MICROGRID MANAGEMENT BASED ON ECONOMIC AND TECHNICAL CRITERIA

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ABSTRACT

Microgrids have gained much attention in recent years thanks to the promise of enabling enhanced energy load demand management and thus, combined with DER, optimizing energy resources allocation while decreasing the investment in underutilized infrastructures. Still, many aspects must progress in order to enable their full deployment, regulatory and technical. In this paper we focus on microgrid management in scenarios belonging to a unique stakeholder and propose a two level architecture and a novel combination of optimization algorithms to exploit the different control capabilities of the envisioned devices (schedulable, dimmable and thermal-like), including RES and electrical vehicle fleets. The results from the simulation of three different scenarios encourage the use of these devices and provide technological and economical insight.

1. INTRODUCTION

For many years diesel generators and Uninterruptible Power Supply units (UPS) have been used to prevent critical loads in facilities from power outages. This initial idea has evolved to the microgrid concept thanks to development of high efficiency Combined Heat and Power generators (CHP), the increasing penetration of Renewable Energy Sources (RES) and Information and Communication Technologies (ICT). Microgrids are currently considered to play a key role in the future smart grid to manage demand through Distributed Energy Sources (DER), reduce losses in energy transportation and pave the way to a more sustainable planet. Far from being a reality, many barriers have to be overcome, not only technical but also legal. Energy Management Systems (EMS) have to be extended with advanced algorithms and sensing to manage load demand, production and storage capacity taking into account not only electrical measures but weather conditions, economic signals and energy provider constraints. Also, interaction with utilities and distribution system operators (DSO) has to change adding bidirectionality in communications and energy exchange.

The work here presented has been developed in the framework of DER-IREC22@MICROGRID [1]. The main goals of this project are: creation of a platform for microgrid experimentation in the 22@ district of Barcelona, identification of technical barriers for its adoption, evaluation of the EV impact, and analysis of new energy management strategies taking into account the interaction between microgrids and electric distribution networks.

The focus of this paper is to present the design of a management system to optimize the performance of a microgrid taking into account technical and economic criteria and the results obtained in the simulations performed with the prototype developed within the project.

2. STATE OF THE ART

Microgrid research based on simulation studies, hardware laboratory projects and field tests are currently being developed in Europe, the USA, Japan, Canada and India [2]. In Europe, it is worth to mention the results of More Microgrid FP6 project that after studying appropriate control techniques and demonstrating the feasibility of microgrids operation through lab experiments conducted field tests with actual microgrids in several pilot sites round Europe [3]. In the USA, it is relevant the role of Galvin Electricity Initiative [4] and CERTS [5]. The first one proposes policies for the electric system transformation, develops prototypes based on smart microgrid technology and introduces quality management techniques, and the second one extends the concept of an EMS for a microgrid and tests reliability at a full-scale test bed.

From the many aspects involved in the operation of a microgrid, this paper focuses in its control system. There are different approaches when designing it, such as a centralized configuration, with a unique agent (head agent) like the one proposed by CERTS [5], or following a distributed configuration of a Multi-Agent System (MAS) [6], involving several agents acting and being able to take their own decisions. Furthermore, there are hierarquical configurations that merge the two architectures mentioned previously. In such architectures, devices are organized in a hierarchical scheme so that each level reports to the element of its higher level. Non-technological aspects affect the most appropriate design: a MAS is more appropriate when the devices on the microgrid search for its particular benefit, i.e., they belong to different owners, while a centralized configuration is more suitable when the microgrid is seen as a whole.

So far, the main topics that have been tested are automatic transitions between grid-connected and islanded (with no electric connection to the grid) mode of operation, voltage and frequency stability, and electrical protections against fault currents. However, there are still unsolved challenges regarding load modeling and EV impact in microgrids and, for extension, in smart grids. Indeed, specific load control features going beyond switch on/off, such as dimming according to context variable or changing set-points, need to be explored. Regarding EV, its behavior should be studied as a load and as a source when operating in V2G mode. Optimization algorithms developed for such systems must consider all these control capabilities.

3. MICROGRID'S MANAGEMENT ARCHITECTURE

The selected scenario in this paper, for the design of the microgrid management system, is the one envisioned in the early stages of microgrid model adoption, i.e., when all devices within a microgrid belong to a unique stakeholder or equivalently when it is operated by an Energy Service Company (ESCO). Another aspect that has been considered in the design is the time response: prices, demand reduction requests, or forecasted weather conditions have a resolution no greater than 15 minutes, while voltage or frequency control, especially in islanding mode, require a real time control in the milliseconds range. The proposed architecture design for microgrid management can be seen in Fig. 1.

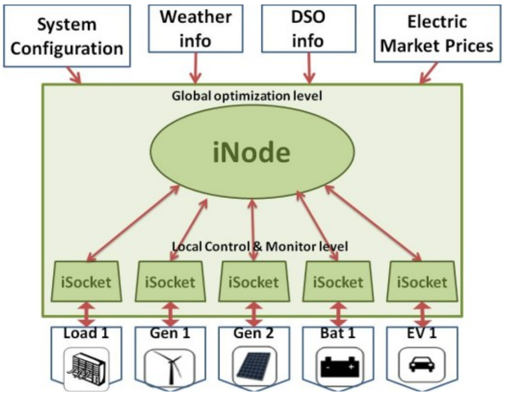


Fig. 1: Architecture proposed for microgrid management

A two-level hierarchy is defined. The central control unit, named iNode, is in charge of performing a global optimization for the microgrid taking into account current and forecasted values for inner power demand, production, storage capacity, power exchange capacity with the grid, price tariffs, weather conditions and potential emergency signals coming from the grid. The result of the optimization is a plan containing the power set-points for each device for the next hours. The optimization horizon, which is configurable, has to be set according to forecasted data available, microgrid operation needs and, eventually, electric market operation. Typically, it is set in the range of 24-48 hours because of main forecasted data availability. The resolution of set-points is set in the range of 5-15 minutes according to input data resolution. The set-points to be applied in the next period are dispatched down to the iSockets, the control elements at the bottom of the hierarchy. The iSockets are in charge of the local real time control at each device and are required to operate in the range of seconds or less. Note that voltage control, power factor, turbine speed, frequency stability are handled at this level. iSockets also send up-to-date status and measurements to iNode periodically or when the controlled device cannot fulfill the set-point assigned. When relevant deviations are detected because of model inaccuracy or unexpected conditions, a quick response mechanism based on spinning power reserve (also calculated as part of the schedule plan) is activated to balance the microgrid power and new power set-points are sent to the affected devices.

Regarding device models, they are categorized as sources, sinks or bidirectional devices depending on whether they generate, consume or both. A model consists of two components: *i)* the technical component contains the parameters required to compute the power production/demand and *ii)* the economic component includes the cost of power and quantifies the Quality of Service (QoS) perceived by the user using bonuses and penalties. As sources, micro-wind turbines and PV panels have been modeled. The technical model provides the maximum available power as a function of generator parameters and weather conditions. The economic model specifies the cost per kWh produced based on ROI criteria and adds a penalty for wasted energy (renewable energy not used is wasted). Loads, considered as sinks, are classified according to the management possibilities they offer:

- Time-controllable or schedulable: the power curve for a work cycle is known but the activation time can be modified. The technical model includes periods of time where the load can be activated and break points where the work cycle can be interrupted and resumed later. The economic part is modeled using penalties for not finishing the work cycle before all the activation time periods expire and for increasing number of interruptions. The most representative example is a washing machine.
- Power-controllable or dimmable: the power consumed can be diminished a certain percentage depending on context parameters. A penalty factor to quantify QoS impact describes the economic model. Lighting is a typical example of a dimmable load.
- Energy-controllable or thermal-like loads: they permit to modify the work cycle, meaning activation time and power consumed. In general, they can be seen as an energy storage device with a certain amount of losses. The main technical features of the model are the efficiency to convert electric power to the energy to be stored (i.e. heat) and the loss coefficient that can be context-dependant. The economic parameters quantify the QoS perceived by the user for deviation of the expected energy stored. Basically, this is the case of heating and cooling devices.

Batteries are categorized as bidirectional devices (whether fixed or as part of an EV) for which the storage capacity, the State Of Charge (SOC) at the beginning of the optimization period and the intended one at the end, and the SOC-V curve are provided. From the economic perspective, the cost per kWh provided or stored based on ROI, a penalty to avoid deep discharge cycles that shorten battery life cycle, and a bonus for exceeding minimum SOC required are configured.

Finally, power exchange between grid and microgrid is characterized by the maximum power that can be imported (buy) from the grid or exported (sell) to the grid which can be affected by demand reduction request or support to the grid request. The economic model includes prices per kWh and penalties to exceed the power thresholds in case of emergency conditions. The price of electricity includes two terms, one for supplied energy based on market price and another one for connection fee, which the microgrid has to pay both when buying and selling.

4. OPTIMIZATION ALGORITHMS ANALYSIS

The goal of a microgrid management system is to find the optimum trade-off between minimizing the cost of energy consumed inside the microgrid while maximizing the revenue for the energy sold to the grid and the QoS perceived by microgrid users. Four main aspects need to be modeled: the load demand, the energy production, the storage inside the microgrid and the energy exchange with the grid. As mentioned in Section 3, each device allows different levels of control. While dimmable and thermal-like loads, batteries and RES allow continuous power control (within a certain range) that can be managed using linear programming, schedulable loads introduce discrete variables (ON/OFF) that turn the optimization problem into NP-hard. The amount of potential combinations, even in a small scale microgrid, makes the exhaustive exploration of solution space unfeasible to come with a solution in the 5-15 minutes time range. We have taken a novel approach combining two algorithms according to the features above mentioned.

The selected linear programming approach has been a Minimum Cost Network Flow (MCNF) where dimmable loads, EVs, storage capacity available in batteries are sink nodes and renewable microgenerators, grid exchange (import) and energy stored in batteries are source nodes. A node for each device and time interval (5-15 minutes optimization period) is created. Links costs represent energy cost, while links capacity is constraint to maximum power according to device features.

For the schedulable loads optimization, we have analyzed the performance of a set of suitable algorithms from the literature, namely: Greedy, Simulated Annealing (SA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO) and Monte Carlo Tree Search (MCTS). They have been analyzed in an evaluation scenario consisting in scheduling 30 randomly generated loads within a period of 50 time units. Maximum amount of power varies randomly within the 50 time units range in such a way that it is not possible to provide power to all loads simultaneously. The total amount of possible combinations, taking into account that all loads have to complete their work cycle within 50 time units is $1.89 \cdot 10^{41}$. The objective function defined to measure the goodness of a solution is composed by two terms: one that measures the distance to power limit and adds a penalty when it is violated; the other, much lower compared to the violation term, penalizes the delay on the activation time.

The results obtained for the different algorithms can be seen in Table 1 (averages are computed over 50 experiments). Note that positive values indicate that the power necessary to supply all active loads exceeds power available at some time interval (penalty for overcoming the limit is 730). Evaluating the trade-off among simplicity of implementation, small number of parameters to be tuned, evaluation time and degree of optimization obtained, the algorithm selected to manage schedulable loads in the microgrid control management system has been SA.

	Best solution	Average solution	Finds a solution without limit violations
Greedy	747.4	760.3	No
SA	-6.7	402.4	Yes
PSO	725.0	728.0	No
ACO	-6.7	305.7	Yes
MCTS	-6.7	-6.7	Yes

Table 1: Performance of different optimization algorithms on the evaluation scenario

5. SIMULATION SCENARIOS

In this section we present three selected scenarios to show load demand management *i)* based on variable tariffs and demand reduction requests, *ii)* based on own generation and storage capacity, and *iii)* under outage conditions.

Devices' technical features have been obtained from manufacturer data sheets, weather conditions correspond to real data from Barcelona, and energy prices are based on electric market prices in Spain. Taking into account this data, we will study the degree of optimization achieved by the management system and some economic insights to be considered for their exploitation.

5.1. Price demand response and demand reduction request

The first scenario is aimed to demonstrate how load demand can be controlled by economic signals (variable tariffs) and non-economic signals (demand reduction requests) to explore the savings that can be achieved and the load side management capabilities. The microgrid is composed by a cleaning service EV fleet of 21 vehicles, where the energy supplied by the grid during a week should be minimized. The policies analyzed are: Flat, Time Of Use (TOU), Critical Peak Pricing (CPP), Real Time Pricing (RTP). Additionally, we introduce a demand reduction request sent by the DSO to study how the microgrid responses to such high priority signal.

Parameters of EV operation are known, such as arrivals and departures (EVs work in shifts), battery capacity, State of Charge (SOC) when arriving, and their minimum SOC required when leaving. Power set-points could range from 0 to 3.4 kW. The QoS is determined by the achievement of SOC required; a penalty for the missing load is applied when the level is not achieved and a bonus when exceeded.

5.2. Enhance microgrid management capacity

The second scenario is aimed to demonstrate how RES and storage capacity enhance load demand control when loads cannot be shifted to off-peak hours. Load demand control can relieve the grid from saturation situations, and including RES and batteries allow the microgrid to supply critical load demand in case of grid outages. The pay-back has taken into account, not only €/kWh generated, but QoS and avoided investments in grid infrastructures. The scenario proposed is to manage a hotel facility for a July weekend. The microgrid has to manage schedulable loads (3 washing machines, 6 dishwashers), dimmable loads (3 lighting areas) and thermal-like loads (4 air conditioned areas). The basic case is fostered firstly by the addition of a 3.5 kWp PV panel and a 3.5 kWp wind generator, and finally, by including a battery and 2 EV charging points. The iNode receives periodically price tariffs based on TOU policy and weather conditions (actual and forecasted) that affect not only the energy production based on renewable sources but also the air conditioning behavior and lighting dimmable margin. The details for the configuration of this scenario, which is the most complete in terms of devices, can be seen in Table 2 (detailed configuration for scenarios 1 and 3 is omitted due to space constraints).

5.3. Peninsula operating mode

This scenario focuses in the load demand of an office building for a workweek. Two different areas for lighting and air conditioning have been defined, in order to reflect the impact of weather conditions (temperature, solar irradiation, natural lighting) and usage. The microgrid has also RES (a 30 kWp PV panel), a 92 A·h battery and a 7 EV fleet that can be operated in V2G mode.

The office building has been configured to operate in peninsula mode, where the microgrid is connected to the grid and benefits from its voltage and frequency stability control system, but keeps the power imported from the grid to zero. Eventually, it supplies power to the grid when entering in emergency mode. Instead of investing in static capacity storage in the form of Li-Ion batteries, it is envisioned the usage of the storage capacity of the corporate fleet of EVs operated in V2G mode. Note that although legal adjustments are required to regulate such type of relationship among the stakeholders involved, technical advances have been made in this direction, developing charging points capable to either charge or discharge EV [8]. Finally, a penalty for high charge/discharge currents is introduced to avoid deep cycles, helping not to shrink battery life cycle.

6. SIMULATION RESULTS

6.1. Price demand response and demand reduction request

Table 3 lists the cost of the energy supplied to the fleet in the optimization period for the 4 price policies analyzed.

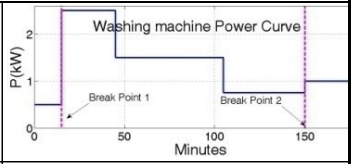
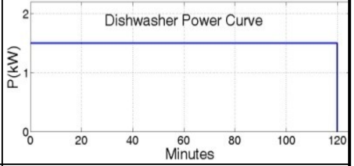
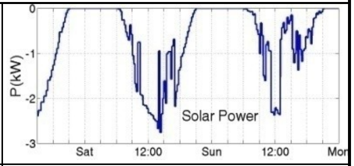
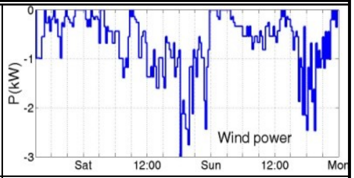
<table>
<tr><td>Optimization parameters</td><td>Horizon
Resolution
Period</td><td>48 hours
15 minutes
72 hours</td></tr>
<tr><td rowspan="2">Grid connection</td><td>Technical Parameters</td><td>Pmax: 69 MW
Pmin: 0</td></tr>
<tr><td>Economic Parameters</td><td>TOU policy<table><tr><td></td><td>Weekday</td><td>Sat</td><td>Sun</td></tr><tr><td>€/MWh</td><td>[35,75]</td><td>[35,50]</td><td>[45,55]</td></tr></table>Fix connection fee: 25 €/MWh</td></tr>
<tr><td rowspan="2">Air Cond.</td><td>Technical Parameters</td><td>Pmax 8 kW SetPoint Temp 23 °C
Zone1/Zone2 with direct sunlight
Zone3/Zone4 are inner areas</td></tr>
<tr><td>Economic Parameters</td><td>Penalty factor to be applied over energy cost:
2 for ±1°C deviation
10 for ±2°C deviation</td></tr>
<tr><td rowspan="2">Washing machine</td><td>Technical Parameters</td><td> </td></tr>
<tr><td>Economic Parameters</td><td>Retry penalty: 10 €/retry
Non-service penalty: 500 €/kWh
Wasted energy penalty: 1000 €/kWh</td></tr>
<tr><td rowspan="2">Dishwasher</td><td>Technical Parameters</td><td> </td></tr>
<tr><td>Economic Parameters</td><td>Retry penalty: 10 €/retry
Non-service penalty: 1000 €/kWh
Wasted energy penalty: 1000 €/kWh</td></tr>
<tr><td rowspan="2">Lighting</td><td>Technical Parameters</td><td>P=1 kW
Zone1: ON always
Zone2: ON from 20:00 to 07:00
Zone3: ON from 21:00 to 01:00</td></tr>
<tr><td>Economic Parameters</td><td>Dim factor of 10% allowed</td></tr>
<tr><td rowspan="2">PV panel</td><td>Technical Parameters</td><td> </td></tr>
<tr><td>Economic Parameters</td><td>Price : 0.15 €/kWh
Wasted energy penalty: 100 €/kWh</td></tr>
<tr><td rowspan="2">Wind turbine</td><td>Technical Parameters</td><td> </td></tr>
<tr><td>Economic Parameters</td><td>Price : 0.40 €/kWh
Wasted energy penalty: 100 €/kWh</td></tr>
<tr><td rowspan="2">Battery</td><td>Technical Parameters</td><td>Qmax: 141 A·h Pmax 10.5 kW
$SOC_0 = 50\%$ $SOC_1 = 25\%$</td></tr>
<tr><td>Economic Parameters</td><td>Price = 0.04 €/kWh
Penalty = 50 €/kWh missed at the end</td></tr>
</table>

Table 2: Configuration for enhanced management microgrid capacity scenario

Additionally, the degree of optimization achieved compared to a non-optimized management, meaning the EV starts charging when plugged, is presented.

Price policy	Cost of energy (€)		Savings (%)
	Optimized management	Non-optimized management	
Flat tariff	261.69	261.69	0.0
TOU	206.17	280.56	26.5
CPP	212.62	297.53	28.5
RTP	220.71	252.42	12.6

Table 3: Cost of energy for 4 different price policies

The results show that it is possible to achieve some savings even when no DERs are present by managing the charge of EV. The savings depend on the price spread between maximum and minimum price and time spread between the charging and parking time. The scenario has been defined using realistic data for prices and EV shifts. For this EV 21 fleet, 4400 €/year could be spared with the CPP policy.

Furthermore, in the case of a high priority demand reduction required by the grid, the microgrid reduces the demand (even if it occurs during low prices period) adapting its schedule and power levels to the new power availability (see Fig. 2). In this case, the QoS in the microgrid is not affected since the level of charge at departure time is assured, and the grid has avoided a complete outage thanks to load demand management.

6.2. Enhance microgrid management capacity

For the depicted hotel, without DER the iNode's actions are limited to schedule loads taking into account energy prices and time constraints. As expected, potential savings for this scenario are small (1.5 %) since the modeled schedulable loads cannot be shifted to off-peak hours without affecting the QoS.

On the other hand, the addition of RES on such situations, i.e., when the highest demand occurs at peak price hours, has a positive effect in the economic balance with the grid since the importation of grid energy at high prices is avoided. For PV panels, the peak production would match peak demand in this scenario. For the case of wind power, the additional installation of storage capacity enhances the management capability to balance generation and load demand. Fig. 3 illustrates the effect of adding RES and batteries to the hotel facility in terms of energy imported to the grid, waste of renewable energy and cost of energy paid to the grid. As we can observe, the energy imported from the grid is reduced more than 60% when RES and batteries are added.

Note though, that the installation and maintenance costs of RES should be taken into account when performing the complete economic analysis. Although we are aware that current prices will change in the future, we perform some calculations to obtain some interesting insight. The cost of energy produced by RES, calculated using ROI criteria, is 4.95€ for solar and 15.34€ for wind sources, while the savings for energy not bought to the grid correspond to 5.05€ and 2.74€ for the two sources respectively. Further, we need to consider that the fee for the contracted power to the grid (16.28€ for this 3-day scenario) could be reduced when adding RES and batteries due to a lower maximum power level required. Finally, we should take into consideration that subsidies for grid prices may disappear in the future. Therefore, although RES and batteries can be installed to prevent power outage situations and keep critical systems running, some set-ups (such as the PVs in our scenario) may be worthwhile also in normal operating modes for cost savings.

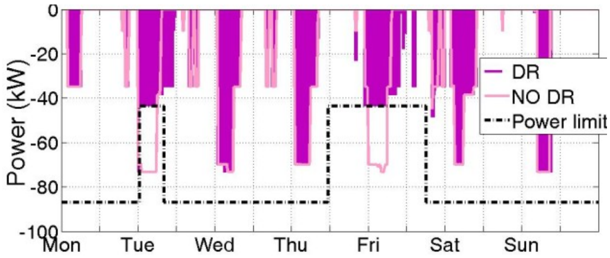


Fig. 2: Power bought to the grid when demand reduction request (DR) applied compared to no demand request

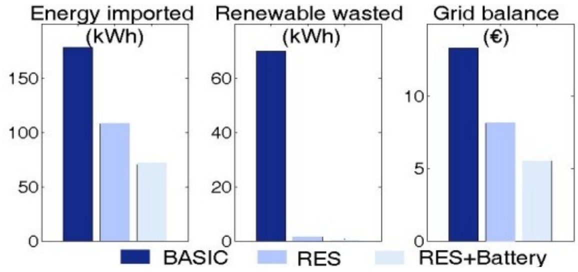


Fig. 3: Enhancement of management capacity adding RES and batteries for the hotel facility microgrid

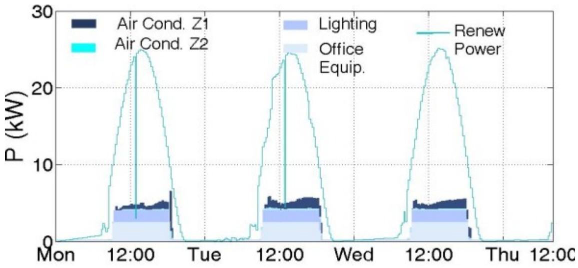


Fig. 4: Load demand and energy production for office building microgrid

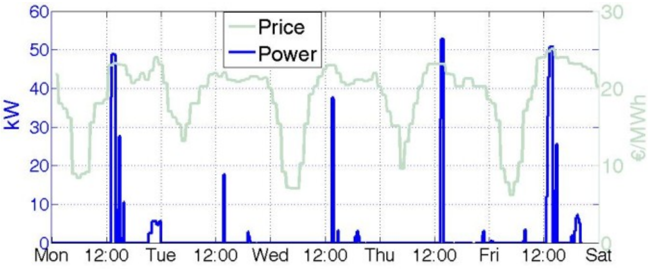


Fig. 5: Power and prices for energy sold to the grid in scenario 6.3

6.3. Peninsula operating mode

In this scenario, the energy produced for the PV panels covers the inner load. In fact, there is a surplus of energy that can be sold to the grid. The EV batteries increase not only the storage capacity but also the flexibility to adapt the demand to the renewable energy production. As seen in Fig. 4, although the office building demand increases during peak hours (energy needed for cooling when temperature rises), there is an excess of power coming from the PVs that can be used to charge batteries or to sell it to the grid. Since the prices at peak hours are very attractive, the strategy adopted is to sell energy to the grid when prices are higher and charge EV batteries at off-peak hours, as seen in Fig. 5.

This scenario shows how a microgrid can balance power and support the grid, avoiding the investment in fix energy storage capacity, which nowadays is only justified for non-interruptible critical loads supply.

7. CONCLUSIONS AND OUTLOOK

In this paper we have proposed a microgrid architecture based on two hierarchical levels to manage scenarios with a single owner, or where a common optimization is pursued. Further, the combination of two different types of algorithms has been proposed to exploit the diverse control capabilities of the envisioned devices (schedulable, dimmable and thermal-like) in order to achieve an optimal microgrid management with DER.

The results obtained in three different simulation scenarios show how microgrids offer the capability to design a load demand curve avoiding peak hours and minimizing the investment in expensive underutilized infrastructures. Further RES appear to enhance microgrids operation while managing load demand and supporting the grid in emergency conditions.

However, several issues rose, which should be addressed to motivate their market adoption. Batteries turn to be a key element to meet power production with load demand, but they are still very expensive compared to current market electricity price spread. EVs could be a good candidate to substitute fixed batteries to play this role in certain scenarios. Utilities must promote attractive offers, e.g., in terms of variable tariffs, to counteract initial investments. Finally, microgrid operation will be only possible if regulators and device manufacturers are able to meet expectations.

As future work, we plan to study a multi-microgrid scenario where microgrids participate on an energy market, provide ancillary services and spinning reserve to the grid.

8. ACKNOWLEDGMENTS

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