synergies of service science and (service) operations research. Figure 1 illustrates the synergies of the two disciplines. Service science defines the service orchestration that is subject to analysis, and, thereby, increases the effectiveness of service operations research. Note that the latter, aims at making optimal decisions, which require precise service definition, i.e., that optimal decision making requires insights into the structure of the considered application (Meisel and Mattfeld, 2010). With the holistic view of service enabled by service-dominant logic, the boundaries and objectives for applying operations research techniques within the scope of service orchestration can be clearly defined.

Service operations research increases service efficiency by providing the methods required for service design and for optimal service operation. Service operations research can assist in assessing the value of service orchestration for new services or for reconfiguration of existing services. As a consequence, service science researchers and practitioners are provided with guidance on how to modify services in order to maximize service efficiency. In the following section, we provide an approach that uses service science and service operations research for analyzing service orchestration at the example of a real-time energy trading services for a prosumer that owns an e-vehicle.

3 Service Orchestration by the Example of a Real-Time Energy Trading Service with Electric Vehicles

In this section we analyze a service in which a service orchestrator enables a household with an electric vehicle to participate in real-time energy trading. This type of service can be defined as e-vehicle service (Meisel and Merfeld, 2018), i.e. as value co-creation among an e-vehicle provider (EVP) and a skills and technology provider (STP), where the latter acts as the service orchestrator. The two entities co-create financial value in terms of energy cost reductions, as well as ecological value by increasing the consumption of renewable energy. By means of a simulation study, we analyze the impact the service orchestrator's design decisions about generation capacity and storage capacity have on service value, i.e., on energy cost savings and on the degree of self-sufficiency of the residential prosumer's energy system. Service science is required to describe the problem and service operations research provides the appropriate analysis tools. In Section 3.1 we elaborate on the main service entities and the resources they contribute to the e-vehicle service. In Section 3.2 we propose a mathematical model for operational decision making in a real-time energy trading service. The model enables simulation of service operations, and is therefore required to assess service design decisions. In Section 3.3 we present the experimental setup of our simulation study. In Section 3.4. we show the results of our simulation study.

3.1 Service Orchestration as Resource Integration

Figure 2 illustrates the primary service entities, their basic interaction as well as their primary operand and operant resources. The prosumer acts as an e-vehicle provider (Meisel and Merfeld, 2018). For value creation the EVP has to provide the necessary resources. The operand resources of the EVP are the electric vehicle, as well as the household energy system (including residential energy load, residential energy generation, and other energy storage devices). During value co-creation the EVP grants the STP access to these operand resources. The EVP uses ICT in order to share the operant resources in form of information about the vehicle (e.g., battery charge levels, geographical location and idle times) as well as about the residential energy load (e.g., present (and future) energy demand) with the STP. The STP uses this information for managing the EVP's energy system effectively and efficiently.

The primary operand resource of the STP is the smart grid infrastructure that is required for energy system management and real-time energy trading. This infrastructure includes smart meters (for enabling time-dependent billing by measuring energy consumption from the main grid for each point in time) and ICT (e.g., for receiving market price signals or for information sharing with the EVP). In order to reduce the residential carbon footprint, the STP equips the household with solar panels and stationary energy storage units. With this technological setup the STP is able to increase the household's self-sufficiency, i.e., making it more resilient to main grid failures. The STP also provides the e-vehicle (dis-)charging station allowing the e-vehicle to become an operand service resource. All of these technological requirements might be acquired from other market facing entities, and could either be leased to the EVP or sold for permanent ownership. Either way, the STP has to decide on the optimal configuration of the technological setup and has to be granted operational access to all operand and operant resources for energy management.

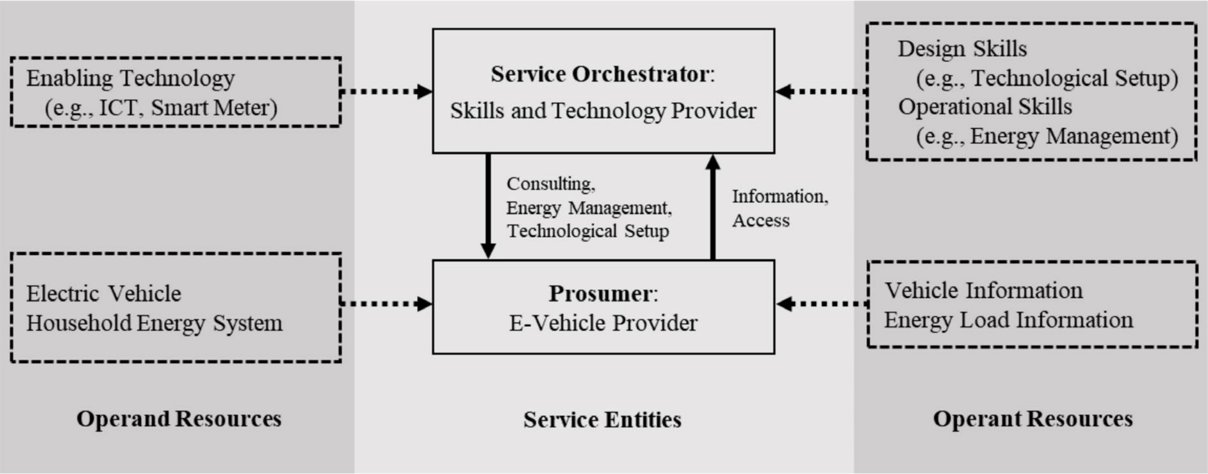


Figure 2. Service entities, operand and operant resources in an e-vehicle service.

The primary operant resources of the STP can be classified as design and operational skills. Alongside the technological setup decision, the STP has to make the service design decision on energy market participation (i.e., selecting the energy market or energy tariff to use, and establishing the necessary requirements for market participation). The main operational skill of the STP concerns the operational management of the energy system. The STP has to be able to derive informed decision about energy flows within the EVP's energy system. Therefore, the STP should have access to or be able to make good forecasts for future system states. The STP embeds the energy management skills of people into an IT artefact. Thereby, the information technology becomes an integral component of the service by functioning as an operant and as an operand resource (Lusch and Nambisan, 2015). The STP actively manages the EVP energy system. The STP aggregates and integrates all relevant operand and operant resources from the EVP and possible other service entities to maximize service value. The STP thereby acts as a service orchestrator for enabling the EVP to participate in real-time energy trading and increasing the co-created value of various service entities, e.g. the EVP, the grid, or technology manufacturers. By reconfiguration of the service system the STP acts as a service innovator (Breidbach and Maglio, 2015; Maglio and Spohrer, 2013).

3.2 Design Decisions and Operational Decisions of the Service Orchestrator

While ecological benefits motivate residential prosumers to participate in energy markets, financial benefits typically offer the strongest incentives (Parrish et al., 2020). Therefore, the service orchestrator should aim at minimizing the prosumer's energy costs, while revealing the service's ecological impact. As service orchestrator the STP has to make design decisions regarding the technological setup, which critically influences the service's financial and ecological value (where the former can be measured in terms of cost reductions, and the latter can be measured as the prosumer energy system's degree of self-sufficiency). In order to determine the best technological setup, we simulate service operations under different technological setups (i.e., with different residential energy generation capacities and with different energy storage capacities), and measure the service system performance (i.e., the financial value and the degree of self-sufficiency) resulting from these resource configurations.

To maximize service system performance for a given resource configuration, the STP needs to make the right operational decisions about energy flows during service operation. These decisions are made both sequentially in the course of time and subject to uncertainties, such as varying energy generation and volatile market prices. In order to solve the resulting dynamic decision problem, it must be modeled mathematically as a dynamic decision process (Powell and Meisel, 2015).

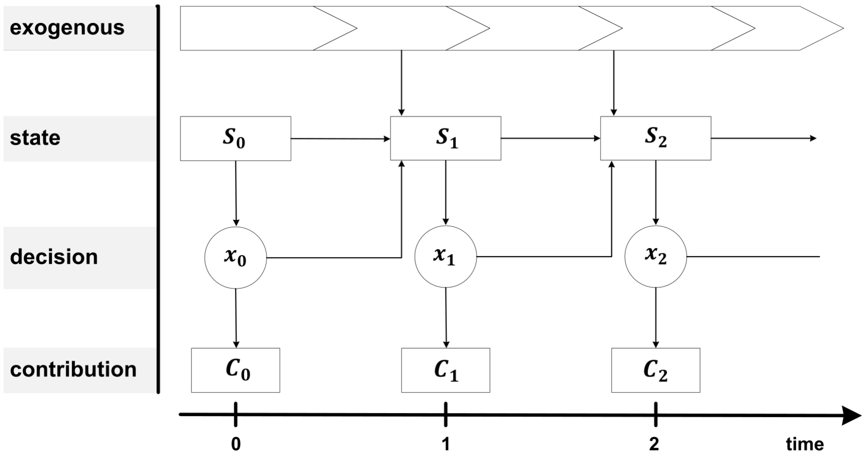


Figure 3. Key elements of a dynamic decision process (c.f., Meisel (2011)).

Figure 3 illustrates the key elements of such a process. Based on the state S_t of the service system at point in time t, the STP derives decisions x_t about the energy flows in the system for the next time interval. These decisions determine the current contribution C_t to the overall system performance. The successor state S_{t+1} is reached at the end of the next time interval, and is determined by S_t, by x_t, as well as by the uncontrolled exogenous influences that the system is exposed to (energy load, energy generation, energy price and mobility demand). Meisel and Merfeld (2020) provides a model for the dynamic decision process of a real-time energy trading service for a prosumer, and proposes a method for deriving the decisions about energy flows. In the following, we extend this established approach by a stationary battery within the prosumer's (EVP's) energy system. The extended model serves as the basis for the simulation study presented in the following sections.

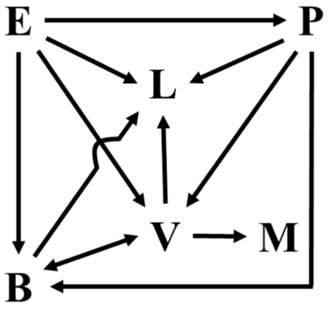


Figure 4. Energy flows within the prosumer's (EVP's) energy system. Arrows represent possible energy flows between residential load ('L'), energy generator ('E'), stationary battery ('B'), energy market ('P'), electric vehicle ('V') and mobility demand ('M').

The STP has to make decisions about energy flows at discrete points in time $t \in \{0, \dots, T\}$ over a given time horizon. Figure 4 illustrates the energy flows at a point in time t. The STP may use generated energy ('E') for charging the e-vehicle ('V'), for charging the stationary battery ('B'), for satisfying residential energy load ('L'), and for sales transactions at the energy market ('G'). The STP may buy energy from the market for charging the e-vehicle, for charging the stationary battery, and for satisfying residential energy load. The e-vehicle can be discharged for satisfying residential energy load (using vehicle-to-home (V2H) technology), for charging the stationary battery, or for satisfying mobility demand ('M'). The stationary battery can be discharged for satisfying residential energy load or for charging the e-vehicle. The decisions at time t are:

$$x_t = (x_t^{EL}, x_t^{EB}, x_t^{EV}, x_t^{EP}, x_t^{PL}, x_t^{PB}, x_t^{PV}, x_t^{VL}, x_t^{VB}, x_t^{BL}, x_t^{BV}),$$

with capital letters in the superscripts denoting origins and destinations of energy flows (c.f., Figure 4).

The STP bases these decisions x_t on the current system state $S_t = \left(L_t,\ E_t,\ P_t,\ M_t,\ B_t, V_t^{soc}, V_t^{ttr}, f_t\right)$, where L_t represents the household's current demand for energy, E_t is the current generated amount of renewable energy, P_t is the current real-time energy price, M_t is the energy demand for a tour starting at t, B_t is the current amount of energy in the stationary battery, V_t^{soc} is the current amount of energy in the e-vehicle, V_t^{ttr} is the current amount of time steps remaining until the e-vehicle returns to the EVP's charging station (i.e. $V_t^{ttr} = 0$ indicates that the e-vehicle is on-site), and f_t are current forecast values. We assume that the STP is able to generate or access forecasts for $L_{t'}, E_{t'},\ P_{t'}$ and $M_{t'}$ for all $t < t' < T$ which are represented as $f_t = (f_t^L, f_t^E, f_t^P, f_t^M)$.

The set of feasible decisions at time t is defined by Equations (1) – (13):

$$x_t^{EL} + x_t^{PL} + \eta^v x_t^{VL} + \eta^b x_t^{BL} = L_t, \tag{1}$$

$$x_t^{EL} + x_t^{EP} + x_t^{EV} + x_t^{EB} = E_t, \tag{2}$$

$$\eta^b x_t^{BV} + x_t^{EV} + x_t^{PV} \leq \min\left(\frac{V^C - V_t^{soc}}{\eta^v}, \delta^v\right), \tag{3}$$

$$x_t^{VL} + x_t^{VB} \leq \min(V_t^{soc}, \delta^v), \tag{4}$$

$$\eta^v x_t^{VB} + x_t^{EB} + x_t^{PB} \leq \min\left(\frac{B^C - B_t}{\eta^b}, \delta^b\right), \tag{5}$$

$$x_t^{BL} + x_t^{BV} \leq \min\left(B_t, \delta^b\right), \tag{6}$$

$$V_t^{ttr} \leq K y_t^V, \tag{7}$$

$$1 - V_t^{ttr} \leq K(1 - y_t^V), \tag{8}$$

$$y_t^M \leq K(1 - y_t^V), \tag{9}$$

$$M_t \leq V_t^{soc} + K(1 - y_t^M), \tag{10}$$

$$x_t^{EV}, x_t^{PV}, x_t^{BV}, x_t^{VL}, x_t^{VB} \leq K(1 - y_t^V)(1 - y_t^M), \tag{11}$$

$$x_t^{EL}, x_t^{EB}, x_t^{EV}, x_t^{EP}, x_t^{PL}, x_t^{PB}, x_t^{PV}, x_t^{VL}, x_t^{VB}, x_t^{BL}, x_t^{BV} \geq 0, \tag{12}$$

$$y_t^V, y_t^M \epsilon \{0,1\}. \tag{13}$$

where y_t^V and y_t^M are binary variables indicating whether or not the e-vehicle is on-site at time t and whether or not the e-vehicle departs for a trip at time t, respectively. We denote the parameters of the stationary battery storage as B^C (maximum capacity), η^b ((dis-)charge efficiency) and δ^b ((dis-)charge rate). Likewise, the e-vehicle's maximum storage capacity, (dis-)charge efficiency and rate are denoted as V^C, η^v, and δ^v, respectively. K is a very large number that is required for computational reasons.

The decision about energy flows create costs $C(S_t, x_t)$ at each point in time. These costs are the sum of cost for buying energy from the market and mobility demand dissatisfaction costs, minus earnings from selling energy to the market:

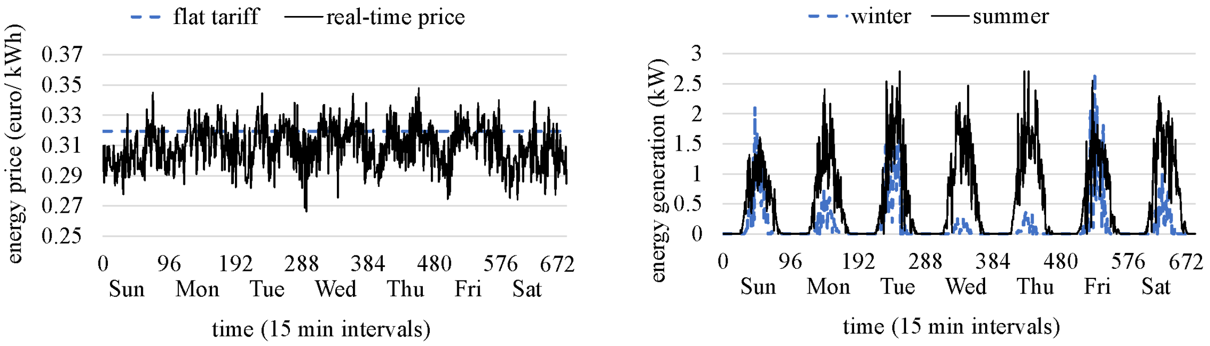
$$C(S_t, x_t) = P_t(x_t^{PB} + x_t^{PL} + x_t^{PV}) + \alpha M_t(1 - y_t^M) - P^E x_t^{EP},$$

where P^E is the fixed feed-in compensation per kWh, and α is a penalty fee for mobility demand dissatisfaction. Note that in our experiments mobility demand dissatisfaction is impossible due to the assumptions of a very large penalty fee and day-ahead knowledge of transportation demand, which is a common assumption in such services (see, e.g., Sabillon et al. (2018), Wu et al. (2017)).

In Section 3.3, we provide the experimental setup of our simulation study, and show how we generate in our simulation model the exogeneous influences on energy price (P_t), residential load (L_t), residential energy generation (E_t), and mobility demand (M_t).

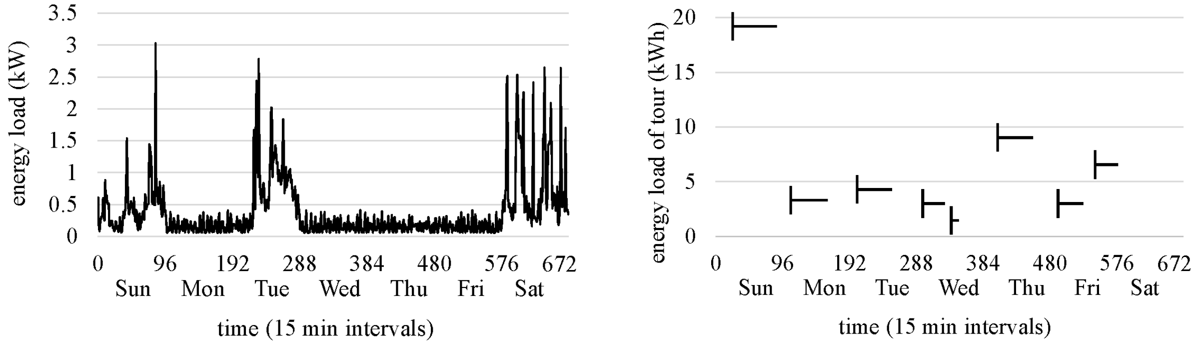
3.3 Experimental Setup

Alongside knowledge in the fields of service science and service operations research knowledge about the energy market, solar generation, residential energy load and residential mobility demand is required in order to derive appropriate assumptions regarding the experimental setup and to adequately simulate exogeneous influences. In the following we describe the experimental setup and present the methods used for simulating all four exogeneous influences. Figure 5 illustrates example sample paths for energy prices (Fig. 5a), energy generation (Fig. 5b), energy load (Fig. 5c), and transportation demand (Fig. 5d).



a) Energy purchase prices.

b) Solar energy generation (3kWp).



c) Residential energy load.

d) Residential transportation demand.

Figure 5. Example sample paths of simulated data for the four exogeneous influences.

We analyze service orchestration for a real-time energy trading service with a residential prosumer owning an e-vehicle, a solar array, and a stationary storage. The STP as service orchestrator can generate trading arbitrage by interacting with the energy market. We assume that the STP can sell excess solar energy to the market for a fixed feed-in compensation (P^E) of 7.14 ¢ per kWh (Federal Network Agency of Germany, 2021). Further, we assume that the STP has access to a real-time pricing tariff that depends on the current energy price at the European Power Exchange (EPEX) market. Similar real-time tariffs are already promoted to private consumers (see, e.g., https://www.awattar.de/tariffs/hourly). In Germany, the energy price consists of three main components: the price of the acquisition and sale, the fees for using the main grid, and the state-imposed components such as taxes, levies, and surcharges. The fix costs accumulate to approximately 24.19 ¢ per kWh (Federal Ministry of Economics and Technology of Germany, 2021). The energy purchase price at time t is:

$$P_t = 1.19(24.19 + P_t^{EPEX}),$$

where P_t^{EPEX} is the energy price at the EPEX market at time t, and where 1.19 represent the value added tax. In order to measure energy cost savings, we compare the costs resulting with the real-time energy trading service with energy costs that would occur if the prosumer only has access to a static benchmark electricity price. We set this benchmark price to 31.94 ¢ per kWh which represent the average energy price in Germany in 2020 (Federal Statistical Office of Germany, 2020). We use the simulation model presented in Meisel and Merfeld (2020) for deriving the quarter-hourly intraday spot prices of the EPEX market. The model is able to capture daily, weekly and seasonal patterns by using the TBATS

(Trigonometric seasonality, Box-Cox transformation, ARMA errors, Trend and Seasonal components) method proposed by De Livera et al. (2011). Figure 5a illustrates the model output by example of simulated real-time energy prices for a week in the summer season, and contrasts these prices with the benchmark price. It can be observed, that while real-time energy prices are typically lower than the benchmark flat tariff, the difference is less than 5 ¢ per kWh, and real-time prices are occasionally higher than the benchmark flat tariff.

The STP equips the EVP's house with a bidirectional charging station with an instantaneous (dis-)charge rate of 11kW. The bidirectional charging station can be used to charge the e-vehicle's battery and to retrieve energy from the battery in order to satisfy residential energy load or in order to be stored in a stationary storage unit. As (dis-)charging is associated with losses (Apostolaki-Iosifidou et al., 2017), we assume a (dis-)charging efficiency of 90 % for both the electric vehicle. We assume that the STP can equip the EVP with a stationary battery with battery capacities ranging from 1 to 10 kWh. We base the remaining battery specifications on the current model of the Tesla Powerwall, i.e., we assume a (dis-)charging efficiency of 90 % and (dis-)charge rate of 5 (Tesla, 2021). The STP can also provide a solar array consisting of 1 to 10 solar modules with 1 kWp each. For simulating solar energy generation, we use the solar model presented in (Meisel and Merfeld, 2020) which reflects both main influences on solar energy output, i.e., the typical daily pattern, which is depending on both the season of the year, as well as general weather situation of the current day (Mellit et al., 2014; Antonanzas et al., 2016). Figure 5b displays an exemplary sample path of residential energy generation for a summer and a winter week with a solar array of 3 kWp. The figure shows that energy generation follows a daily pattern, differs from day to day, and depends on the season of the year.

The EVP contributes to the service with the residential energy load, with a 50 kWh e-vehicle, and with the demand to use this vehicle for transportation. We assume that the EVP lives in the suburbs, works full-time and uses the electric vehicle for the daily 10 km commute (which correspond to the average commute in Germany (Dauth and Haller, 2018)). We further assume that the EVP is living in a four person household including two children. We rely on the activity-based models provided by the tool actiTopp (Hilgert et al., 2017) for deriving mobility demands, and use the publicly available implementation (Keirstead, 2014) of the model by Richardson et al. (2010) to generate weekly residential loads depending on activities of household members induced by the seasons of the year. By example of a summer season, Figure 5c and Figure 5d illustrate the prosumer's residential energy load and mobility demand over the course of one exemplary week, respectively. Figure 5c shows that residential energy load varies throughout the day with occasional load spikes of high consumption. In Figure 5d, vertical lines indicate the departure times of tours and horizontal lines indicate the energy load of that tour as well as it's duration. The figure illustrates that the model generates several trips per week with different durations and energy loads.

3.4 Financial and Ecological Value of a Real-Time Energy Trading Service

In this section, we reveal the influence the service orchestrator's design decisions regarding the sizing of residential energy storage and generation have on the financial and on the ecological value of a real-time energy trading service for a prosumer owning an e-vehicle. We vary the size of the solar array between 0 and 10 kWp (i.e., 0-10 solar modules of 1 kWp), and the size of the stationary battery between 0 and 10 kWh (i.e., 0-10 storage modules of 1 kWh). We simulate over the course of one week with $T = 672$ time intervals (of 15 minutes), and calculate the service performance values with a total of $N = 3{,}000$ simulated weeks (in equal shares weeks of summer, of winter and of transitional season). We estimate the expected financial value and the expected degree of self-sufficiency by simulating sample paths of mobility demand exogeneous processes and by then calculating the sample averages:

$$\textbf{annual energy cost savings} = \frac{52}{N}\sum_{n=1}^{N}\sum_{t=0}^{T}(P^f(L_t + \frac{M_t}{\eta^v}) - C(S_t, X_t^\pi(S_t)),$$

where P^f is the benchmark energy tariff of the household, and

$$\textbf{degree of self-sufficiency} = 1 - \frac{1}{N}\sum_{n=1}^{N}\frac{\sum_{t=0}^{T}(x_t^{PL} + x_t^{PV} + x_t^{PB})}{\sum_{t=0}^{T}(L_t + \frac{M_t}{\eta^v})}.$$

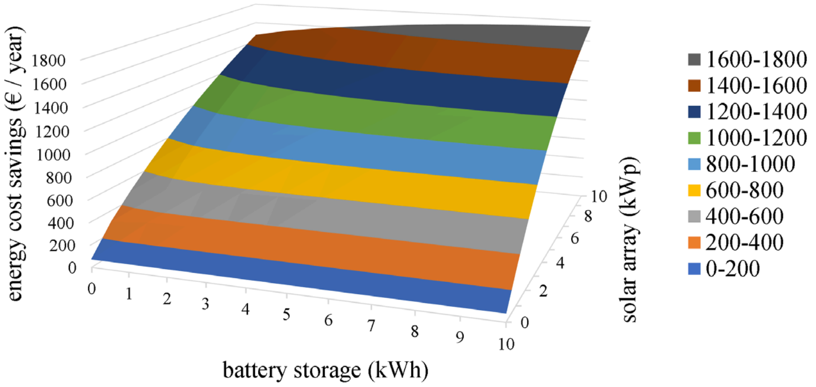
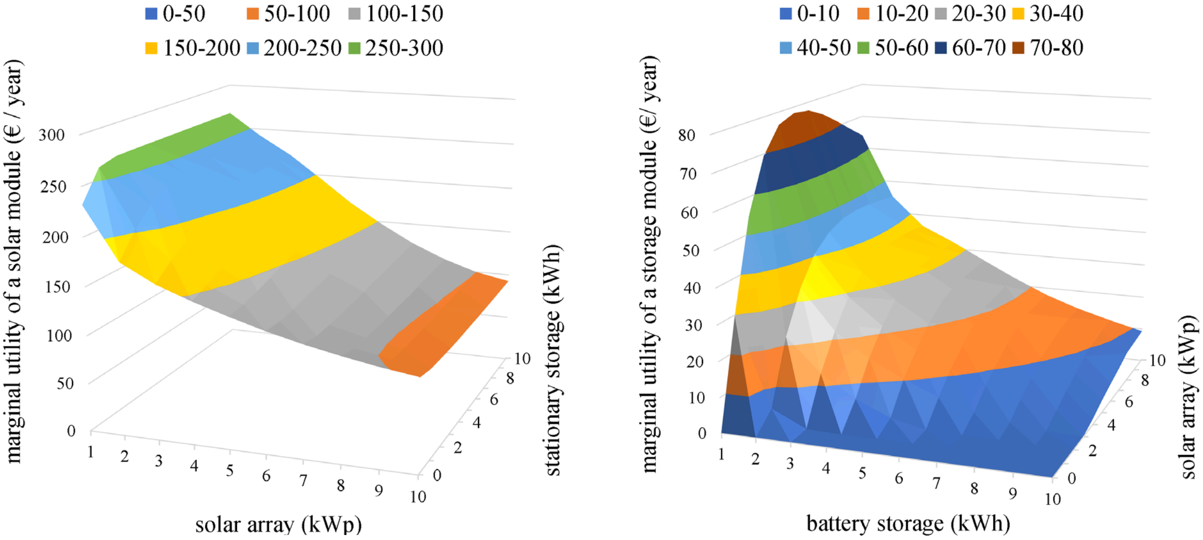


Figure 6. Annual energy cost savings with a real-time energy trading service depending on the stationary storage and solar generation capacity.

Figure 6 illustrates the annual energy cost savings of the proposed service depending on the size of the stationary battery (0 - 10 kWh) as well as on the size of the solar array (0 - 10 kWp). The energy cost savings range from 72 € (no storage modules, no solar modules) to 1747 € (10 storage modules and 10 solar modules). The service is able to create a moderate amount of financial value without any investment in storage or solar as the STP is able to profit from the price differences between real-time energy prices and benchmark tariff. Although the financial value of a full-size battery and a full-size solar array setup is significant, the service orchestrator has to account for technology setup and maintenance cost. Thus, the service is only financially worthwhile if the annual costs of the solar array and the stationary battery are lower than the calculated energy cost savings.

The energy costs savings of a service without any energy generation are independent of stationary battery size. This indicates that using the stationary battery as energy buffer between the energy market and own consumption is not worthwhile. This can be explained by the facts that (1) energy transactions with the stationary battery are subject to losses due to the battery's (dis-)charging efficiency, and that (2) the difference between the dynamic real-time energy price and the benchmark flat tariff is not sufficient to account for these losses. However, if solar generation is included in the service, the financial gain increases with energy storage. For example, a service with a 10 kWp solar array is able to increase the financial value by 280 € if a 10 kWh stationary battery is provided instead of none.



a) Marginal utility of solar modules. *b) Marginal utility of storage modules.*

Figure 7. Marginal utility of solar and storage modules in a real-time energy trading service.

Figures 7a and 7b illustrate the marginal utility of solar modules and the marginal utility of storage modules, respectively. Note, that for illustrative reasons the x-axis and y-axis are swapped in Figure 7b. Figure 7a shows that the marginal utility of a solar module monotonically decreases with the number of solar modules. The decreasing utility can be explained by the fact that the highest value of the generated energy can be gained from self-consumption due to the rather low feed-in compensation of 7.14 ¢/ kWh. However, even the utility of the 10th solar module is 90 €. This is not surprising as the solar module generates energy 'for free'. The 10th solar module is only financially beneficial if it costs less than 90 € per year. Figure 7a further shows the impact of stationary battery capacity on the marginal utility of solar modules. The marginal utility of the first solar module is highest for a storage capacity of more than 3 kWh (267 €), and lowest without a stationary battery (232 €). This also reflects the fact that self-consumption should be financially preferred over selling energy to the market.

Figure 7b shows that the marginal utility of storage modules monotonically decreases with storage capacity. The marginal utility of storage modules critically depends on the number of solar modules in the service. Without any energy generation the marginal value of storage is 0 € (due to the combined effect of (dis-)charging efficiency and price gap between real-time prices and flat tariff). The marginal utility of the first energy storage module is highest (78 €) for a solar array of 5 kWp. The reason for the lower marginal value for larger solar arrays is that the energy storage has a maximum charge rate of 5 kW. Hence, if the solar array produces more than 5 kW the excess energy that cannot be consumed directly or stored has to be sold to the energy market. Moreover, we observe that the threshold at which the marginal value of energy storage modules is zero depends on the generation capacity: 4th storage module (with 1 kWp solar), 7th storage module (with 2 kWp solar) and 10th storage module (with 3 kWp solar). These thresholds mark the battery capacities after which an additional storage module does not increase self-consumption.

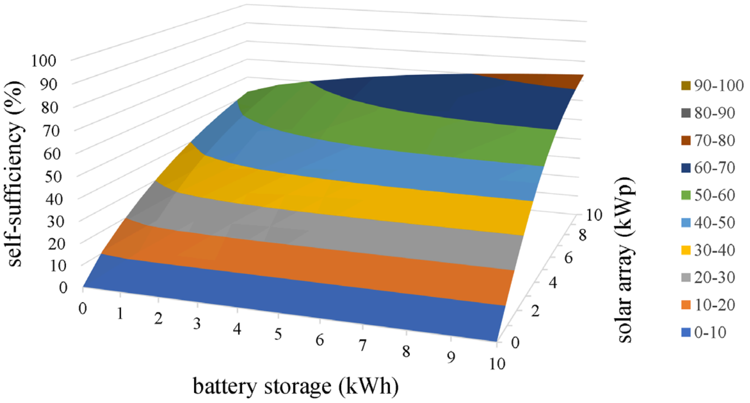
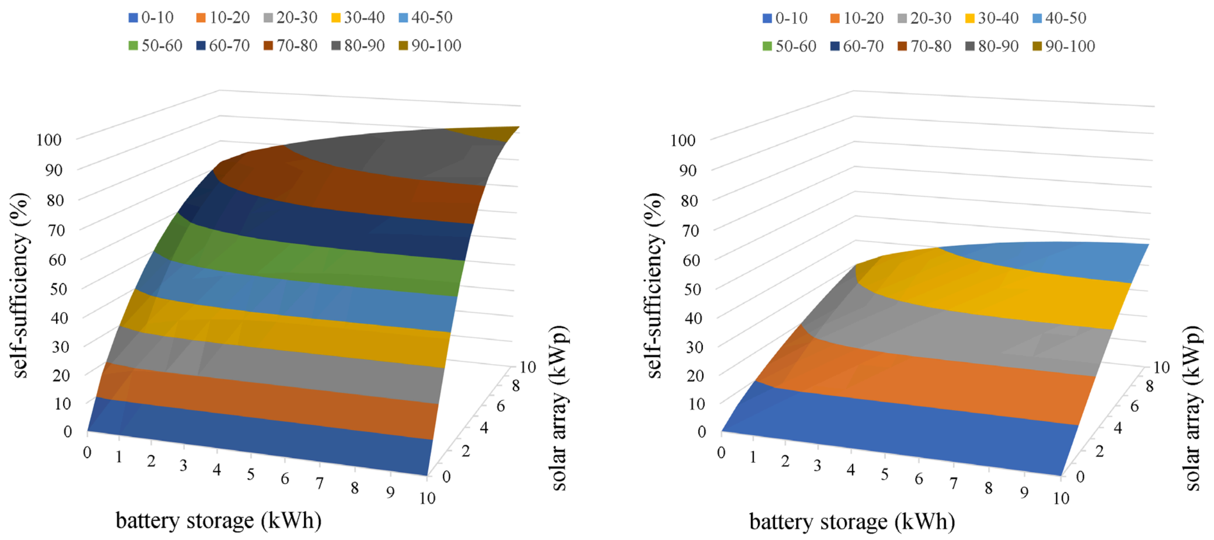


Figure 8. Degree of self-sufficiency in a real-time energy trading service depending on energy storage and solar generation capacity.

Figure 8 illustrates the degree of self-sufficiency in a real-time energy trading service with respect to the stationary battery and the solar generation capacity. The figure shows that for services with solar generation the degree of self-sufficiency increases monotonically with the number of solar modules as well as with the number of storage modules. The impact of energy storage size is more significant the more solar modules are used. The threshold of 50 % self-sufficiency is reached at 10 kWp (without any energy storage), at 7 kWp (1-2 storage modules), at 6 kWp (3-5 storage modules) and at 5 kWp (more than 6 storage modules). The maximum self-sufficiency of 73 % is reached with a 10 kWp solar array and a 10 kWh battery. Our preliminarily experiments have shown that the degree of self-sufficiency cannot be increased significantly after this threshold. One reason is the limited charge rate of the stationary battery, and another is the energy generation dependency on the seasons of the year.



a) Summer season. *b) Winter season.*

Figure 9. Degree of self-sufficiency in a real-time energy trading service depending on energy storage and solar generation capacity in the summer and the winter season.

Figure 9a and 9b illustrate the degree of self-sufficiency that is reached in the summer season and in the winter season, respectively. The figures show that while in summer the degree of self-sufficiency can reach 92 %, the degree of self-sufficiency is less than 48 % in the winter. While adding additional solar modules might increase the degree of self-sufficiency slightly, it is financially not worthwhile as the additional generated energy in the summer cannot be consumed but has to be sold to the energy market.

4 Discussion

The proposed transdisciplinary approach to service orchestration combines knowledge of service science and service operations research. Service science is used in order to adequately describe real-time energy trading services as emerging new services in the energy markets that co-create value with residential prosumers. The description emphasizes that residential households primarily become prosumers in order to create financial impact, while recognizing the eco-consciousness of individuals. The technology setup decisions (sizing of solar array and stationary storage unit) are identified to play a critical role in such services. A simulation study (that relies on a service operations research model of a dynamic decision process) is performed in order to assess the impact of these setup decisions on the service's financial and ecological value. Thereby, we apply existing service operations research methods to a new application. Furthermore, the proposed approach uses knowledge of other disciplines, such as engineering and statistics, in order to derive appropriate assumptions regarding the service layout (e.g., (dis-)charging technology), and in order to be able to simulate energy market prices, small scale solar energy generation, residential energy load, and residential transportation demand.

Our empirical results reveal that real-time energy trading services can generate significant financial value as well as a high degree of self-sufficiency for the prosumer's energy system. The results indicate that such smart grid prosumer services can represent valuable business opportunities for potential service orchestrators, and that the financial value as well as the degree of self-sufficiency critically depend on the size of solar energy generation and stationary battery storage. The insights gained by this analysis can guide service orchestrators in choosing the technological setup in order to satisfy prosumer needs and maximize the co-created value. The service orchestrator has to take the interdependence of the decision variables (solar and storage size) into account when making the service setup decision. The orchestrator should consider the expected energy cost savings when making the investment decision about the technological setup. Moreover, the orchestrator should discuss the implications service setup has on both aspects of service value (financial and ecological) with the EVP. Thereby, the orchestrator is able to base the final service setup decision on the EVP's preferences.

However, in order to provide a comprehensive guideline on how to realize smart grid prosumer services, even more transdisciplinary research is required. For example, the prosumer's monetary valuation of the degree of self-sufficiency should be studied. Similar studies have been performed in order to assess energy consumers' willingness to pay for green energy tariffs (Dutta and Mitra, 2017). The service might also be extended by including the option of time shifting residential energy load (Friis and Haunstrup Christensen, 2016), and by accounting for prosumer's monetary valuation of convenience and comfort of energy use. Moreover, the service should be studied by enhancing the simulation model by advanced stochastic processes that are able to represent different degrees of mobility demand uncertainty (Merfeld and Meisel, 2022). Although information sharing can have positive ecological impact for green information systems (Meacham et al., 2013), prosumers might have privacy concerns regarding information sharing. Therefore, research is needed for assessing the prosumers' privacy requirements for the ICT used in smart grid services. The used ICT has to account for the prosumer's requirements by, e.g., implementing privacy-by-design (Gimpel et al. 2018; Schaar, 2010) mechanisms. As smart grid prosumer services have positive grid effects, the option of governmental subsidies should also be included into service setup decisions. These subsidies might include direct fiscal purchase incentives, as well as financial incentives for increasing the self-consumption of renewable energy (Zakeri et al., 2021). The service itself could also be extended by studying peer-to-peer (P2P) energy trading (Guo et al., 2021) or trading at day-ahead markets (Finnah et al., 2022).

Our discussion shows that the proposed approach provides valuable insights for practitioners that act as service orchestrators. However, we also reveal that an even higher degree of transdisciplinary research on the topic of service orchestration is needed in order to fully accommodate real-world applications.

5 Conclusions

In this work, we discuss the current changes in the energy market from a service-dominant logic perspective. We identify the need for service orchestration for services in the energy market, and highlight the potential of transdisciplinary research on this topic by revealing synergies between service science and service operations research. We take a transdisciplinary approach to analyzing the financial and ecological value of service orchestration for the example of a real-time energy trading service with a prosumer owning an electric vehicle. We perform a simulation study in order to assess the impact that the decisions on the dimensions of energy storage and energy generation units have on both the financial value of the service and the degree of self-sufficiency of the prosumer household. Furthermore, we discuss the proposed approach to supporting service orchestration of smart grid prosumer services, and highlight the need for an even larger degree of transdisciplinary research.

Our work provides insights on the design and operation of real-time energy trading services, that are valuable for both researchers and practitioners acting as service orchestrators. From a research perspective, many avenues for future work on leveraging the integration of operations research and service science exist. On the one hand, service operation researchers can build upon our simulation study, e.g., for analyzing the impact of changing technological features such as the e-vehicle charge rate, for studying the impact of different energy price tariffs, for studying other types of prosumers, or for proposing advanced policies for solving the underlying dynamic decision process. On the other hand, service science researchers can further deepen the understanding of service orchestration for prosumers in the smart grid from a methodological standpoint, e.g., by studying the prosumers' willingness to participate and the prosumers' valuation of self-sufficient renewable energy supply. Our work shows that transdisciplinary research on service orchestration can support the transition towards a sustainable and efficient energy system.

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