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Allocative and strategic effects of privacy enhancement in smart grids

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ABSTRACT

Local energy markets are a promising approach for automatic and efficient matching of renewable energy with household demand in smart grids. Therefore, such markets can help to improve power system reliability and at the same reduce emissions. However, to participate in such markets, customers need to disclose private consumption data. A number of studies show that such data records may reveal a broad range of personal, sensitive information on the inhabitants. Privacy-enhancement mechanisms can be applied to preserve the privacy of individuals to modify the data reported to the market. Yet, these mechanisms can lower allocative efficiency and alter theoretical properties of the market mechanism.

In this paper, we characterize both theoretically and numerically the effect of privacy mechanisms applied in a local energy market scenario. Our model considers demand side flexibility as well as energy storage systems. Furthermore, we allow for a free specification of the desired privacy enhancement level. We show that under certain natural assumptions market mechanisms retain in-expectation incentive compatibility despite the presence of privacy enhancement. Our numerical analysis based on real-world data shows that the welfare impact of privacy enhancement mechanisms is limited. Furthermore, energy storage can mitigate this efficiency loss to a large extent.

1. Introduction

Historically, the electricity grid is tailored to a centralized generation structure. At its core, there are few large power plants generating electricity for a large number of consumers [1]. However, reducing the CO_2 emissions of the energy production requires the integration of renewable sources, such as photovoltaic sites and micro combined heat and power plants. These sources are volatile and distributed. Compared to a large power plant, each of them produces only a small amount of power and cannot be controlled centrally. Due to their variability, integration of renewables remains a big challenge on today's power system.

Smart grids [2], the ICT-enabled electricity networks of the future, facilitate new operational paradigms [3,4]. A case in point is the establishment of local energy markets. These are a means for matching regional energy demand and renewable supply [5,6]. More 'local' (i.e. in spatial proximity of generation) energy consumption can help to improve integration of renewables and minimize transmission losses [7]. In order to work efficiently, local energy markets rely on truthful power-consumption information revealed by the participants, e.g., private households. In such

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markets, customers cover their energy needs by bidding for the required energy amounts over short time intervals. Consequently, a customer's consumption behavior is encapsulated in these bids. Yet a number of studies show that such fine-grained power consumption data can reveal significant amounts of private information [8,9], including wealth, daily routines and household size. Consequently, electronic market systems in smart grids should strive to preserve privacy properties [10]. Privacy enhancement methods distort sensitive values, e.g., energy consumption levels. By doing so, they are able to retain a certain level of privacy despite personal data being revealed to the market.

However, distorted bids are likely to induce less efficient allocations. Depending on the nature of the distortion, more or less energy than actually needed may be allocated. Hence, privacy enhancement may lead to additional costs for consumers. In this paper, we quantify these privacy costs in a local energy market with demand side flexibility and storage. Due to a large number of possible influence factors (e.g., customer privacy preferences, demand side flexibility as well as supply and demand patterns), it is difficult to fully characterize this welfare loss in a general fashion. For instance, realistic supply and demand patterns are complex random processes, and the privacy enhancement methods applied add complexity as well. A general model covering all these details will lack expressiveness.

To understand the relationship of privacy enhancement and local energy markets, we model a smart grid marketplace with privacy enhancement methods together with a customer demand model. We characterize customer-bidding behavior and determine formal characteristics of the interplay between components of our model. This includes the definition of general properties of privacy enhancement methods. Furthermore, we show that a privacy-aware auction retains incentive compatibility with respect to valuations if the privacy enhancement method is monotonic and marginal utility is independent of the demand level.

Subsequently, we instantiate a numerical evaluation using empirical load and generation data. By means of simulations we quantify the costs of privacy enhancement. Specifically, we assess the economic effect of varying numbers and types of generators, demand properties and storage endowments. The experiments illustrate the relationship between distortion level and welfare loss incurred. Further, we can quantify the positive effect of storage in the presence of privacy enhancement methods. Small scale electricity storage can reduce privacy-induced welfare loss by almost two-thirds. In summary, this paper explores the economic effects of different privacy levels. As such, it offers a concrete application scenario to evaluate the actual impact of recent privacy enhancement methods.

The remainder of this paper is structured as follows. In Section 2 we provide an overview of related research on smart grids and privacy enhancement techniques. The market model is described in Section 3. Subsequently, we present theoretical results derived from the model in Section 4. The following Sections 5 and 6 introduce the parametrization and evaluation of a simulation-based instantiation of the model. Section 7 concludes.

2. Related work

2.1. Privacy in smart grids

Renewable sources for electricity generation are distributed and volatile by nature. The efficient utilization of such sources is an important part of the smart grid vision. Local energy markets efficiently coordinate decentralized generation of electricity [5]. Generators of renewable energy as well as consumers participate in such local markets and trade energy over short time intervals, e.g., 30 min or less. Transparency obligations like the EUC 543/2013 mandate the publication of comprehensive market data. Market transparency is key to ensure market liquidity and hence market efficiency [11,12].

Yet, fine-grained power consumption records contain sensitive personal information [9]. For example, appliances have a characteristic power consumption pattern over time called the load signature [8]. This facilitates the detection of appliances [13] or even the currently selected TV channel [14]. Removing personal identifiers like name or address is not sufficient, since the data itself is identifying [15]. Consequently, power consumption data is subject to privacy legislation, e.g., European Directive 95/46/EC.

To mediate between the diametric goals of market transparency and customer privacy-protection, local energy markets need to incorporate appropriate privacy-enhancement techniques. To this end, Buchmann et al. [16] investigate the impact of privacy enhancing methods on the expenses of individuals and as a measure for the impact on data utility. While their work is related to our research, their approach is limited to simple strategies, bidding exactly one limit price which does not take different valuations of energy into account. In addition, they do not account for demand-side energy storage and do not provide any formal characterization of the relationship between privacy enhancement and incentive compatibility.

In contrast, Kalogridis et al. [17] as well as Varodayan and Khist [18] both rely on the use of energy storage for privacy protection. In both cases a stationary storage is used to completely mask the load signatures of the underlying household appliances. However, these results are mainly anecdotal and rely on an arbitrarily large storage system. We follow the general idea by investigating the economic interplay between privacy enhancement and a fixed storage system with limited capacity. This allows us to compare the previously orthogonal dimensions of storage costs and privacy.

2.2. Privacy enhancement techniques

There is a broad variety of approaches to protect the privacy of individuals in a data set, see [19] for a survey. In general, one can distinguish between approaches facilitating individual privacy preferences and approaches with a common privacy parameter for the entire data set. In the local energy market scenario, individual preferences let each household decide the degree of distortion and privacy independently of others.

The well-known k-Anonymity principle [20] is an instance of the latter case, jointly modifying the data of groups of