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Optimal Control of Distributed Energy Generation & Storages for Flexibility Provision on the Residential Level

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Abstract: Increased adoption of decentralized, variable renewable energy generators will require improved and up-dated methods for managing the increasingly complex energy balancing procedures in future networks. One way to aid in accomplishing this is by exploiting demand side management opportunities available from operating flexibilities and storages available in micro grids. This research aims to quantify and visualize the maximum potential deviations in grid experienced power flows, referred to as flexibility corridors found in residential micro gird systems which could be accessible for use by grid services. To achieve this, a model is developed through sets of mixed integer linear programming formulations, representing a residential PV-CHP micro grid with thermal and electric storages. An energy management system is operated using a rolling horizon optimization approach. Flexibilities are then evaluated based on the predicted state of certain critical components in the system. The system is then resimulated reflecting scenarios in which grid operators signal systems to exploit the entirety of both positive and negative flexibility options. Reactions to the system after such events are then analysed and cost modifications in the altered system operations are deter-mined.

Keywords: energy management, optimization, micro grid, cogeneration, storages, photovoltaic

1. INTRODUCTION

Traditionally, decision making policies for the energy sector have aimed to minimize overall net-work costs and reduce environmental impacts from energy production, while at the same time satisfying the supply-consumption balance of an ever in-creasing energy demand. With the increased penetration of decentralized variable renewable energy sources in the grid, congestion issues due to unexpected and volatile power generation are likely to occur, requiring additional support infrastructure or updated grid management policies. In order to help develop a more reliable and stable grid of the future at minimal costs, it will be required to plan ahead and make best use of energy storages and demand flexibilities available in energy net-works [Silvente (2015), Ma et al (2013), Cochran (2014), Sipiliotis (2016)].

Exploiting energy flexibilities through policies of demand side management (DSM) is a fairly mature concept, yet to date has been applied mainly to industrial applications and any large scale residential opportunities are so far lacking in implementation. Understanding what energy flexibilities may exist in residential systems and applying advanced predictive forecasting procedures may help provide grid operators with new valuable opportunities for quick energy balancing procedures at the source of consumption, helping reduce any flexibility gaps that may be created. DSM policies may even prove to be so beneficial and economically preferred that certain largescale grid expansion projects may be deferred as a result [Sipiliotis (2016), Li (2018)]. This concept has gained traction amongst planners and operators to the point where metrics to assess flexibilities of power systems have been developed and are being used in long-term project planning [Lannoye (2011), Papaefthymiou (2016)]. To plan flexibility usage in networks, proper predictive control techniques will first need to be defined and systems modelled before optimization procedures can be developed. Based on the anticipated optimized operation plans it may then be possible to determine the system flexibility potentials available based on forecasted system states.

The concept of energy flexibilities in its simplest form can be taken as an alteration in energy production or consumption patterns based on an external trigger or signal, such as from grid operators, in order to help provide services like energy balancing for the system [Ottessen (2018)]. The work presented here aims to build on top of this by introducing the idea of a systems flexibility corridor. This idea has been touched on in previous work, for instance termed as a flexibility envelope in [Nosair (2015)]. For the extent of this research, the concept will be defined as:

"The adjustable operating power range of a system from standard operations that is both technically feasible and in which consumer comfort is not greatly affected in order to help meet external energy balance requirements of networks"

Once systems are accurately defined, these corridors can then be quantified and mapped based on seasonal and temporal availabilities, accessible to grid services when required. Through simulation framework it is possible to predict the difference in energy consumption between operating scenarios and hence added costs to consumers through these altered operations. Energy management systems (EMS) used in operating systems of the future will need to accurately predict power production from renewable energy sources, forecast for loads and plan power storages while at the same time providing real time energy balancing [Lu (2009)]. Additionally, in order to exploit flexibilities potentials in real life scenarios, they should be represented as ever changing dynamic functions capable of reacting to external signals [Junker (2018)]. By pooling together residential systems, smaller actors may benefit by forming flexible building clusters, allowing for profile smoothing, larger storage options and easier market access for energy trading through reduced unit costs [Ottesen (2018), Vigna (2018)]. If operators have the options of a variety of aggregated residential flexibility sources in terms of quantity, availability and relative costs of triggering each, they may effectively request usage of such options.

This research aims to develop such EMS which will first determine an optimal operating plan for systems based on a cost minimization strategy to the consumer. From the determined predicted state of critical system components, flexibility corridors can be portrayed to determine if systems can offer significant flexibility options. Forecasted flexibilities will be quantified and visualized based on their seasonal and temporal availabilities and finally a cost evaluation for utilizing such flexibilities will be conducted after simulations of triggering each flexible option is completed.

2. METHODOLOGY

2.1 Model Definition

Models reflecting a residential system consisting of a rooftop PV array, electric battery, micro combined heat and power plant (μ-CHP) and thermal energy storage unit have been developed by sets of mixed integer linear programming (MILP) equations. A system schematic is depicted in Fig. 1.

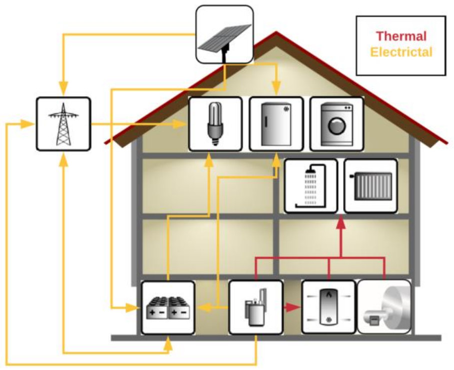

Fig. 1. PV-CHP model outline complete with thermal and electri-cal energy flows. Battery-grid connection is allowed during certain flexibility scenarios

System inputs provided include synthetically generated thermal & electric load profiles representing a multifamily housing unit as well as historical weather data including PV generation profiles from 2017 for Freiburg, Germany [Fischer (2015)].

Models defined reflect several specified system operating strategies. The first is reflecting a consumers' desire to minimize total system costs, followed by two scenarios based on grid operators' desire to operate in an up or down power regulating scenario.

Model parameters selected have been chosen to reflect a system capable of maximizing energy self-sufficiency. The maximum power output of the CHP unit has been selected in accordance with standard guidelines, whereas the primary motor operates near 5,000 hours of the year. A secondary motor has additionally been included to increase flexibility options and to help meet peak thermal demands, operating for roughly one third of the entire year. For PV sizing, a 10 kWp system was selected with the appropriate battery sizing based on several manufactures guidelines for maintaining energy independence given the selected residential floor space and expected electric demands. Fig. 2 highlights the load duration curves of both thermal and electric loads with the PV and CHP generation for the year, used in determining the system size.

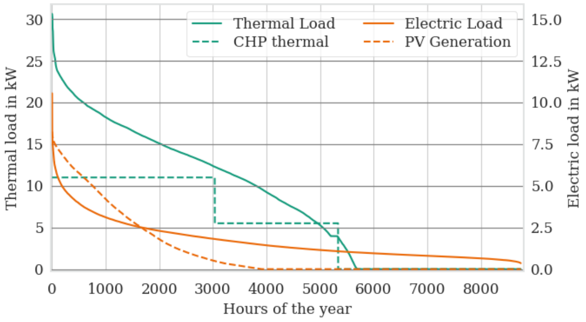

Fig. 2. Load duration curves reflecting the thermal (green) demand with corresponding CHP generation and electric (orange) demand with corresponding PV generation for the year

2.2 Simulation of Models

Through model predictive control techniques in a rolling horizon algorithm, the optimal operation of the system is determined in a cost minimizing (profit maximizing) fashion by optimizing MILP equations and constraints. A Python framework is used to iteratively loop through annual sub-files containing viable input data and systems are solved using CPLEX. One day control horizons and seven day prediction horizons are used to approximate a daily operation plan with updated weekly weather forecasts. Flexibilities are then calculated based on the expected condition of several critical system states, particularly the storage options available and current operational status of energy generators.

After an ideal operating plan is determined, the system is categorized into the seasonal states of summer, winter and transitional periods (combining fall and spring) based on the astronomical seasonal dates. The flexibility corridors are then quantified and mapped accordingly and classified based on their seasonality. The system is then resimulated under each season to mimic in-stances where grid operators send a signal to call for a full usage of both positive and negative flexibilities for a one hour timeframe and cost modifications through altered operations determined. Here, positive flexibility refers to up-regulation whereas negative flexibility refers to the down-regulation of power usage in the network. Finally, the system response after the onset of un-expected flexibility triggers is examined with a detailed analysis on the modified state of conditions.

2.3 *Analysis of Results*

The total flexibility of power consumption/feed-in available in the model is determined in terms of both quantitative amounts as well as seasonal availabilities. Additionally, costs associated with calling flexibilities are calculated. A qualitative analysis of system operations after flexibility events is completed to determine the altered state of system components.

3. RESULTS

3.1 *Components of Flexibility*

The model defined is fairly complex in terms of energy flows, storage options and the intricacy be-tween components paired with demands; as such, defining the total system flexibility first requires an individual analysis on a component by component basis, prior to being able to pool all resources together. Component based system flexibility options available are highlighted in Fig. 3, complete with the constraining factors that each flexibility option is dependent on. In the case that only a partial amount of total system flexibility is required, indi-vidual options may be called upon. In this case, they have been outlined above in ascending order in terms of both consumer convenience as well as efficiency in energy usage.

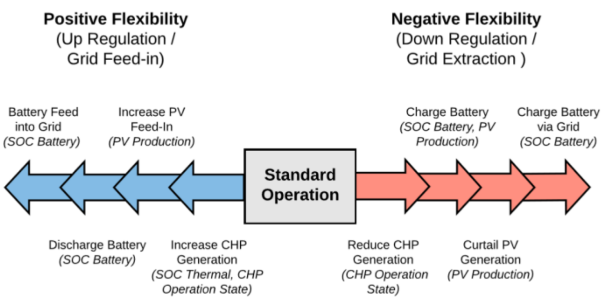

Fig. 3. Flexibility options with system constraints of the PV-CHP system

3.2 *Observed Seasonal Trends*

After simulating the model to optimize operations for a year, the total expected flexibility potential of the system has been determined and analyzed by comparing the state of energy generators in the system and the state of charge (SoC) of storage options. As previously mentioned, system parameters defined were chosen to reflect an ideal residential complex capable of maximizing self-sufficiency of their energy requirements. Simulated results then tend to rely highly on self-storage capabilities with energy generally being over-produced and scarce grid purchases. Given the selected region analyzed, the system was considered to operate in three distinct seasonal trends of summer and winter seasons, with a third in-between timeframe, referred to as the transitional seasons.

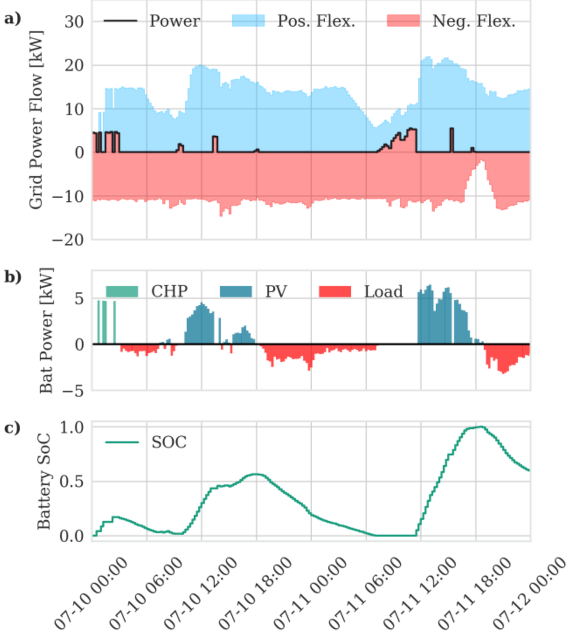

Fig. 4. Exemplary summer days of the system high-lighting a) the grid power exchange with flexibility corridors b) battery power flow and c) battery SoC

Warm summer periods typically observe large PV generation with little to no thermal demands. Throughout proper battery usage, large amounts of grid purchases can be avoided. Positive flexibility potentials throughout CHP generations were determined to exist however they are quickly com-promised due to overheating scenarios in the thermal storage paired with a lack of thermal demand. Both system-wide positive and negative flexibility options are present, which are primarily offered through exploiting the operation of the battery and modifying PV generated electricity flow. Flexibility corridors and battery management of the system for exemplary summer days are presented in Fig. 4. Sharp decreases in negative and positive flexibilities are observed once the battery nears critical maximum and minimum charge states respectively. This is further highlighted through the battery management, which is observed on the second day.

Winter periods on the other hand consist of large thermal demands, with a very insignificant PV generation. Battery usage becomes less important as the constant CHP generated electricity is more than enough to meet all forecasted electric demands, while also selling an additional amount of energy consistently into the grid. Over this time frame, positive flexibility options are lacking, as the system is already producing its maximum power potential for the most part. The large grid feed-in observed from the system however results in high amounts of consistent negative flexibility options. A sample period highlighting the flexibility corridors is presented in Fig. 5.

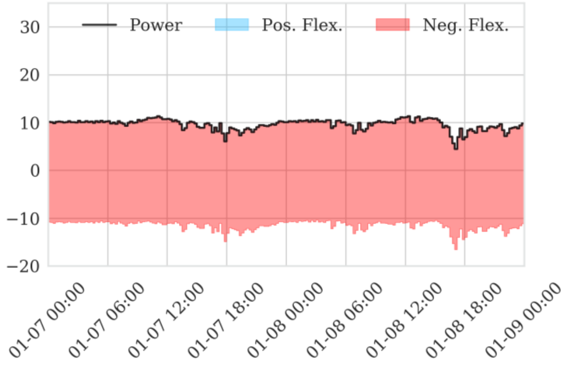

Fig. 5. Grid power exchange under optimal operation for exemplary winter days with flexibility corridors of the system

The transitional seasons tend to provide much more interesting system conditions observed. Moderate thermal loads paired with higher PV generations reflect both the extreme trends seen in both summer and winter periods. This results in a system with much more erratic and variable power production resulting in harder to predict system conditions. Exemplary days from this period have been chosen to be highlighted throughout the simulation of flexibility events in the following section.

3.3 *Flexibility Simulations*

Various exemplary days throughout the year have been selected and re-simulated where an unpredicted one hour trigger from operators is provided, to exploit the entire positive and negative flexibility options from the system, between 16:00 – 17:00. The system-wide flexibility corridors and corresponding response to the system for sample days over the transitional season are portrayed in Fig. 6. It can be seen that grid feed-in over these periods is much more sporadic compared to both winter and summer periods due to high and variable peak generation.

A summary highlighting the source of the determined flexibilities over these exemplary days on a mean value basis is listed in Table 1. It is determined that the most influential aspect in the system in regards to flexibility options relies on the state of battery operation, providing the most amounts of both positive and negative options. The CHP unit is also able to provide significant amounts of flexibility, yet favors down-regulation options as it is very often already feeding the grid its maximum power output. PV options remain limited to small amounts of down-regulation as all PV generated electricity is already being fed into the grid. It should also be noted however that the mean values for PV electricity depicted may be misleading, as these options are available through highly variable peak values throughout the day with and no value throughout the nighttime.

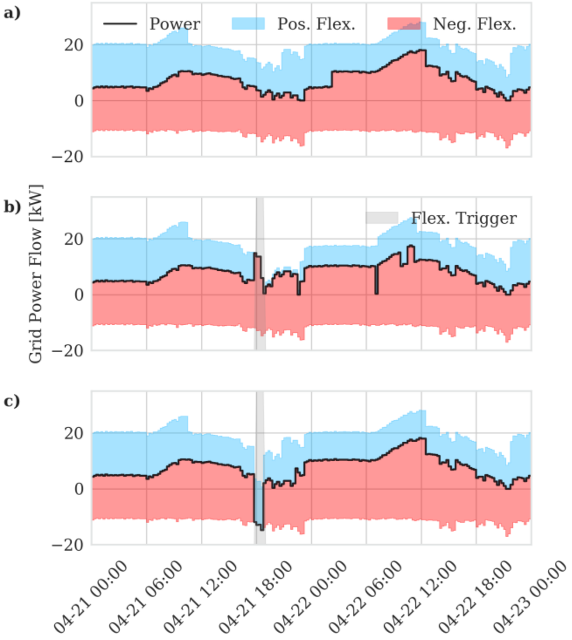

Fig. 6. Flexibility corridors of exemplary transitional days under a) standard operation b) positive flexibility event and c) negative flexibility event

After a positive flexibility event was observed for a full hour, the system appears to have depleted all positive flexibility options that follow in the near term. This is resulting from the electric battery fully draining its charge to the grid over the trigger event. Additionally, as there is no PV generation overnight which follows and both CHP motors are in operation, there is no possibility for up-regulating any additional power into the network. The system does not return to its approximate ‘standard state’ until some CHP generated electricity slowly recharges the battery. As the system predicts consistent electricity production over the short-term, there is not a high importance for maintaining a high battery charge. System wide negative flexibilities remain un-phased after such an event, as all down-regulating possibilities still exist, while the operating profile itself is only slightly modified from altered battery operations. Throughout the event, the system was determined to provide an additional total of 8.66 kWh of energy into the net. The power fed into the grid came solely from the battery charge, as there were no options to further up-regulate the CHP or PV production at this specific time. The modified battery operating profile is highlighted in Fig. 7.

Table 1. Component-based mean values of flexibilities observed over exemplary transitional days

Component	Positive-Flex	Negative-Flex
CHP	2.23 kW	6.63 kW
Battery	9.98 kW	10.02 kW
PV	0.0 kW	2.09 kW
Total System	12.21 kW	18.74 kW

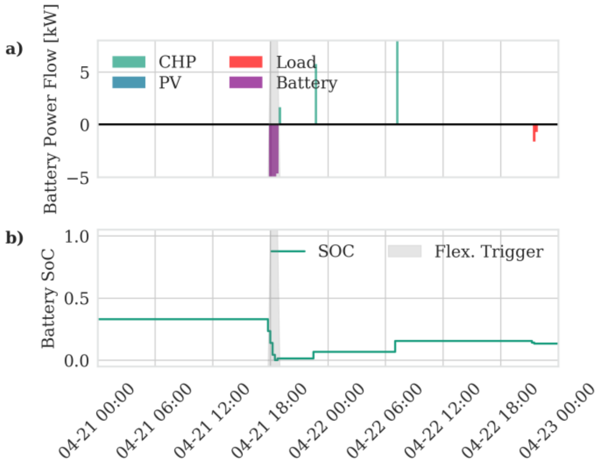

Fig. 7. a) Battery power flow and b) SoC of the system during a positive flexibility event over exemplary transitional days

Under a negative flexibility event, the system shuts down all CHP production and curtails the small amount of PV generation that exists, while additionally charging the battery to its maximum and supplying the load entirely from grid energy. Following such an event, the system appears to return almost immediately to its 'standard state' as deter-mined from the base conditions, with the exception that the battery maintains a higher charge. An additional 13.16 kWh total of energy was consumed by the system over this period from the network. The modified electric demand profile and PV generation is highlighted in Fig. 8.

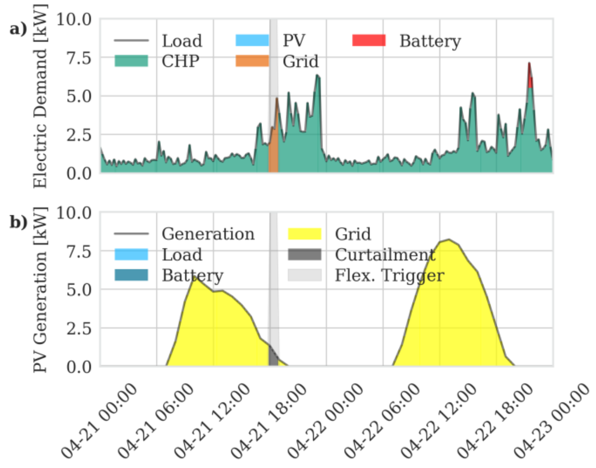

Fig. 8. a) Electric demand profile and b) PV generation curves of the system during a negative flexibility event over exem-plary transitional days

3.4 Cost of Flexibility

Each exemplary period examined was for a full 48-hour period of system operation, with a flexibility event triggered on the first day of simulations. This aims to take into account an appropriate amount of time for the system to respond and to return to its normal operating state. System costs were then analyzed for each full timeframe to determine the altered total energy costs comparing base conditions with both positive and negative flexibility operations. Costs account for meeting all thermal and electric demands, associated throughout CHP and boiler operating costs, as well as the purchase and sales of electricity from the grid. A summary of flexible energy availabilities and associated costs from simulating exemplary days is presented in Table 2.

Total energy flexibility utilized for each case typically ranged between 8 and 15 kWh under each trigger event. Flexibility costs have been deter-mined in terms of additional €/kWh of system costs compared to standard base conditions and evaluated against the average cost of power used in the simulation of 0.25 €/kWh. Given the previous flexibility simulation outlined over the exemplary transitional days, additional system costs in utilizing such flexible options was determined to be 0.240 €/kWh and 0.359 €/kWh for positive and negative flexibility respectively.

Table 2. Cost and availability of energy flexibility in the system based on exemplary seasonal observations

Season	Metric	Positive Flexibility	Negative Flexibility
Winter Days	Energy *(kWh)*	-	12.34
	Cost *(€/kWh)*	-	0.234
Summer Days	Energy *(kWh)*	15.52	10.90
	Cost *(€/kWh)*	0.137	0.139
Transitional Days	Energy *(kWh)*	8.66	13.16
	Cost *(€/kWh)*	0.240	0.359

2. DISCUSSION AND CONCLUSION

An EMS was successfully programmed to determine cost minimizing operations of system models representing a residential PV-CHP system. The system is capable of determining approximated states of various system components based on the predicted operation plan, then calculating both positive and negative flexibility options on a component basis available for DSM opportunities. The total ranges of power-to-grid possibilities from standard operations, referred to as flexibility corridors, were successfully visualized through aggregating flexibility options at each time step. The sys-tem was then re-simulated reflecting trigger events where flexibilities were to be fully exploited by grid services. The system response was then analyzed and cost differences due to operational alterations were determined. It was found that the sys-tem is able to provide significant amounts of flexibility options to grid services, at relatively moderate to low costs, especially over summer periods of high PV generation and low thermal demands.

It can be concluded that accurately developing a pertinent operation plan for systems through well-developed EMS' can help forecast conditional states in the near future, which is the first step in forecasting flexibility potentials available. The most critical aspects in defining these flexibilities are the state of available storage options and cur-rent status of energy generators. Once algorithms are perfected, this may be a very useful tool for grid operators to use, capable of providing cost effective DSM options through exploiting residential system operations and storages. To reach wide scale adoption of this technology however, requires some additional considerations.

Various alternate system definitions will need to be considered of varying technology and design, reflecting the vast amount of possible configurations which may be present in networks. Incorporating alternate storage sources into models, such as electric vehicles or a residential pool, should in theory increase flexibility of systems through the added electric and thermal buffers they can provide. The model developed here is inaccurate from reality, as it works off of a system with perfect knowledge of the future and does not account for any forecasting errors. In reality working systems will need to be able to adapt to dynamic input variables which will result in system states that vary from the original planned operations. Future simulations should analyze to what extent such inaccuracies will affect the flexibility potentials. Additionally, systems developed here do not determine total power duration or energy availabilities in the system, rather only instantaneous power options. For accurate planning, operators would further need to understand the time availabilities of such flexible operations prior to executing a trigger for exploiting them. This could be achieved through determining time stamp data for each component beforehand, or visualizing flexibility corridor graphs as 3D representations whereas the third axis infers duration of flexible operations, or the total flexible energy availability.

Essentially, for practical adoption of such energy balancing strategies, more sophisticated and advanced EMS' will need to be developed, capable of dynamically and continually computing the actual from forecasted states, with power and energy availabilities, as well as an expected cost of modifying system operations. Such network management improvements may not only be economically beneficial, but inevitable in maintaining secure energy systems of increasing energy demands in the future.

REFERENCES

J. Silvente, G. M. Kopanos, E. N. Pistikopou-los, and A. Espuña, "A rolling horizon opti-mization framework for the simultaneous en-ergy supply and demand planning in mi-crogrids," Applied Energy, vol. 155, pp. 485–501, 2015.

J. Ma, V. Silva, R. Belhomme, D. S. Kirschen, and L. F. Ochoa, "Evaluating and Planning Flexibility in Sustainable Power Systems," IEEE Trans. Sustain. Energy, vol. 4, no. 1, pp. 200–209, 2013.

J. Cochran et al., "Flexibility in 21st Century Power Systems," 21st Century Power Part-nership, 2014.

K. Spiliotis, A. I. Ramos Gutierrez, and R. Belmans, "Demand flexibility versus physical network expansions in distribution grids," Applied Energy, vol. 182, pp. 613–624, 2016.

J. Li, F. Liu, Z. Li, C. Shao, and X. Liu, "Grid-side flexibility of power systems in in-tegrating large-scale renewable generations: A critical review on concepts, formulations and solution approaches," Renewable and Sus-tainable Energy Reviews, vol. 93, pp. 272–284, 2018.

E. Lannoye, D. Flynn, and M. O'Malley, "The role of power system flexibility in generation planning," in 2011 IEEE Power and Energy Society General Meeting, Detroit, MI, USA, 2011, pp. 1–6.

G. Papaefthymiou and K. Dragoon, "Towards 100% renewable energy systems: Uncapping power system flexibility," Energy Policy, vol. 92, pp. 69–82, 2016.

S. Ø. Ottesen, A. Tomasgard, and S.-E. Fleten, "Multi market bidding strategies for demand side flexibility aggregators in electricity mar-kets," Energy, vol. 149, pp. 120–134, 2018.

H. Nosair and F. Bouffard, "Flexibility Enve-lopes for Power System Operational Plan-ning," IEEE Trans. Sustain. Energy, vol. 6, no. 3, pp. 800–809, 2015.

D. Lu and B. Francois, "Strategic framework of an energy management of a microgrid with a photovoltaic-based active generator," in 2009 8th International Symposium on Advanced Electromechanical Motion Systems & Electric Drives Joint Symposium, Lillie, France, 2009, pp. 1–6.

R. G. Junker et al., "Characterizing the ener-gy flexibility of buildings and districts," Ap-plied Energy, vol. 225, pp. 175–182, 2018.

I. Vigna, R. Pernetti, W. Pasut, and R. Lollini, "New domain for promoting energy efficien-cy: Energy Flexible Building Cluster," Sus-tainable Cities and Society, vol. 38, pp. 526–533, 2018.

D. Fischer, A. Härtl, and B. Wille-Haussmann, "Model for electric load profiles with high time resolution for German households," En-ergy and Buildings, vol. 92, pp. 170–179, 2015

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