A Mechanism Design for a Sustainable Integration of Renewable Energy

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***Abstract*—Renewable energy is often not produced at times of high demand. With a high penetration of renewables this may result in an overloaded grid, increased losses and possibly also curtailment. While time-based pricing of electrical energy may mitigate the problem at a low penetration level, this article shows that this pricing approach may even increase the problem in future scenarios wherein renewable energy becomes a dominant factor.**

This article proposes a nonlinear incentive scheme that stimulates investments in renewables and rewards coordination of supply and demand. In this scheme, billing is based on system costs (e.g., energy availability and grid load) and not based on net annual energy consumption.

The proposed scheme is combined with a mechanism that encourages cooperation between customers to further decrease system costs and increase sustainable energy use. The mechanism has a game theoretic foundation to ensure truthfulness. The evaluation contains a simulation study, which details the effect on a low voltage grid, and the impact on losses and voltage.

***Index Terms*—Demand-side management, decentralized energy management, game theory, mechanism design, nonlinear optimization**

I. Introduction

To ACHIEVE a sustainable energy supply, several countries introduced subsidies for photovoltaic (PV) panels and for energy neutral houses in general. In some countries, e.g., the Netherlands, customers are mainly billed for their annual energy demand, which implies that customers (to some extent with tax exemption [1]) can deduct produced energy from the consumed energy. This incentive does not take into account that a lot of energy is produced when domestic demand is low and used during hours with hardly any local renewable production. By this, the electricity grid is implicitly considered as a "battery". While this works when penetration of PV is low (i.e., during the PV peaks there is often still enough demand), in the German situation this already leads to problems, where in some parts of the grid the local production sometimes far exceeds the demand [2]. This leads to overloaded infrastructure, curtailment of abundant PV energy and higher transportation losses. A main reason for this is that customers receive an incentive that is not good for the overall system.

Since the current system rewards are based on the annual energy production, it is optimal for a customer to maximize energy production independent of time. To achieve this (in western Europe), customers face their PV panels south to maximize the energy produced, which results in a simultaneous PV peak around noon. However at these times domestic consumption is relatively low.

Another consequence of incentives that stimulate (annual) self-consumption of electrical energy is that customers purchase electric vehicles (EVs). However typically, EV owners in western Europe start charging their car around 18:00 [3] on top of the normal consumption peak, which does not coincide with the PV production peak.

A commonly suggested counter measure is some form of time-based pricing (e.g., time-of-use (ToU) pricing, critical peak pricing or real-time pricing). But studies show that this may result in load synchronization [4] and thereby it may only shift the load peak [5]. This effect will even increase when smart appliances and home energy management systems (HEMS) are used. Since automated systems then make decisions that are cheapest for the individual customer, strong reactions to the incentive can be expected. For example, (every) such system will start charging an EV at maximum power when a cheap time interval begins, which results in an even stronger time synchronization with high ramp rates.

To take the reactions to such incentives into account, time-based pricing should be studied from the perspective of *optimization* and *game theory*. This article argues that time-based pricing and kWh-based billing in general do not lead to a system optimal behavior, and may even lead to a situation where the problem only increases when there is a lot of flexibility controlled by HEMS.

Instead, this article takes a radically different approach to domestic incentive schemes and argues that (nonlinear) system costs such as availability of energy, grid overloading, self-consumption, customer satisfaction and predictability of the energy supply must be considered and we show that this can be achieved in a way that satisfies all stakeholders. In this approach game-theoretic aspects are used to stimulate investments and behavior that is good for the system as a whole (i.e., for the majority of stakeholders). Based on their results in [1], Dóci and Vasileiadou suggest that "[...] incentives addressing mainly the gain and normative motivations could be the most effective triggers, if we want to support the spread of renewable energy communities.", which is exactly the type of long term incentive that we propose in this research.

In the next section we briefly describe how this can be achieved and in Section III some conclusions are drawn.

II. Approach

To derive an incentive scheme with a direct correspondence to the system costs, we start with a model of the grid. Each customer either increases or decreases the load at several grid segments, and the proposed incentive scheme matches the costs added/reduced for the considered grid segments. For this a quadratic cost term is used, since this assigns higher costs to higher loads and favors the decrease of losses [6]. Since losses result in heating of grid components, this also results in a decrease of the aging of these grid components (e.g., transformers [7]). At the generation side, costs for thermal generators are also quadratic functions [8]. Note, that quadratic functions are easier to minimize than many other nonlinear functions (e.g., absolute values) that may equally well be used to reduce some cost components such as self-consumption, etc.

To be able to bill(/reward) customers for the load they add(/deduct) to(/from) existing peaks, loads from other customers on shared grid segments need to be taken into account. This suggests that in the future smart grid such aggregate data needs to be shared for (near) optimal decision making, as was also concluded by, e.g., [8]. To improve the situation further, a demand-side management scheme wherein customers cooperate to further decrease the costs on shared grid segments (e.g., a feeder) is desired. We show that this problem is strongly NP-hard for multiple devices, which implies that an efficient solution to this problem is out of reach and some heuristic is needed. Instead of solving the problem centrally, we propose a decentralized heuristic with a centralized coordinator between the customers. Based on derived requirements and rules for the mechanism, we are able to derive a unique mechanism and coordination algorithm. This mechanism is based on techniques from game theory and ensures truthfulness. Whereas a well accepted state-of-the-art research [8], which combines DSM with game theory, does not work for energy neutral houses since the billing is proportional to the daily consumption (Eqn. (22) in [8]), our approach does support this scenario and even stimulates system optimal behavior when investments in, e.g., renewables are made.

The proposed methodology is evaluated using two different cases. The first case compares both (linear) time-based pricing and our proposed mechanism (without coordination of collaboration) and it determines their influence on investments in renewable energy. Our proposed mechanism supports customers to place PV panels in an orientation that is better for the system, even when the resulting annually produced energy is slightly lower, while in the linear pricing scenario the customers may do the exact opposite. We also study the influence of both mechanism on the installation decisions and the resulting availability of renewable energy and power quality.

The second case looks at the coordination and demand-side management aspects of this research. Since the coordination builds on heuristics, we study what can be achieved in a realistic practical setting. Different levels of PV and smart appliances (e.g., EVs) are considered, and load flow calculations are used to study the impact on an existing dutch LV grid. Details on the influence of the mechanism on the losses, power quality and self-consumption are given.

III. Conclusions

Current incentive schemes only work when the penetration of renewables is relatively low. For situations where renewable energy is dominant, we need new approaches. This article studies how such an incentive scheme can be designed and shows how demand-side management can complement the scheme.

The full article creates a model of relevant parts of the system (grid *and* energy supply), formulates requirements for an incentive scheme, and presents a new incentive scheme that fulfills these requirements. This scheme *does* motivate investments (e.g., in renewables) in a way that is sustainable for the whole system and for the energy supply in the long term. The evaluation studies the impact of our mechanism on different system aspects (e.g., self-consumption, level of curtailment, losses and power quality).

To complement the incentive scheme, a demand side management approach is derived to coordinate between domestic customers in order to decrease the system costs further. This study shows the impact of this demand-side management scheme (with and without active collaboration), indicates how rewards are allocated among participants, and presents the impact on the aforementioned system aspects. We observed that next to the targeted system costs, also the predictability of the energy demand of a group of houses improves significantly due to the proposed incentive. By this, also the cost of generation of non-renewable energy may be reduced.

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