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Who gets my flex? An evolutionary game theory analysis of flexibility market dynamics

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HIGHLIGHTS

- Competitive DSO compensation price ranges, differ on case by case basis.
- Low forecast error variability causes less efficient flexibility allocations.
- Equilibrium confidence intervals narrow as amount of flexibility providers increase.
- EGT is ideal for analyzing strategic choice dynamics of competing business cases.

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ABSTRACT

Maintaining a real time balance between energy consumption and production is challenging when faced with increasing penetration of Renewable Energy Sources (RES) because of the increased variability in generation output. Demand-Side Management (DSM) techniques address this issue by steering consumers' energy off-take, thereby enabling further penetration of RES. Present paper addresses the problem of overproduction from distribution grid connected wind generation. We present and analyze two business cases in the Belgian-European energy landscape for using upward consumption flexibility to deal with excessive wind power injection. We focus on the perspective of the flexibility providers and the strategic choice they face in choosing the business partner that maximizes their expected financial compensation. Evolutionary game theory is used to model this strategic choice and to provide a framework for quantifying realistic financial compensation bounds based on real world market and wind production data for multiple locations in Belgium. Results show that in a competitive market setting compensation payments for flexible power consumption are higher when dealing with higher wind forecast error levels. These results validate the economic benefits of having accurate wind production forecasts.

1. Introduction

The ability to monitor and manage power delivery in real-time has been defined as one of the key components that distinguishes smart grids from conventional power grids [1]. This component is crucial in supporting the adoption of more secure, sustainable and innovative practices in energy consumption and production. To this effect, the European Commission has put forth the 20-20-20 objectives [2] causing a gradual increase of installed Renewable Energy Sources (RES) capacity in Europe [3]. This increase in RES penetration has also lead to an increase in energy production variability because of the less predictable nature of renewables such as wind and solar.

Energy production variability combined with a growing energy demand, partially caused by the increased adoption of electric vehicles (EVs) and plug-in hybrids, has made it more challenging for system operators to maintain the consumption-production balance. Maintaining this balance is paramount to the safe and stable operation of power systems in general. In order to achieve this, flexibility is a necessity both on the consumption and on the production side.

Although wind production resources have successfully participated in ancillary service programs [4], these resources are still often subject to various incentive and support mechanisms that impede their entry into ancillary service markets. In the Belgium energy domain, wind energy production is supported by green certificates and priority

Abbreviations: ANM, Active Network Management; BRP, Balance Responsible Party; DLR, Dynamic Line Rating; DSM, Demand-Side Management; DSO, Distribution Grid Operator; EGT, Evolutionary Game Theory; ESS, Evolutionary Stable Strategy; ODE, Ordinary Differential Equation; RES, Renewable Energy Sources; TSO, Transmission System Operator

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dispatch. Energy produced under priority dispatch should at all times be prioritized over other energy sources when satisfying customer energy demands. For ancillary services from wind production to remain economically viable, the loss of green certificates should also be compensated when production curtailment is called for. With decreasing support for new conventional power production facilities in favor of renewables, the flexibility needed to curb system imbalances needs to come from the consumption side until regulatory frameworks properly incentivize the use of RES in the ancillary service markets. The authors of [5] further describe the relationship between support schemes and system balancing with increasing wind production in more detail and from a market perspective. Policy recommendations are made to address challenges and issues stemming from certain support schemes used. This work focuses on the use of consumption flexibility to address similar issues but while retaining these support schemes. To the best of the authors' knowledge, addressing technical issues arising from renewable support schemes has gained limited attention in literature.

1.1. Upward consumption flexibility

The use of consumption flexibility to modify the energy demand can be categorized as Demand-Side Management (DSM). For DSM, a distinction can be made between upward and downward flexibility. In literature these two aspects of DSM are often considered together in the form of load shifting. Load shifting can be accomplished either through direct consumption shifting [6], by using energy storage solutions [7] or through both simultaneously in the form of the scheduling and charging of electric vehicles and plug-in hybrids [8]. In literature the two aspects are also considered separately. Making the distinction between upward and downward flexibility products can lower the entry barrier for flexibility providers by allowing them to only provide upward or downward flexibility.

A large body of DSM research is focused on the use of downward flexibility, or the ability to decrease one's consumption to satisfy a shortage of energy (negative system imbalance) [9]. Examples of negative imbalance occurrences can be found in winter times when heating requirements are generally higher and solar production might under-perform because of the limited amount of daylight hours.

On the other hand, the potential for production surpluses has been identified as one of the major challenges faced in the effort to increase RES penetration [10]. This work focuses on using upward consumption flexibility or the ability to increase one's power consumption to satisfy production surpluses (positive system imbalances). Upward consumption flexibility has been proposed as a valuable resource for facilitating wind production integration in contemporary power grids as demonstrated in [11]. Positive system imbalances can, for example, occur when unexpected peak production from renewables meets RES under priority dispatch and conventional generation in must-run conditions [12]. Some conventional generation units cannot be curtailed because they provide frequency regulation services needed to maintain grid stability while other generation units can be very uneconomic to scale down (e.g. nuclear generation). This phenomenon has also been labeled as the incompressibility of power systems [13]. Clear market signals for the need of upward consumption flexibility during periods with incompressible positive system imbalances have been observed for Belgian and other European energy markets in the form of negative prices [14]. Negative prices can occur in the day-ahead, intra-day and balancing markets under different conditions but all supporting the need for upward consumption flexibility.

DSM literature often assumes the availability of flexibility providers. Such an assumption is not unreasonable. The potential for upward consumption flexibility in energy-intensive industries has been described in the context of increasing RES penetration in Germany by Paulus and Borggrefe [15]. Processes capable of load shifting are demonstrated to be valuable by providing upward flexibility. Similarly Lund et al. offer a comprehensive survey of DSM flexibility potential in the context of variable RES. This survey includes load shifting potential and upward flexibility in industry. Upward flexibility is in literature often defined as one aspect of load shifting. Lund et al. offer a comprehensive survey of DSM flexibility potential in the context of variable RES including load shifting potential and upward flexibility in industry [16]. In terms of residential flexibility, D'Hulst et al. illustrate the asymmetry of estimated available flexibility in favor of upward flexibility [17]. In this work, similar assumptions are made on the availability of consumption flexibility and more specifically, upward consumption flexibility. Where literature often focuses on employing consumption flexibility towards singular goals [18], this work contrastingly considers competing interests in contracting flexibility providers for different business cases.

Beside the use case of providing upward flexibility as an ancillary service to the Transmission System Operator (TSO), two business cases for employing this upward flexibility cost-effectively are identified and presented. The first business case benefits a Balance Responsible Party (BRP) suffering imbalances from wind forecast errors because of the wind production in their portfolios. These imbalances usually incur imbalance costs that can be partially avoided by harnessing consumption flexibility to offset these imbalances. Literature shows that balancing of up to 1.5 MW of overproduction from wind generation can be achieved using demand-side flexibility [19]. The second business case benefits a Distribution Grid Operator (DSO) aiming to avoid distribution grid congestion from increased wind injection in medium voltage grids. Integrating new wind production elements into existing distribution grids can cause congestion problems that are usually mitigated by curtailing wind production. In such cases, DSOs have to compensate the wind generation owners for their loss of income. Employing consumption flexibility can, in some of these cases, avoid curtailing wind generation [20].

To render these business cases positive for all parties involved, some form of financial compensation must be offered to the flexibility providers participating in these demand-response programs. From the point of view of the flexibility provider, it is beneficial to choose the most lucrative business partner to offer their flexibility. Depending on the business case, this flexibility might be activated differently and therefore, financial remuneration can also vary between business cases. Another factor influencing the amount of financial reward that can be reaped from these programs is the amount of other flexibility providers participating in the same program. Maximizing the expected reward gained by making choices while these rewards depend on the choices of other parties, is one of the application domains of game theory. The concrete focus of this work is analyzing the strategic choice that flexibility providers face in deciding which business partner to offer their flexibility by using tools from Evolutionary Game Theory (EGT).

1.2. Evolutionary game theory

In general, game theory provides tools and solution concepts for analyzing strategic choice situations in terms of expected payoffs or rewards [21]. Concretely, game theory provides a mathematical framework for explicitly modeling strategic behavior and interaction and analyzing resulting decisions, making it ideally suited for evaluating different business cases from an economic optimization point of view. Classical Game theory has been well used to model and analyze DSM mechanisms in literature. Direct negotiation between consumers to achieve consumption peak shaving is analyzed in [22] while load shifting is encouraged by a mechanism between consumers and utilities in [23].

In this work specifically, we use EGT to model and analyze how this strategic choice of multiple flexibility providers might change over time given different parameters such as activation fees and the location of wind energy resources. Tools from EGT literature can provide insight into how robust the market shares of two different business cases competing for a common resource, in this case the flexibility providers,