Flexibility Provision by Active Prosumers in Microgrids

Rodrigo M. Castro
Faculty of Engineering of the
University of Porto
Porto, Portugal
up201604423@up.pt

Mohammad S. Javadi
INESC TEC
Porto, Portugal
msjavadi@gmail.com

Sérgio F. Santos
INESC TEC and Portucalense
University Infante D. Henrique
Porto, Portugal
sdfsantos@gmail.com

Matthew Gough
FEUP and INESC TEC
Porto, Portugal
mattgough23@gmail.com

Morteza Vahid-Ghavidel
FEUP and INESC TEC
Porto, Portugal
mv.ghavidel@gmail.com

Joao P. S. Catalão
FEUP and INESC TEC
Porto, Portugal
catalao@fe.up.pt

Abstract— **This paper focuses primarily on the flexibility of active prosumers in an islanded microgrid operation. The main objective is finding the best strategy to implement on an existing medium voltage grid, with several consumers, with the capability of producing some power for the grid operation, via Renewable Energy Resources (RES), or thermal Units, generally gas turbines, also there is the capability of some energy storage through batteries. Since power output of RES has a cost per kw of zero, it is greatly important to find the best combination of these resources who best suit the test system. For the purposes of these tests, the available investment funds are unlimited, although, there are some constraints regarding maximum RES penetration and ESS capacity.**

Keywords— *Demand Response, Electrical Energy Storage Devices, Smart Grids, Islanded microgrids, Renewable energy, Active prosumers, Distributed generation.*

NOMENCLATURE

Indices

i	Bus Index
d	Day Index
s	EES Index
l	Line Index
t	Time Index

Variables

$PG_{i,t,d}$	Power generation at unit i at time t
$PD_{i,t,d}$	Demand at bus i at time t
$SU_{i,t,d}$	Binary decision variable of start-up
$SUC_{i,t,d}$	Cost of Start-up unit i at time t
$SD_{i,t,d}$	Binary decision variable of shut-down
$SDC_{i,t,d}$	Cost of Shutdown unit i at time t
$I_{i,t,d}$	Binary decision variable of unit commitment
$P^{EES,\sim}_{s,t,d}$	Discharge /charge power of EES s
$Eng^{EES}_{s,t,d}$	Energy stored in EES s
$\delta_{i,t,d}$	Voltage bus angle
$\lambda_{i,t,d}$	Locational marginal price at bus i at time t

Parameters

N_B	Number of thermal units
N_T	Number of hours under study
N_L	Number of transmission lines
EES^{max}	Maximum capacity addition of EES devices
X_l	Reactance of transmission line l
α, β	Acceptable range for DR implementation
ω	Maximum acceptable change for hourly demand
STU_i, SDU_i	Start-up/shut-down cost of unit i

Symbols

max, min	Maximum and Minimum
S, R	Sending, Receiving end bus

I. INTRODUCTION

As renewable energy's technology evolves, the market interest from small and medium consumers grows. With the objective of lowering electricity prices, what was once a unidirectional power flow from large, centralized power units now becomes more distributed with RES (Renewable Energy Resources) and small thermal generators. The need to establish control strategies and implementation of these systems is also on the upswing. The RES penetration also means an increased instability in both frequency and voltage, with the implementation of local Energy Storage Systems (ESS), and adequate inverters it becomes possible to mitigate this issue. Nevertheless, ESS are still quite expensive, so an optimal sizing and location strategy of ESS and RES systems is needed.

A. Motivation

At the time of planning for most of the existing grids, the installation of RES or ESS was not considered, since it either did not exist yet, or was too expensive at that moment in time. Nowadays, it is becoming more and more common for small grids and ever large high voltage grids to be upgraded, with this new type of clean generation. Since these grids already exist, it is crucial to study the very well, to implement the correct system for optimal benefit. Thus, while planning, the site and size of installed RES power is key. Some areas may not be fit for solar PV or wind, so new strategies need to be found.

These types of changes have mostly the objective of reducing operational costs of the grid, resulting in lower prices for the costumers, also in most cases. Also, in some cases, it can also improve the quality of the electrical signal wave, that being better voltage values, more stability in frequency and an increase in grid reliability. Since RES have a cost per kWh produced of zero, they are very helpful in lowering overall costs of power.

Nevertheless, too much or too little RES penetration may have a negative impact on the grid. If it is too low, the price difference may not be felt or the investment in cost per kW of installed PV or wind may be too high.

On the other hand, if there is a massive penetration of RES, those advantages discussed prior, are lost. Voltage spikes may appear in certain buses, frequency may become unsynchronized from the nominal values and in the end, protection devices such as fuses, or circuit breakers may shut down parts or the entire grid. So, finding the optimal values for RES, ESS and possible local thermal units is crucial to maintain a stable a secure system.

B. Literature Review

In general energy distribution follows the traditional scheme, from the very large power plants to the local consumers far away from them[1]. Most recently, the idea of increasing the control and oversight of smaller, local LV grids, has been rising giving birth to the Microgrids [2]. Operating such microgrid in islanded mode has its own challenges, namely, maintain the loads without load shedding; frequency and voltage parameters within the considered parameters; guarantee grid stability even with dynamic and loads and manage power generation and storage [3].

The active prosumer element provides a key role, by producing and possibly storing some of the power it requires it may invert the traditional unidirectional power flow[4]. In a microgrid, these prosumers can also trade power with each other, the term prosumer comes from joining consumer and producer [5].

As both solar photovoltaic power (PV) and wind turbines evolved and became more economical sustainable, its implementation started to appear not only in large scale wind and solar farms, but also for the average consumer[6].

Managing a microgrid without any RES, already requires a very fine-tuned control strategy, due to the lack of inertia, which the main grid has plenty of [7]. When adding RES, this problem becomes even more apparent, since its output is highly inconsistent and varies almost every second [8]. To solve this issue a very useful solution is the adoption of energy storage systems, not only can they provide the system with a reserve capacity in odd periods when the demand is higher than predicted, but their main purpose is to be used as a safeguard [9]. Since Energy Storage System (ESS) are still quite expensive in cost per kWh of storage its application must be very carefully planned and the purpose of it as well [10], in this case its main objective is to support the grids stability by using controllers throughout the microgrid, a central controller receives that information an takes measures to assure good and continuous functionality [11].

The flexibility provision has three main actors[12]:

- Prosumers: as mentioned before, it is a consumer that not only consumes power from the main grid, but also has the capability of injecting upstream
- Aggregators: the entity responsible for connecting the various prosumers in a microgrid, it facilitates their connection with the global market
- Distribution System Operator (DSO): Responsible for the transfer of power from medium and low voltage lines to the consumers. Must guarantee power demands

It is vital for the correct operation of the microgrid that there is a high level of coordination between all these parts. Without it the system may fail or not be economically feasible[13].
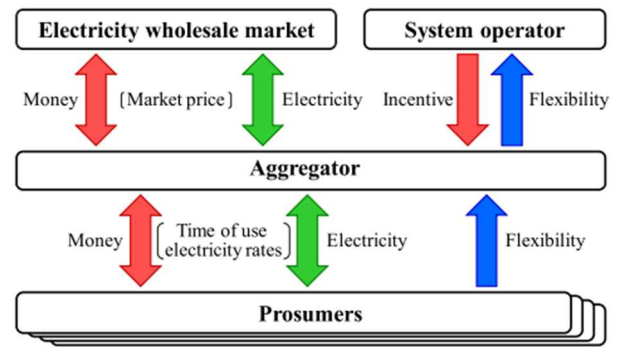

Fig. 1. Relations between aggregators, prosumers, market, and system operator [14].

As it is possible to observe in Fig. 1, the multiple relations between all the agents involved. The interconnection of all those parts helps to add flexibility and stability to the system.

C. Contribution

The core contribution of this manuscript is the enhancement of a strategy to reduce operational costs of a microgrid by using RES, ESS and thermal units. By maintaining its penetration at the maximum allowed to get the best benefits it can provide. Through testing different arrangements and combinations of RES, ESS and local thermal units it is possible to determine the best ratios and physical installation quantities to improve the value of energy.

By using mixed-integer linear programing which can find with each scenario where it is best to produce locally with thermal units and RES, or to import some power from the main grid, since there is a dynamic ToU tariff which changes every hour. The use of ESS power is also calculated in other to assure the lowest price of energy production. The existence of RES adds therefore an increased flexibility to the main grid, since now it needs to provide a smaller part of the global microgrid loads.

D. Paper Organization

This paper is composed of five sections. Section II presents the theory of the planned prototype used to find the optimal solution. In Section III it is possible to find the mathematical formulation is presented, along with the necessary assumption, and operational problems of the grid. Section IV not only presents the results from the best scenarios of the various tested, but also the original system without any kind of RES, ESS or local thermal units, it also demonstrates the best location for installing the various parts of the system. The final thoughts and conclusion may be found in Section V.

II. CONCEPTUALIZATION OF THE MODEL

As described in section II, several assumptions regarding RES penetration and ESS capacity installed where taken into consideration. This is the first constraint to this model. Since in many real-world scenarios, the designer of these types of systems, cannot install a random excessive amount of RES or ESS, most of the times due to budget constraints or just not having the available natural resources (wind, or open areas decent enough to create a solar farm). Thus, in every case there are limitations to accessible resources.

Consequently, the location of the various RES, ESS and Thermal units needs to be determined before the next problem is calculated.

The second part of this model focuses on the final cost problem. It uses a mixed integer linear programing problem (MILP), by considering each day with 24 timeframes of one hour each. The programing is executed using Time of Use DR for a day ahead operation.

The two issues described above depend on each other and can be changed as testing progresses to find the optimal solution which satisfies both.

III. MATHEMATICAL PROBLEM FORMULATION

A. Objective Function

The key function of this work is to determine how the Micro Grid should be design in a way to minimize the costs if running it. By experimenting with different amounts of RESs penetration, diesel generation quantities also taking into consideration the hourly changes of RESs productions and price variations of main grid. The main objective function is to minimize the total operating cost (TOPC), as follows:

Min

$$TOPC = \sum_{d=1}^{365} \sum_{i=1}^{N_B} \sum_{t=1}^{N_T} \left[F_{ci}\left(PG_{i,t,d}\right) + SUC_{i,t,d} + SDC_{i,t,d} \right] \quad (1)$$

The operational cost is calculated daily, and the system operator is responsible for determining the best strategy for that specific day, it performs the unit commitment (UC) problem to ascertain the best status of generation of the multiple power units as well as state of charge (SoC) of the EESs (charging or discharging of available energy storage units).

B. Assumptions

Before conducting any of the scenarios, some assumptions were needed.

For starters, and considering stability issues in the microgrid, the maximum penetration of RES is 20% of the peak power demand of 3.715MW, giving a maximum value of combined PV and Wind power of 743 kWp, which for purposes of availability of such machines was rounded up to 750 kWp. The same strategy was adopted for the ESS system, giving a maximum of 750kWh capacity. Regarding ESS, the maximum discharge and charge rate per hour is 10% of its maximum capacity, and the minimum store energy is also 10% of its maximum.

On the other hand, as for the location of the thermal units, RES and ESS, the chosen strategy, was to first locate in which buses were the larger loads located, and place these elements there, so the chosen buses are: Buses B7, B8, B24, B25, B30 and B32.

C. Operational Problem of the microgrid

The fundamental Operational Problem of the microgrid is the UC question. In this thesis an integer linear programing concept is used to solve it. Here, specifically, it is not a quadratic or cubic cost function since the thermal generators to be used are small and different combinations of them with multiple power targets can be set in order linearize the overall cost function Eq. (2) describes the running cost of thermal generators. Eq. (3) defines the minimum and maximum output of thermal generation units. In Eq. (4) are de decision variables that determine if the generators should start up or shut down.

Start up and shutdown costs and their respective binary variables can be demonstrated respectively by Eq. (5) and Eq. (6).

Eq. (7) is responsible for determining that the sum of all imports from the main grid, plus production of thermal units, RES and battery discharge/charge must be equal to the demand. Eqs. (8)-(12) are responsible for dealing with ESS installed in the system. The dynamic energy stored is shown in Eq. (8).

Minimum and maximum energy levels are modelled by Eq. (9), on the other hand, Eq. (10) deals with the initial (at t=0h) and final (at t=24h) energy values in the batteries, the levels are the same for each day. Eqs. (11) and (12) describe the hourly rate of charging and discharging. Since the resolution is based on hour-by-hour time frames, in each hour frame, either they are charging or discharging power to the loads.

Eq. (13)-(15) are used for the DC power flow. The amount of power that circulates is given by Eq. (13), the various capacities of the transmission lines ate in Eq. (14). In the reference bus the voltage angle is zero, Eq. (15) [15].

$$F_{ci}(PG_{i,t,d}) = a_i + b_i PG_{i,t,d} \quad (2)$$

$$PG_i^{\min} I_{i,t,d} \le PG_{i,t,d} \le PG_i^{\max} I_{i,t,d} \quad (3)$$

$$SU_{i,t,d} - SD_{i,t,d} = I_{i,t,d} - I_{i,t-1,d} \quad (4)$$

$$SUC_{i,t,d} = SU_{i,t,d} STU_i \quad (5)$$

$$SDC_{i,t,d} = SD_{i,t,d} SDU_i \quad (6)$$

$$PG_{i,t,d} + P_{i,t,d}^{RES} + P_{s,t,d}^{EES,Dis.} - PD_{i,t,d} - P_{s,t,d}^{EES,Ch.} =$$
$$\sum_{l \in NL_i} PL_{l,t,d} \perp \lambda_{i,t,d} \quad (7)$$

$$Eng_{s,t,d}^{EES} = Eng_{s,t-1,d}^{EES} + P_{s,t,d}^{EES,Ch.} . \eta^{EES,Ch.} - P_{s,t,d}^{EES,Dis.} / \eta^{EES,Dis.} \quad (8)$$

$$Eng^{EES,Min} \le Eng_{s,t,d}^{EES} \le Eng^{EES,Max} \quad (9)$$

$$Eng_{s,t=1,d}^{EES} = Eng_{s,t=24,d}^{EES} \quad (10)$$

$$0 \le P_{s,t,d}^{EES,Ch.} \le P^{EES,Ch.,Max} I_{s,t,d}^{EES,Ch.} \quad (11)$$

$$0 \le P_{s,t,d}^{EES,Dis.} \le P^{EES,Dis.,Max} I_{s,t,d}^{EES,Dis.} \quad (12)$$

$$PL_{l,t,d} = \frac{1}{X_l} \left(\delta_{l,t,d}^S - \delta_{l,t,d}^R \right) \quad (13)$$

$$PL_l^{\min} \le PL_{l,t,d} \le PL_l^{\max} \quad (14)$$

$$\delta_{l,t,d}^{ref} = 0 \quad (15)$$

The focus of the programing algorithm using this mathematical formulation is to find the lowest cost of operation for the whole 24h period.

Thus, it calculates when it is the best period to charge and discharge the batteries, when is it the better hour to use the thermal units or grid power, and of course, all the power generated from RES, is used since its price, unlike the grid or the generators is zero.

IV. SIMULATION RESULTS

For the purpose of testing this model, the standard IEEE 33 Bus system was adopted, as provided in Fig. 2. The hourly load share of each bus is provided in Table I.

The grid includes 32 transmission lines connecting all the 33 buses, and the system is only supplied by the main grid in bus 1 by a HV/MV transformer. The loads are distributed in 24 timeframes of 1 hour each completing a full 20-hour day, also each bus has its own load. The sum of all the loads and load distribution is presented in the graphs below, Fig. 2 and Fig. 3.

By looking at Table I, it is possible to locate where the largest loads are sited, Buses B7, B8, B24, B25, B30 and B32 have the largest loads, this is a very helpful analysis to help solve the master problem, since it becomes easier to spot possible locations for the Thermal units and RES. On the other hand, by comparing the results in Fig. 6, and the loads in Fig. 2, a possible location for ESS installation also reveals itself.

To test the mathematical model, multiple simulations were assessed. Here the four most relevant will be presented. As presented in Table II, the three scenarios with RES, wind power and solar PV and ESS values for each one.
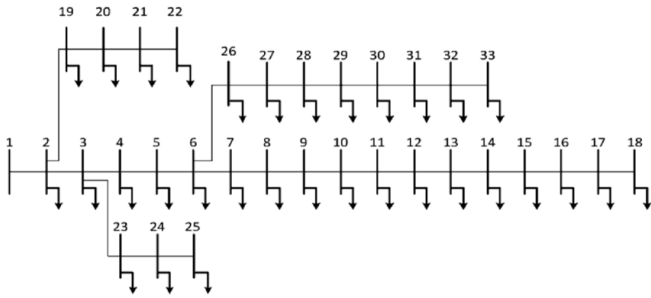
Fig. 2. Standard IEEE 33 Bus system

TABLE I. LOADS DISTRIBUTION PER BUS

Bus	Load Percentage	Bus	Load Percentage
B2	3%	B18	2%
B3	2%	B19	2%
B4	3%	B20	2%
B5	2%	B21	2%
B6	2%	B22	2%
B7	5%	B23	2%
B8	5%	B24	11%
B9	2%	B25	11%
B10	2%	B26	2%
B11	1%	B27	2%
B12	2%	B28	2%
B13	2%	B29	3%
B14	3%	B30	5%
B15	2%	B31	4%
B16	2%	B32	6%
B17	2%	B33	2%

From observation of Fig. 4, it becomes clear that imports from the main grid are much lower from 12:00 onwards, that happens due to the fact that before that, it is cheaper to import power, rather than turn on the generators within the micro grid. That fact is even more evident in Fig. 5, on all of the 3 tests with thermal units they all turn on at full power again at 12:00.

TABLE II. SCENARIOS SPECIFICATION

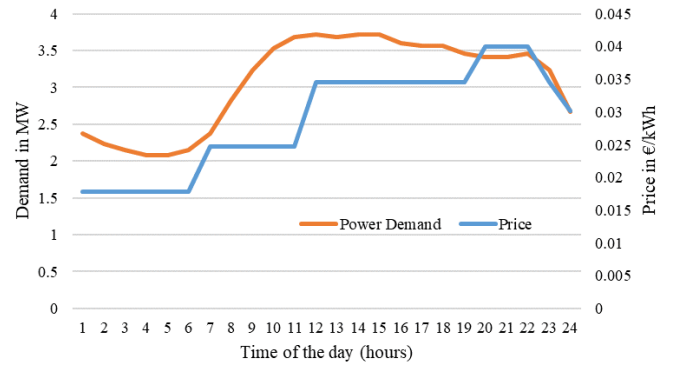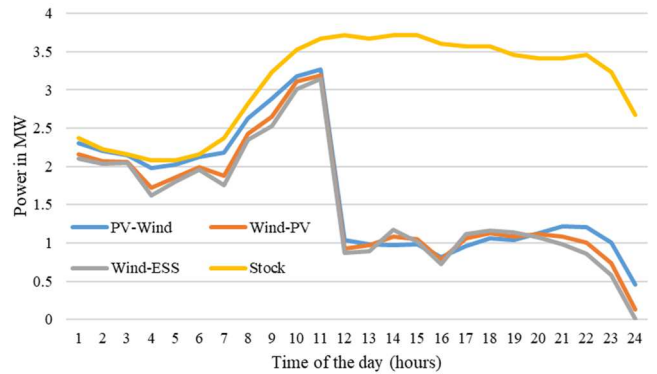| Simulation Case	PV (kWp)	Wind power (kWp)	ESS (kWh)	Thermal Gen. (MW)
Stock system	0	0	0	0
PV-Wind	550	185	375	2.1
Wind-PV	185	550	375	2.1
Wind-ESS	0	750	750	2.1

Fig. 3. Total system load and price in each timeframe
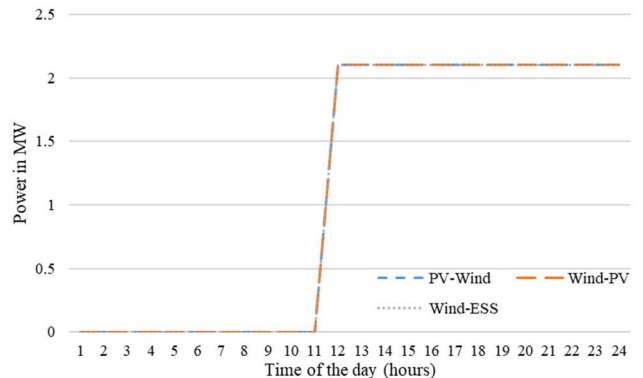
Fig. 4. Power imports from the main grid via Bus 1
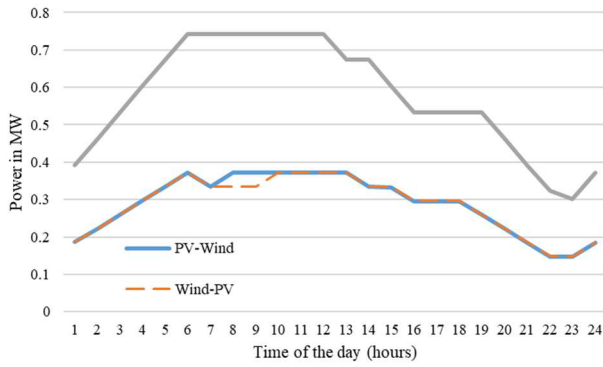
Fig. 5. Thermal generation in the micro grid

Fig. 6. Energy stored in ESS.

Simulation Case	Total daily Price (€)	Reduction (%)
Stock system	2.225	-
PV-Wind	1.857	16.54
Wind-PV	1.793	19.42
Wind-ESS	1.757	21.03

On Fig. 6, the energy stored in ESS is displayed, it shows that all of the systems, follow a similar pattern of charging and discharging throughout the day. When compared with Fig. 2, it becomes apparent why the charging and discharging happen in those time frames. From the period of 00:00 to 6:00 all the batteries charge, because energy is cheap in those hours. A period of constant charge follows. At that time, PV production is increasing, and it is still not worth to spend stored power. Around the same time as PV production goes down, there is also a Wind power gap, at that same time the price goes up. Considering these events, it is now worth to spend that stored power.

Finally, in Table III, the final cost of operation for each system is provided. Of all the scenarios tested, these last three gave the best results, when compared to the stock system. As it is apparent, the systems with higher Wind power penetration instead of PV can provide lower prices. This is, since solar PV can only provide power during daytime, and it achieves a peak performance only once a day at around 13:00. Therefore, wind power may have several peaks per day, on any hour, providing cheap power at any time of the day. The implementation of ESS may also influence the price, but not by much, as it becomes apparent in Table III, double the amount of ESS only reduced the price by another 2%.

The implementation of this system may also significantly improve the flexibility of the main grid. As seen on Fig. 4 the dependency of the microgrid is much lower from 12:00 onwards, by lowering the need to import power from Bus 1, in case of Islanding event, the MG may be able to sustain itself for longer, with less power curtailments. As future work, with improved ESS costs, a higher RES penetration would be possible, since there would be a better control for frequency and voltage. As RES penetration increases the overall cost would decrease even more, possibly reaching a cost of zero is most days of the year. As mentioned before, the overall impact of ESS in the final price is marginal, nevertheless, its existence is crucial for maintaining the stability of the microgrid. Since

V. CONCLUSIONS

In this research, a solution for optimizing usage of RES, distributed thermal generation and ESS systems, to lower the overall energy cost is proposed. Through testing different approaches by varying RES, ESS and thermal generation, an optimized solution is found. Although the Wind-ESS system is the cheapest to run, it implicates double the amount of ESS, for only less than 2% final savings. Still, a 19.42% improving not only means that the costumer is saving, but also

improving grid reliability and lowering emissions due to the presence of RES. It is also essential to note how the location of the RES, ESS and Thermal units is determined, in a real-world scenario there may be many more constrains that the designer needs to take in consideration.

REFERENCES

[1] E. A. Pina, M. A. Lozano, and L. M. Serra, "Allocation of economic costs in trigeneration systems at variable load conditions including renewable energy sources and thermal energy storage," *Energy*, vol. 151, pp. 633–646, May 2018, doi: 10.1016/j.energy.2018.03.083.

[2] G. C. Kryonidis, E. O. Kontis, A. I. Chrysochos, K. O. Oureilidis, C. S. Demoulias, and G. K. Papagiannis, "Power Flow of Islanded AC Microgrids: Revisited," *IEEE Trans. Smart Grid*, pp. 1–1, 2018, doi: 10.1109/TSG.2018.2799480.

[3] E. Aprilia, K. Meng, H. H. Zeineldin, M. A. Hosani, and Z. Y. Dong, "Modeling of distributed generators and converters control for power flow analysis of networked islanded hybrid microgrids," *Electr. Power Syst. Res.*, vol. 184, p. 106343, Jul. 2020, doi: 10.1016/j.epsr.2020.106343.

[4] M. S. Javadi, R. Azami, and H. Monsef, "Security constrained unit commitment of interconnected power systems," *Int. Rev. Electr. Eng.*, vol. 4, no. 2, pp. 199–205, 2009.

[5] R. Bonetto, T. Caldognetto, S. Buso, M. Rossi, S. Tomasin, and P. Tenti, "Lightweight energy management of islanded operated microgrids for prosumer communities," in *2015 IEEE International Conference on Industrial Technology (ICIT)*, Seville, Mar. 2015, pp. 1323–1328. doi: 10.1109/ICIT.2015.7125281.

[6] C. Klessmann, A. Held, M. Rathmann, and M. Ragwitz, "Status and perspectives of renewable energy policy and deployment in the European Union—What is needed to reach the 2020 targets?," *Energy Policy*, vol. 39, no. 12, pp. 7637–7657, Dec. 2011, doi: 10.1016/j.enpol.2011.08.038.

[7] I. Diagne and L. Mili, "Enhancing inter-area steady-state stability margins with microgrids," in *2013 IEEE Industry Applications Society Annual Meeting*, Lake Buena Vista, FL, USA, Oct. 2013, pp. 1–5. doi: 10.1109/IAS.2013.6682533.

[8] A. Kafetzis, C. Ziogou, K. D. Panopoulos, S. Papadopoulou, P. Seferlis, and S. Voutetakis, "Energy management strategies based on hybrid automata for islanded microgrids with renewable sources, batteries and hydrogen," *Renew. Sustain. Energy Rev.*, vol. 134, p. 110118, Dec. 2020, doi: 10.1016/j.rser.2020.110118.

[9] S. H. R. Ahmadi *et al.*, "Hybrid fuzzy decision making approach for wind-powered pumped storage power plant site selection: A case study," *Sustain. Energy Technol. Assess.*, vol. 42, p. 100838, Dec. 2020, doi: 10.1016/j.seta.2020.100838.

[10] M. S. Javadi, A. Anvari-Moghaddam, and J. M. Guerrero, "Robust energy hub management using information gap decision theory," in *Proceedings IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, 2017, vol. 2017 https://doi.org/10.1109/IECON.2017.8216073.

[11] J. Gouveia, C. Gouveia, J. Rodrigues, L. Carvalho, C. L. Moreira, and J. A. P. Lopes, "Planning of distribution networks islanded operation: from simulation to live demonstration," *Electr. Power Syst. Res.*, vol. 189, p. 106561, Dec. 2020, doi: 10.1016/j.epsr.2020.106561.

[12] F. Lilliu, A. Loi, D. Reforgiato Recupero, M. Sisinni, and M. Vinyals, "An uncertainty-aware optimization approach for flexible loads of smart grid prosumers: A use case on the Cardiff energy grid," *Sustain. Energy Grids Netw.*, vol. 20, p. 100272, Dec. 2019, doi: 10.1016/j.segan.2019.100272.

[13] H. Tan, H. Zhong, Q. Xia, C. Kang, and H. Dai, "Exploiting Integrated Flexibility from a Local Smart Energy Hub," in *2020 IEEE Power & Energy Society General Meeting (PESGM)*, Montreal, QC, Canada, Aug. 2020, pp. 1–5. doi: 10.1109/PESGM41954.2020.9281984.

[14] T. Kumamoto, H. Aki, and M. Ishida, "Provision of grid flexibility by distributed energy resources in residential dwellings using time-of-use pricing," *Sustain. Energy Grids Netw.*, vol. 23, p. 100385, Sep. 2020, doi: 10.1016/j.segan.2020.100385.

[15] M. S. Javadi, K. Firuzi, M. Rezanejad, M. Lotfi, M. Gough, and J. P. S. Catalao, "Optimal Sizing and Siting of Electrical Energy Storage Devices for Smart Grids Considering Time-of-Use Programs," in IECON Proceedings (Industrial Electronics Conference), 2019, vol. 2019-October, pp. 4157–4162. https://doi.org/10.1109/IECON.2019.8927263.