THE IMPACT OF DISTRIBUTION GRID INJECTION LIMITS ON THE INVESTMENT STRATEGY OF PROSUMERS

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Overview

To accelerate the low-carbon transition and align energy sector CO_2 emissions with the challenging targets set by the Paris Agreement, countries are seeking a comprehensive uptake of renewable energy sources (RES) (IEA, 2017). Consequently, RES capacity has increased significantly, in parallel to noteworthy cost reductions (Luthander et al., 2015). The expansion in capacity of distributed photovoltaic (PV) systems has perturbed power systems' historical "one-way" model (de Oliveira e Silva et al., 2017). Large, variable injection quantities, both in energy and power, from roof-top PV systems to the distribution grid, are known to lead to voltage variations, negatively affect the grid's voltage regulators and considerably complicate grid balancing (Shivashankar et al., 2016). Since grid capacity is limited and upgrades can be costly, feed-in of excess power is typically prevented by PV inverters switching off during local overvoltage events. However, these switch-offs may entail significant opportunity costs to the solar panel owner (Ranaweera et al., 2016). The academic literature proposes to manage such issues using a combination of PV power injection limitations and energy storage systems (ESS). The work of Ranaweera et al. (2016), e.g., looks to maximise the daily economic benefits of a PV system coupled with battery energy storage while curtailing power injection to the grid. Other studies focus on how the presence of a PV grid injection cap promotes the attractiveness of local storage investment and self consumption (Williams et al., 2013; de Oliveria e Silva, 2017).

The primary aim of this work is to analyse the effects of power injection limitations, established by distribution grid operators, on prosumer behaviour and concomitant investment strategy, while taking into account storage as well as inverter constraints. The analysis is founded upon a case study of a simplified electricity system which seeks to emulate the Belgian setting. The system consists of several interacting agents: consumers, conventional generators, renewable generators, and the energy-only wholesale market operator. Each consumer has the ability to invest in both ESS and PV capacity, thus becoming a so-called prosumer with a limited freedom to withdraw as well as inject electricity to the low-voltage grid. The model, representing a non-cooperative game, yields a competitive equilibrium. In a second stage, the distribution system operator's (DSO) grid constraints and grid upgrade investment costs will be taken into account, as well as the option to invest in new centralised renewable and conventional generation capacity. As the levels of residential PV rise, this study makes a critical contribution to the literature by assessing the household-level economic benefits of PV systems coupled with ESS and injection limitations while reflecting the constraints of the distribution grid.

Methods

We study a non-cooperative game between the suppliers and consumers on a wholesale market. The suppliers include renewable and conventional generators while the consumers encompass industrial, commercial and residential demand. The equilibrium problem is formulated as a mixed complementarity problem (MCP). The energy only market functions as a go-between, connecting all players and ensuring clearing of the market by matching supply and demand. This implies that there is a single, perfectly competitive wholesale market to which residential consumers have direct access (no barriers to entry). Non-residential consumers of electricity are not explicitely modelled but their demand, assumed to be inelastic, is accounted for by the market operator. The prosumer decides how much electricity he generates, how much he withdraws/injects, how much capacity he installs for PV and storage, as well as how much he charges and discharges to his storage system. Considering all these decision variables, the overall aim of the prosumer is to optimize his investment and minimize his costs, i.e., his electricity bill. Conventional generators (comprising base,

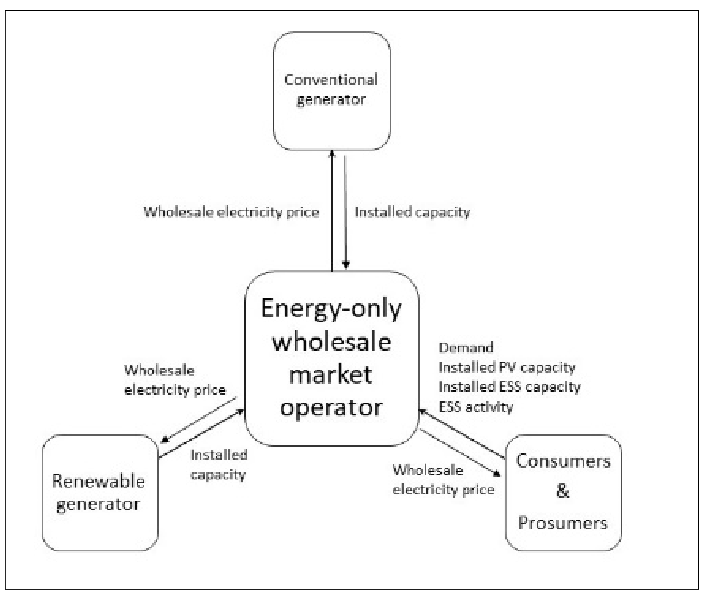

Figure 1: Agents in the non-cooperative game and their exchanged variables.

mid and peak load technologies) as well as renewable generators, decide upon how much electricity they generate and how much capacity to install. The aim of generators is to maximize profits and optimize any investments made. The option to invest in generation capacity is only considered in the second phase of the analysis, allowing separation of the short-term trends (i.e., investments made by consumers, which have short term lead times) and the long-term equilibrium.

Envisioned Results

Leveraging the model described above allows the exploration of different types of distribution grid injection limitations to evaluate which of these methods yields greatest maximization of social welfare. The research will look at the effects of constant PV-power injection limits, limits based on load and PV power generation profiles and time-dependent grid feed-in limits. The first case study will focus on constant PV-injection limits and analyse their effects over a year-long period. Several different household types, having unique electricity demand profiles, will be taken into account for both prosumers and consumers in order to capture potential variations in strategies. Varying ratios of prosumers to consumers will also be considered. Particularly, this case study will allow for a greater understanding of prosumer behaviour and how this key player is to extract greatest economic benefit from its investments under a distribution system injection limit. The model will provide detailed insight as to how injection limitations shape PV investment of prosumers, as clearly, one needs to strike a balance between augmented revenue made by installing larger PV systems and revenue loss from inability to inject PV-power into the distribution grid. Results will illustrate if the prosumer has greater incentive for self-consumption or greater gain from feeding in power. It is possible that the prosumer prefers a system of autarky, or perhaps, considering the cost of storage this may not be possible and he, instead, attains largest gains from installing only small storage systems. The case study will quantify how much ESS capacity the prosumer will invest in, if any, based on how much PV he installs. Furthermore, results will illustrate how the actions of prosumers affects consumers, a greater number of prosumers than consumers might negatively affect the latter in terms of cost shifts. Results will also allow the researcher to understand how well-being at aggregate level is affected by grid injection limits and who the dominant actors are.

Conclusions

Integrated PV systems around the world have, over the past few years, undergone rapid progress, drastically increasing PV penetration levels in the low voltage (LV) grid. However, the increased power injection from decentralised PV systems has raised several technical issues on the grid, these mainly pertain to voltage stability and reversed power flow patterns. In order to mitigate such complications, without needing to perform substantial grid upgrades, home energy management systems can couple PV panels with energy storage systems and be subject to grid injection limits (Ranaweera et al., 2016). The objective of this work is to analyse the interaction between prosumer decisions, grid injection limits and wholesale market exposure. This is done via a simplified electricity system, representing a single wholesale market and consisting of: prosumers as well as passive consumers, renewable generators and conventional generators. These actors play a non-cooperative game in which each player tries to optimize investments and minimize costs/maximize revenue. They are all linked together by the market clearing agent who ensures that supply and demand are matched at all time steps. Envisioned results include an in depth analysis of diverse injection limit strategies as well as yield extensive insight into prosumer behaviour and associated benefits. Results can also be used to illustrate the potential need for additional price signals from grid operators. Overall, this work lays the foundations for a comprehensive analysis of the welfare effects of grid injection limits.

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