ENERGY MODI: TRANSACTIVE GRID MANAGEMENT SCHEME FOR RESILIENT MICRO-GRIDS

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ABSTRACT

The adoption of renewables leads to an intermittent peak supply of energy during certain parts of the day which results in congestion in the distribution grid and energy scarcity scenarios for community micro-grids in other periods of the day. In this paper, we present a transactive mitigation scheme based on multi-objective steering signals shared between different grid entities to solve gird issues, with a focus on congestion. We evaluate the proposed approach using baseload data from 25 houses in New York by simulating a congestion scenario resulting from cost minimization optimization. We show that the proposed congestion mitigation approach resolves the congestion with minimal sacrifice of the comfort of the residents of the micro-grid.

Index Terms—micro-grids, congestion management, optimization, renewable energy.

INTRODUCTION

Due to the reduced cost of Distributed Energy Resources (DERs) [1], pro-DER policies, and increasing emphasis on energy security, an increase in electrification is observed. In Netherlands, the policy of net-metering (‘salderingsregeling’) [2] has boosted the country to the position of being the EU country with the highest solar capacity per capita [3]. A similar policy is a performance-based incentive (PBI) in the US [4] (e.g. the California Solar Initiative), wherein monthly incentives are paid to the PV system owner over a 5-year period in proportion to the energy produced by the PV system. However, the existing infrastructure has not been designed for the rapidly increasing electrification, resulting in severe congestion in countries such as the Netherlands. According to the distribution system operator (DSO) Liander, the grid has reached its capacity in cities such as Amsterdam preventing new commercial or residential units from acquiring a new or upgraded grid connection [5].

However, the increase in DERs also created another effect, namely, the emergence of micro-grids (MG) formed by communities of prosumers living in geographical proximity to each other [6]. This can help to resolve aforementioned issues by pooling DERs together. In general, such MGs consist of distributed flexibility sources (DF) - e.g. renewable sources of energy, energy storage systems (ESS) and flexible loads such as electric vehicles (EV). Efficient management of these flexible resources within an MG benefits both the MG and the main electrical grid [6] as the flexibility offered by MGs can assist in also managing the higher-level grid.

Based on the above, grid operators came up with techno-legal frameworks to manage or *negotiate* between grid operators and MGs to alleviate grid problems. An example of such a framework is the Universal Smart Energy Framework (USEF) [7]. USEF is a mechanism meant to coordinate the use of the DF offered by MGs to keep the grid within operational limits. Specifically, the framework suggests a traffic light model, where the grid transitions within different operating regimes depending on the severity of the grid issue. In each operating regime, grid operators have different levels of control of their constituent MGs to be able to solve grid issues. Hereby, USEF does not describe the precise operations to be performed by the DSO to solve grid issues in the different operating regimes. This gap is the topic addressed in this paper.

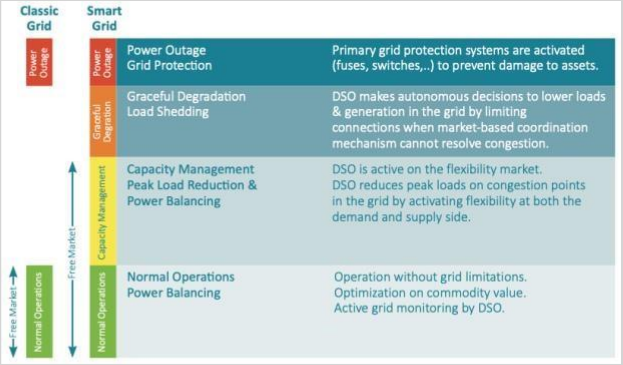
The core contributions of this paper are:

- A transactive congestion management scheme consisting of multi-objective time-varying planning signals (called *energy modi)* for an energy system with multiple entities.
- An evaluation of the proposed energy modi approach on an energy system with an MG consisting of 25 houses and a DSO to solve congestion in the MG.

In the following section, we give a brief description of USEF. Thereafter we explain the algorithm of the proposed energy modi approach and evaluate it using baseload data from 25 houses in New York. Lastly, we discuss the features of the energy modi approach and propose some aspects for future research.

USEF

USEF [7] is a grid management framework presenting a mechanism that uses the DF offered by prosumers to keep the grid within its operational limits while respecting the prosumers’ right to freely connect, trade and dispatch their DF. USEF puts forward a coordination mechanism as an extension of the current European electricity market design. As part of the coordination mechanism, USEF proposes four operating regimes for the distribution grid as shown in Fig. 1. The primary difference between the four regimes lies in the level of control the DSO can have on the MG's energy use.



Primary grid protection systems are activated (fuses, switches,..) to prevent damage to assets.

DSO makes autonomous decisions to lower loads & generation in the grid by limiting connections when market-based coordination mechanism cannot resolve congestion.

DSO is active on the flexibility market. DSO reduces peak loads on congestion points in the grid by activating flexibility at both the demand and supply side.

Operation without grid limitations. Optimization on commodity value. Active grid monitoring by DSO.

Fig. 1: The four operating regimes in the USEF [7]

The starting point of USEF is that the introduction of DERs can cause congestion and scarcity issues due to peak energy demand and supply occurring at different parts of the day. USEF categorizes an energy grid to be in the green operating regime if the energy use is within the operating limits of the grid. When a congestion situation occurs (e.g. due to increased PV production), the energy grid is said to change to the yellow regime where the DSO aims to use available flexibility on the energy market to reduce this congestion. If the congestion persists, then the energy grid enters the orange operating regime where the DSO gradually increases its level of control over the MG's energy use. Lastly, in the red regime the DSO can take the highest level of control over the energy use in the MG to solve the congestion. An example of a possible operation of the DSO in the red regime is the curtailment of PV production.

Within USEF only the general aim of each operating regime is proposed. It remains to specify a clear operational scheme that respects the objectives of the MG as well as that of the DSO with well outlined steps for the yellow and orange regimes. In this paper, we present such a precise congestion mitigation scheme in the form of multi-objective steering signals with gradually increasing levels of DSO control.

TRANSACTIVE CONGESTION MITIGATION APPROACH (ENERGY MODI)

In this section we explain the proposed energy modi approach. Although this approach is applicable to a group of stakeholders, in the following we restrict ourselves to only a single MG and a single DSO as stakeholders for simplicity. We consider a list of N discrete time intervals $T = (1, 2, \ldots, N)$ that form the action window of the DSO. The aggregated power profile of the MG for the N intervals of T is given by $\vec{x} = (x(1),\ x(2), \ldots x(N))$. Each of the two stakeholders is considered to have their own optimization objective given as a weight vector consisting of non-negative values of size T. The weight signal of the MG for its objective is denoted by α_{MG} and the weight signal of the DSO is denoted by α_{DSO}. The sum of the weights of both stakeholders for a given time interval should always be 1, i.e., for each time interval n in T the summation of the optimization objective weights should be 1: $\alpha_{MG}(n) + \alpha_{DSO}(n) = 1$.

If now the DSO changes $\alpha_{DSO}(n)$ it also affects the weight of $\alpha_{MG}(n)$ based on the sum $\alpha_{MG}(n) + \alpha_{DSO}(n)$. Note, that the higher the value of $\alpha_{DSO}(n)$, the higher the impact of the DSO's objective on the aggregate power profile $\vec{x}$ of the MG. The DSO can also determine for which intervals n of the action window T it chooses to have $\alpha_{DSO} \neq 0$. The set of intervals $k \in T$ for which the DSO chooses to impose a positive optimization objective weight i.e. $\alpha_{DSO}(k) > 0$ is denoted as β. Therefore $\beta \in T$ and $0 \leq |\beta| \leq |T|$. Fig. 2. illustrates the use of the variables $\vec{x}$, T, β, α_{MG} and α_{DSO} with an example.

The algorithm for the energy modi approach is as follows. Assume that the MG initially has an optimization objective weight $\alpha_{MG}(n) = 1$ and the DSO has an optimization objective signal $\alpha_{DSO}(n) = 0$ for the for each interval n in action window T. The MG uses the weight signal $\alpha_{MG}(n) = 1$ to optimize for its own objective (e.g. Cost Minimization) resulting in an aggregate power profile $\vec{x}$. Note, that the DSO initializes α_{DSO} as a zero vector and β as an empty set. For each interval $n \in T$ the DSO checks whether the value of $\vec{x}(n)$ violates the grid limit for import and export of electricity given as G_{lim}^{import} and G_{lim}^{export}.

If a grid limit violation is found, for example in interval $n^* \in T$, then the DSO initiates an iterative congestion management process. The aim of the iterations is to perform an exhaustive offline search of DSO control levels $\beta * \alpha_{DSO}$ for all possible combinations of β and α_{DSO} which can solve the congestion. In each iteration, the DSO sets a value for the modi combination (β, α_{DSO}) to send to the MG. The DSO control duration set β is any set of K contiguous intervals that belong to the action window T. For the K intervals in β, the DSO sets a positive optimization weight i.e. $\alpha_{DSO}(k) > 0\ \forall k \in \beta$. With β and $\alpha_{DSO}(k)$ for the current iteration determined, the DSO sends the modi combination to the MG. The MG receives the modi combination, uses it to calculate $\alpha_{MG}(k)$ such that the sum of the optimization weights $\alpha_{total}(k) = \alpha_{MG}(k) + \alpha_{DSO}(k) = 1$, executes a re-planning and finds a new candidate aggregate power profile $\vec{x}$. The DSO checks the power value at each interval of $\vec{x}$ for a grid violation. If no violation is found, then $\vec{x}$ is a feasible profile and the DSO records the control level $\beta * \alpha_{DSO}$ of

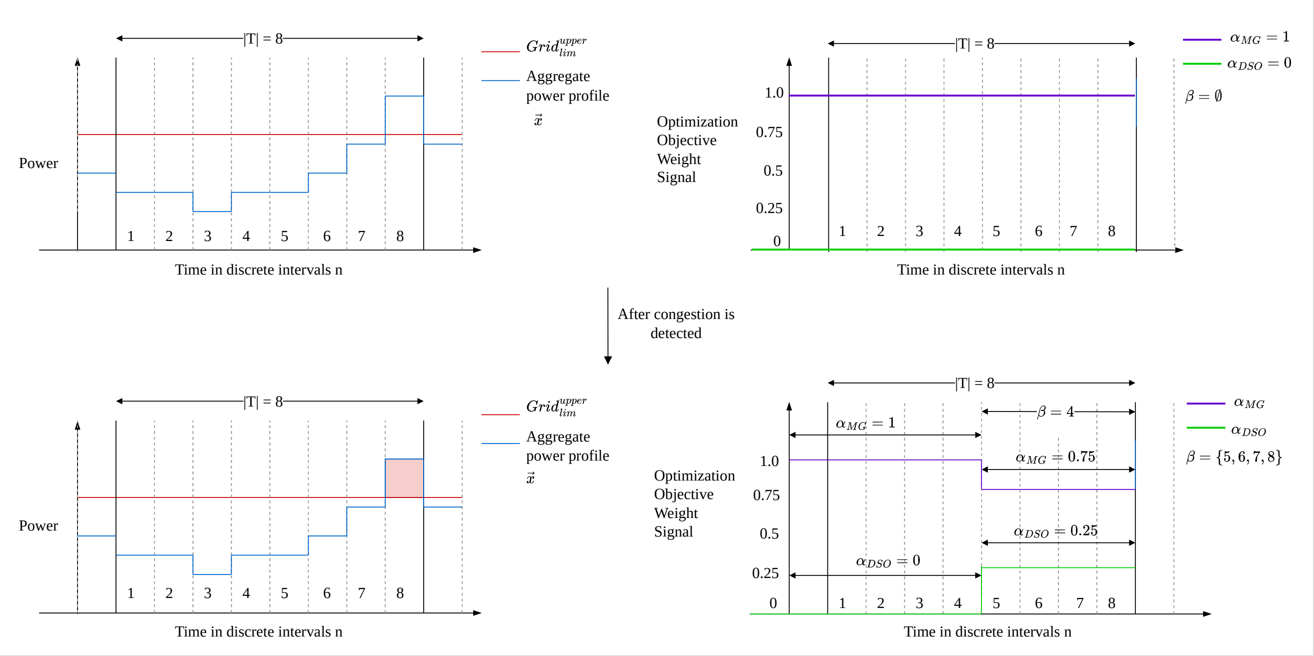


Fig. 2: An example construction of the multi-objective planning signal when congestion is detected with DSO action window of size |T|=8, DSO control duration set of size $|\beta| = 4$, $\alpha_{MG}(k) = 0.75$, $\alpha_{DSO}(k) = 0.25\ \forall k \in \beta$.

the modi combination that results in $\vec{x}$. This concludes one iteration of the energy modi approach. For the next iteration, the DSO changes the modi combination (β, α_{DSO}) and sends $\alpha_{DSO}(k)$ to the MG for the MG to execute a replanning and calculate a new candidate profile $\vec{x}$ to send to the DSO. After candidate profiles for all modi combinations (β, α_{DSO}) are found, the DSO selects the feasible candidate $\vec{x}$ with the least control level $\beta * \alpha_{DSO}$ as the solution. This candidate $\vec{x}$ represents the best compromise between the MG's optimization objective and the DSO's optimization objective to solve the congestion in the action window T. Algorithm 1 summarizes all the steps involved in the transactive congestion management framework.

Generating Modi Combinations (β, α_{DSO})

In each iteration, the DSO changes the control level by changing the modi combination (β, α_{DSO}). This can be done by changing the number of intervals K in β and by changing the weights in the optimization objective weight signal $\alpha_{DSO}(k)$. To construct the control duration set β, the DSO first selects the congestion interval n^* and then selects $(K-1)$ contiguous intervals less than n^*. In case the starting boundary of the action window T is exceeded i.e. $n^* - (k-1) < 1$, then the DSO selects intervals greater than n^*. Therefore, the DSO constructs β by selecting the congestion interval n^*, then attempting to select $(K-1)$ intervals in the past of n^* and if the past is not sufficient then selecting the remaining intervals from the future of n^*. The upper bound of β is the size of the action window $|T|$ and the upper bound of $\alpha_{DSO}(k)$ is $\alpha_{DSO}(k) = 1\ \forall k \in T$.

Algorithm 1 Transactive congestion management framework using multi-objective optimization weight signal.

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Initialization
DSO: Set action window $T$
$\beta = \emptyset$
$\alpha_{DSO}(n) = 0\ \forall n \in T$
$\alpha_{MG}(n) = 1\ \forall n \in T$
MG: Calculate initial aggregate power profile $\vec{x}$.

Grid violation check by DSO
for $n$ in $T$ do
    if $\vec{x}(n) > G_{\lim}^{\text{upper}}$ or $\vec{x}(n) < G_{\lim}^{lower}$ do
        Search Iterations for Modi Combinations $(\beta, \alpha_{DSO})$
        $feasible = [], K = 1$
        Add congestion interval $n^*$ to $\beta$. Add $(K-1)$ contiguous intervals around $n^*$ to $\beta$.
        while K $\leq |T|$ do
            for $k$ in $\beta$ do:
                while $\alpha_{DSO}(k) \leq 1\ \forall k \in \beta$ do
                    Set $\alpha_{DSO}(k) = m\ \forall k \in \beta, m \in (0,1]$
                    Calculate candidate aggregate power profile $\vec{x}$
                    if $\vec{x}(n) > G_{\lim}^{\text{upper}}$ and $\vec{x}(n) < G_{\lim}^{lower}\ \forall n \in W$ do
                        Add $(\beta, \alpha_{DSO}, \vec{x})$ to $feasible$ list.
                    end if
                    Increment weight $m$
                end while
            end for
            Increment $K$
        end while
        Action to solve congestion is $(\beta, \alpha_{DSO}, \vec{x})$ from $feasible$ list corresponding to $arg\ min_{\beta,\alpha_{DSO}} = \beta * \alpha_{DSO}$
    end if
end for
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EVALUATION

In this section we evaluate the energy modi approach with real congestion data. For the evaluations, we use baseload and PV power profiles in 15 mins resolution acquired from May 1st 2019 to October 31st 2019 of an energy community in New York comprising of 25 houses from Pecan Street [8]. In addition to the Pecan Street data, we assign each house an LG Chem RESU 6.5 battery [9] with 5.9 kWh usable capacity and a charging/discharging rate of 4.2 kW as ESS. Additionally, we build our model in Python v3.10 using the Pyomo modelling language v5.7.1 and use Ipopt [10] as the solver. We choose cost minimization as the objective for the MG and peak-shaving as the objective for the DSO.

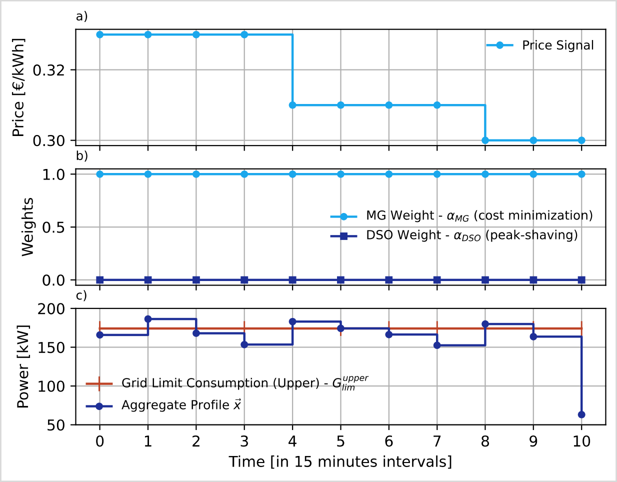


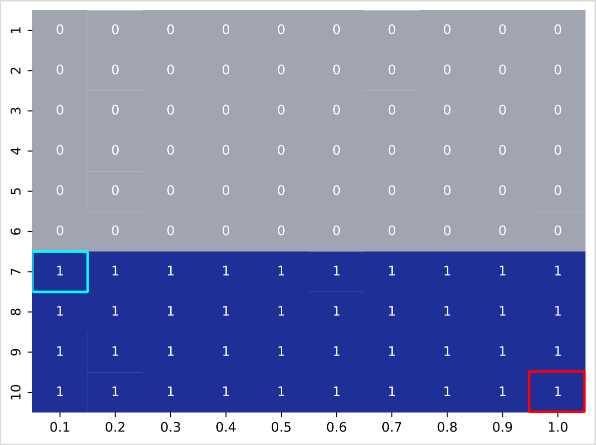
Fig. 3: a) Price signal, b) Initial optimization objective weights and c) the resulting intitial aggregate power profile of the MG for cost minimization objective.

Congestion Detection

Figure 3. illustrates the evaluation case comprising of data of 11 discrete contiguous intervals in the month of July. We choose an action window size $|T| = 10$ intervals. Interval 0 is the present and all intervals from 1 to 10 are part of the action window T. We set a grid limit of $Grid^{upper}_{lim} = -Grid^{lower}_{lim} = 175\ kW$. Fig. 3c shows the initial aggregate power profile of the MG after cost minimization using the price signal in Fig. 3a and the objective weight signals as shown in Fig. 3b. As seen in Fig. 3c, there are multiple intervals with congestion and the earliest congestion interval $n^* = 1$.

Modi Combinations $(\boldsymbol{\beta}, \boldsymbol{\alpha_{DSO}})$

Once a congestion interval is detected, the DSO increases $|\beta|$ from 1 to $|T| = 10$ in steps of 1 and increases α_{DSO} from 0.1 to 1.0 in steps of 0.1 while ensuring that $\alpha_{DSO}(n) + \alpha_{MG}(n) = 1\ \forall n \in T$. For each (β, α_{DSO}) combination the DSO runs the optimization with the Ipopt solver and calculates the new candidate aggregate power profile $\vec{\hat{x}}$ and checks if $\vec{\hat{x}}$ is a feasible profile. Fig. 4 shows a heatmap of the feasibility and infeasibility of each (β, α_{DSO}) modi combination. For the congestion case of Fig. 3c, modi combinations consisting of a value of β ranging from 7 to 10 (inclusive) and a value of α_{DSO} ranging from 0.1 to 1.0 (inclusive) lead to feasible aggregate power profiles for the MG while solving the congestion in action window T. Fig. 5 confirms the same conclusion by showing a heatmap of the total power overshoot of the new candidate profile $\vec{\hat{x}}$ resulting from each modi combination w.r.t the grid limit $Grid^{upper}_{lim}$.



	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0
7	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	1

Fig. 4: Feasible and infeasible modi combinations (β, α_{DSO}). Feasible modi combination with least (cyan rectangle) and highest DSO control level (red rectangle) are marked.

The modi combination with the least level of DSO control i.e. $(\beta = 7, \alpha_{DSO} = 0.1)$ is marked with a cyan rectangle and with the highest level of DSO control i.e. $(\beta = 10, \alpha_{DSO} = 1.0)$ is marked with a red rectangle in Fig. 4 and Fig. 5. Fig. 6 shows the aggregate power profile resulting from both modi combinations. Fig. 6 shows that, in this specific congestion scenario, the modi combination with the least control delivers a better candidate power profile than the combination with the highest control level, specifically in intervals 8, 9 and 10. This is because the peak-shaving objective of the DSO attempts to push the $\vec{\hat{x}}$ close to $Grid^{upper}_{lim}$.

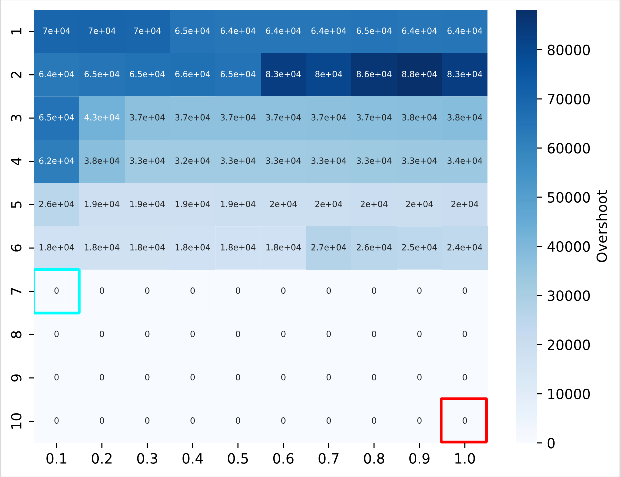


Fig. 5: Total power overshoot of modi combinations (β, α_{DSO}). *Feasible modi combinations are* $(\beta = [7,10],\ \alpha_{DSO} = [0.1,1.0])$

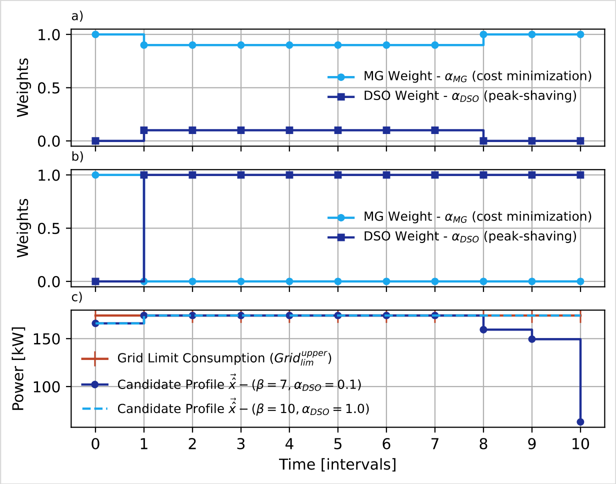


Fig. 6: a) Weight signal for modi combination $(\beta = 7, \alpha_{DSO} = 0.1)$ *and b)* $(\beta = 10, \alpha_{DSO} = 1.0)$. *c) Aggregate power profile* $\vec{x}$ *with either combination.*

CONCLUSION

This paper has put forward a transactive congestion management scheme using simple multi-objective optimization signals for solving congestion at the MG level called energy modi. Energy modi is a precise and simple congestion mitigation scheme that can be implemented in the yellow and orange regimes of USEF and in similar grid management frameworks across the world. An important benefit of energy modi is that it aims to solve congestion with the least compromise on the MG's own objective using multi-objective steering signals without directly imposing operational constraints on individual DERs and DF devices of the MG.

In the future we plan to evaluate the proposed approach against different grid problems such as energy scarcity. Additionally, with the increasing number of MGs, our future aim is to investigate the presented energy modi approach in a multi-stakeholder system consisting of multiple MGs and DSO agents.

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