Prosumers' Optimal DER Investments and DR Usage in Isolated Microgrids.

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***Abstract*— Fostered by environmental concerns, technology evolution and economic improvements, distributed energy resources (DERs) are expected to play a major role in the future electric power delivery. Also, the deployment of Energy Management Systems (EMS) and Smart Meters is paving the way for end-users to adopt a much more active role using demand response (DR) programs by hand of retailers and aggregators. Since resiliency is taking importance nowadays, Microgrids (MGs) are being discussed in the literature. This paper focuses on the MG operating on islanded mode and proposes a local market based approach to manage the economic flows among agents, formulated as a MCP. The paper proposes a model for the optimal investment and operation of DER within a MG under this scheme. End users obtain their optimal operation taking advantage of the existing synergies between electrical and thermal loads. Furthermore, and as a relevant contribution of this paper, a temperature model for buildings, able to consider its thermal inertia, has been developed and included in the optimization formulation in order to better identify the DR capabilities regarding prosumers' thermal needs. Effects of including DER technologies and DR are presented in a case study.**

Keywords- Energy Management; Renewable Sources; Energy Storage; Microgrid Isolated Operation; Demand Response; Microgrid Local Market; Building Themal Model.

I. INTRODUCTION

Future electrical distribution systems will experience significant changes with respect to current distribution networks. They will be closely linked to the concept of Smart Grids defined as an automated power delivery network that uses information and communication technologies to control it in order to obtain a two-way flow of electrical power, high renewable penetration and lower CO_2 emissions among other benefits [1].

Aggregation of loads and DERs are going to be a crucial part in future distribution systems. Not only DERs can reduce thermal or electric consumption in each house independently but also some of them can take advantage of the existing synergies among gas, air conditioning and electricity. Moreover, Energy Storages (ES) and Electric Vehicles (EVs) can modify the current electrical systems operation by being able to provide new ancillary services. Therefore, aggregating resources have two main advantages: the first one is the capability of offering services to the grid from small groups of end users and the second one is to obtain advantages from the global operation of these resources. Other advantages over individual DER operation are described in [2].

Table 1 offers different types of aggregation such as MGs, dispersed aggregation, Virtual Power Plants (VPPs) and EV fleets.

Table 1 Aggregation Summary

Aggregation	**What**	EV	DG	ES	Loads (Residential, Commercial, Industrial)
	Ways	EV Fleets	VPP		-
		Aggregation of dispersed consumers			
		Microgrids			
	Type of services	Buy/Sell Energy			
		Buy/Sell Ancillary Energy Services			
	How	Charging Strategies	Operation Management		Demand Response

Public policies in many countries are trying to mitigate the consequences and to avoid future effects of climate change. These policies lead to more efficient, less polluting and energy self-sufficient systems. In addition, countries are making efforts to provide universal access in developing countries which will result in new decentralized business models. Thus, enhanced efficiency, security and grid resiliency are becoming objectives of high priority in recent times.

However, these goals are very difficult to accomplish. MG seems to be one of the best solutions to address energy challenges such as penetration of renewable energy resources and resiliency. For sure, resiliency is one of the most important contributions that MGs can offer due to their capability of operating without connection to the grid. The importance of resiliency and the use of MGs are being analyzed in Maryland [3]. This solution requires decentralized business models and local market approaches to balance demand and supply and allocate energy prices. Nevertheless, from the point of view of improving system efficiency, centralized schemes may take advantage of economies of scale. Thus, VPPs, EV fleets and remote aggregations of loads would be proper choices.

In our view, different MGs will form the distribution level in future electric systems. If a disturbance happened in any point of the distribution network, an MG can change its operation mode to islanded mode. However, an MG will be connected to the grid during normal operation conditions and it could sell/ buy energy to/from the grid. Separately, buildings do not have enough size to affect the system. For this reason, the role of an aggregator, like an entity, in charge of the operation of the MG would be required.

In addition, end-users will have EMS in order to execute DR programs. DR changes passive buildings to active elements in order to obtain the desired energy objectives [4]. These programs allow modifying the consumption patterns of the end-users in order to obtain the lowest cost in the market. Studies related to DR have increased in recent times. For example, a DR algorithm for primary frequency regulation which minimizes the number of loads modified is presented in [5], and [6] studies DR in residential MGs in order to minimize energy costs and improve the stabilization of the aggregation of residential loads (load-flattening). More algorithms for market models where the aggregator decides the demand pattern are studied in [7] and [8]. In our model, DR can be executed in two different ways: modifying thermal consumptions and shifting a percentage of the electrical demand related to appliances to other periods.

Planning of distributed resources and operation optimization problems have been studied mainly in systems connected to the grid. DG deployment plans (capacities, location and time frame of the investments) are studied in [9] taking into account distribution network reinforcements. [10] obtains the optimal planning and operation of the most common DER under different pricing scenarios in Madrid, Spain through a linear programming model. Apart from these studies, there are tools which investigate the planning and operation of MGs. For instance, Berkeley Laboratory has created a model called DERCAM which analyzes the investments and dispatch of DER that minimize costs or emissions using the following inputs: consumption, weather, DER technology and tariffs data [11]. Similar tools are reviewed in [12]–[14] where they are compared according to different factors such as: the energy sector, the time-step, the geographical area and the time-frame considered in each model.

On the other hand, planning and operating distribution systems in islanded mode is not studied as much as in the grid-connected case. [15] studies a radial distribution network in islanded mode. In this mode of operation, studies are mostly focused on voltage and frequency regulation. For instance, control strategies in an MG for different cases such as grid-connected mode, pre-planned islanding, line-to-ground faults and line-to-line faults are shown in [16]. [17] proposes an MG emergency energy management algorithm which consists of three steps: characterization of the operating state, determining the power disturbance in order to define the amount of load to be shed and the evaluation of the security of the MG during the emergency state. Another example is found in [18] where the islanded system is made up of several loads and three MGs that participate in the local "wholesale" electricity market. In addition, some projects have investigated this topic. For example, the MORE MICROGRIDS project [19] mentions the idea of local markets, although it is not clear in the literature how the production of each unit is going to be set in the islanded mode. [20] operates DERs in an MG as a VPP, but they belong to the same owner who uses priorities to set their operation. However, all these references only consider MGs exchanges and none of them is considering what happens inside a residential MG.

Generally, studies in this topic do not tackle the problem of what happens inside a MG and how generators can decide how much energy they should produce. For instance, [20] has only one agent who decides the operation of the generators and loads; and [18] considers MG like an element which can consume or generate. Thus, the objective of this work is to design the DG and energy storage systems for the optimal operation of a residential MG when it operates in islanded mode. In order to balance generation and demand, a market equilibrium inside the modeled MG has been developed. Other contributions of this work are the temperature model presented, the market approach inside a MG where each agent tries to obtain its better result and the way DR is considered in the model.

To this end, the paper is structured as follows. First of all, Section II describes the operation of our concept of MG and the designs of the market and the temperature model utilized. Afterwards, Section III describes the formulation of the complete optimization model. Later on, Section IV presents the data used and the scenarios analyzed. Next, the results from each scenario are shown in Section V. Finally, a comparison among scenarios is done in Section VI.

II. PROPOSED APPROACH

In our concept of a system made up of several MGs, each one will have an exclusive MG Operator (MGO), which can be selected. This MGO can act as an aggregator of different MGs when the MG acts in grid-connected mode. Grid-connected mode would be the normal operation mode until any contingency happens. If this MGO has enough aggregated energy to participate in the market, it will sell/buy energy to/from it (a1 in Figure 1). However, if the amount of energy is not enough, the MGO will negotiate with a retailer (a2 in Figure 1). During the isolated operation mode, the MGO will be in charge of guaranteeing the balance among users acting as a market operator for them (Figure 1).

In both operation modes, Energy Boxes (EB) from generators and end-users will send their operation parameters (electrical and thermal in the case of houses) to the MGO. Then, the Management System (MGMS) of the MGO will send the commands (prices/power curves) back to the EBs to know how they should operate. When the MG is grid-connected, the price will be the one obtained in the market, whereas in the isolated mode the prices should guarantee the equilibrium inside the MG. To this end, this paper presents a market model for the isolated case where each agent tries to minimize its costs. Additionally, a temperature model which represents a smart thermostat in the energy consumption of a house is included in order to represent the effects of thermal loads in DR.

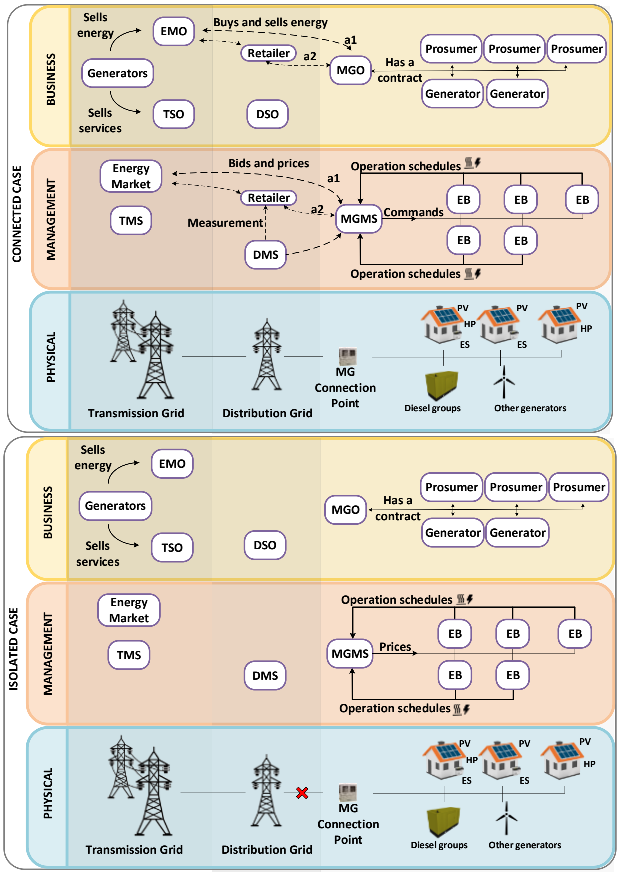

Figure 1: Operation schemes of MGs divided in physical elements, management systems and business actors

Investments should be done considering the total time that a MG operates in grid-connected and islanded mode. This paper focuses on the isolated case as a first approach to combine both operation modes.

A. *Market Model –Problem Description*

As stated earlier, a market model is needed in the isolated case. In practice, this model (Figure 2) consists of different agents (generator and end users) who will send their consumption and supply bids to the MGO, which will check the balance and will send back prices per each hour until generation and demand were matched. Each agent expresses its availability to sell using a cost per kW of energy sold. Each end-user can regulate their consumption controlling the output of their energy storages and their demand profiles. Finally, the final price will be the result of the equilibrium among all the agents.

The previous process could be carried out as a day-ahead market in order to send the final prices for the next 24 hours to the energy boxes. Moreover, more than 24 hours can be executed for long-term investments.

As mentioned, the isolated MG consists of end users and generators of different agents. These generators should be designed to provide the necessary power to the end-users when they do not have DG or energy storages. The reason for that is to be able to supply the energy required in every moment.

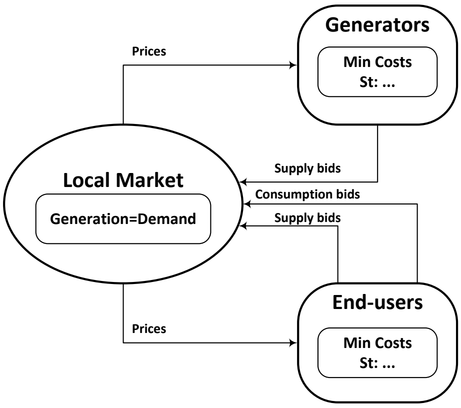

Figure 2: Market flow between agents

B. *Temperature Model*

One step further has been done from [10], [21] where heating systems where included inside domestic thermal usages. In this paper, thermal loads are related to domestic hot water (DHW) and kitchen appliance consumptions. Heating consumption is calculated taking into account the outdoor temperature, and minimum and maximum temperature bounds.

For this particular approach, indoor temperature needs to be represented taking into account variations in outdoor temperature, indoor heat sources and its maximum and minimum values. Figure 3 has been considered as the model to obtain the equations for representing the temperature behavior throughout the day.

In Figure 3, capacitor C represents thermal energy stored by the wall in a house and resistances R_1 and R_2 model the existing convention between the air and the wall. Outdoor temperature T_{out} is considered as a voltage source, since temperature changes are considered negligible in an hour, and heating input Q is symbolized as a current source. Finally, indoor temperature T_{ind} is the voltage level at the output of the current source.

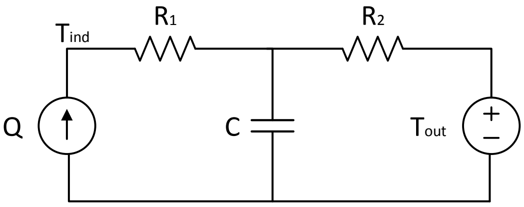

Figure 3: Equivalent electric circuit to represent indoor temperature behavior.

Obtaining the indoor temperature T_{ind} from Figure 3, (1), and applying a simple discretization method (2), we obtain the equation (3) that models the indoor temperature when the sample time T is 1 h:

$$T_{ind} = \frac{T_{out}}{CR_2 s + 1} + Q \cdot \left(R_1 + \frac{R_2}{CR_2 s + 1}\right) \tag{1}$$

$$s = \frac{z-1}{T} \tag{2}$$

$$T_{ind}(t) = T_{ind}(t-1) + \frac{1}{CR_2}\left(T_{ind}(t-1) - T_{ind}(t-1)\right) + Q(t)\cdot R_1 + Q(t-1)\cdot\left(\frac{R_1+R_2}{CR_2} - R_1\right) \tag{3}$$

Without heating systems, the authors estimate that a house can take around 2 days to reach the outdoor temperature. This time will be equal to $5\cdot\tau$, being τ the time constant which is equal to CR_2 in this circuit. [22] studies the optimal thickness for houses in Madrid and it includes a study of the U-values where R_1 and R_2 are estimated as 10ºC/kW. Thus, *C* takes a value of 1kWh/ºC.

III. COMPLETE MODEL

This optimization problem is formulated as a mixed complementarity problem (MCP) that is used to solve equilibrium problems. Although the case study presented here considers a perfect competition ($\theta_i=0$), which is equivalent to a NLP problem whose objective function is the total cost, this formulation allows considering the effect of imperfect competition. Since the following formulation is convex, global optimal solution is guaranteed.

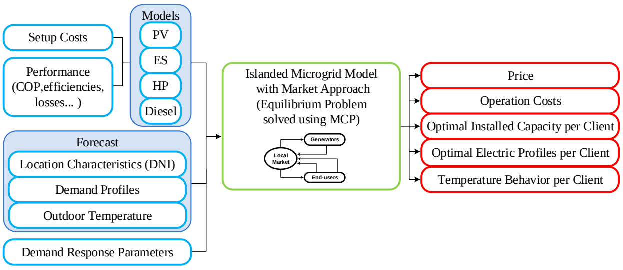

Figure 4: Inputs and outputs of the optimization problem

The designed model presented below is shown in Figure 4. In this scheme, inputs and outputs of the model can be observed. In order to obtain the optimal planning and operation of DERs and their cost in a year, the model needs as inputs the forecast of the geographical characteristics, consumption behaviors and the percentage of load that could be shifted and DER models.

As representative for DG technologies for electric and thermal energy production, solar photovoltaics (PV) and air-source heat pumps (HP) have been selected. Nevertheless, other energy sources are described in our previous studies [10][21] and they can also be included. However, the main difference with previous work is the market approach inside the MG and the temperature model with allow studying thermal loads in detail.

A. Nomenclature

1) Sets:

h	hour
d	day
i	agent
t	type of consumption

2) Parameters:

MCost	Maintenance Cost increment over installation cost (%)
dieselRatio	Power per each liter of fuel (kW/L)
dieselCost	Cost per each liter of fuel (USD/L)
demandShift	Percentage of demand that can be shifted in a day(%). [23]
$sellCost_i$	End-users' minimum price per power sold that they want to receive (USD/kW)
θ_i	Conjectured price- response parameter [(USD /kWh)/kW]
$dieselCapacity_i$	Installed capacity of the retailer generator(kWh)
lossesPV	Total electric losses of PV (%)
lossesHP	Total thermal losses (%)
DNI_h	Direct normal irradiance at hour h (W/m^2) [24]
costPV	Cost per installed kW of PV (USD/kW)
costHP	Cost per installed kW of HP (USD/kW)
costsES	Cost per installed kW of Battery Capacity (USD/kW)
costET	Cost per thermal energy bought (USD/kW)
costENS	Cost per energy not served (USD/kWh)
COP	Coefficient of performance of HP
effBat	Battery charge/discharge efficiency ratio (%)
$demandCurve_{h,\,t}$	Normalized electric demand curves (%), Figure 6and Figure 7. [25]
$demMens_d$.	Normalized demand evolution through the year (%), Figure 8 [25]
demandElecAnnual	Total annual electric demand (kWh) (lighting + Appliances)
$demandThermAnnual_i$	Total annual thermal demand (kWh) (DHW + Kitchen)
$clientType_i$	Type of client in each house.
Tout	Outdoor Temperature (ºC) [26]
$UA=R_1+R_2$	Heat transfer coefficient (ºC/kW) [22]
C	Capacitor (kW/ ºC)

Finally the electric demand is calculated with the following formula taking into account the type of demand curve per each client:

$$demand_{i,h} = demandCurve_{h,t}\cdot demMens_d \cdot demandaElecAnual/365$$

3) Positive Variables:

$powerPV_i$	Installed capacity of PV in house *i* (kW)
$powerHP_i$	Installed capacity of HP in house *i* (kW)
$batCapacity_i$	Installed capacity of the battery system in house *i* (kWh)
$GES_{i,h}$	Electricity sell in house *i* to the grid at hour *h* (kWh)
$GEB_{i,h}$	Electricity bought in house *i* from the grid to meet the demand at hour *h* (kWh)
$BET_{i,d}$	Total thermal energy bought in house c from the grid to meet the daily demand in day *d* (kWh)
$ENS_{i,h}$	Energy Not Served of house *i* at hour *h* (kWh)
$lDiesel_{i,h}$	Liters of diesel used by a diesel generator of house *i* at hour *h*.(L)
$SOC_{i,h}$	Battery State-of-Charge of house *i* at hour *h* (kWh)
$Discharge_{i,h}$	Energy discharged from battery of house *i* at hour *h* (kWh)
$Charge_{i,h}$	Energy charged to the battery of house *i* at hour *h* (kWh)
$decDem_{i,h}$	Decrease in the demand of house *i* at hour *h* (kWh).

$incDem_{i,h}$	Increase in the demand of house *i* at hour *h* (kWh).
$newDem_{i,h}$	New consumption curve after changing the profile. (kWh)
$price_{h}$	Price agreed by all the agents at hour *h* (USD)
$Tind_{i,h}$	Indoor temperature of house *i* at hour *h* (ºC)
$ACInput_{i,h}$	Air Conditioning of house *i* at hour *h* (kWh).
$HPtemp_{i,h}$	Electricity for heating in house *i* at hour *h* (kWh)
$HPther_{i,h}$	Electricity for thermal demand in house *i* at hour *h* (kWh)
$Gastemp_{i,h}$	Thermal energy bought for heating in house *i* at day *d*, hour *h* (kWh)
$Gasther_{i,d}$	Thermal energy bought for thermal demand in house *i* at day *d*, hour *h* (kWh)

B. Mathematical formulation

This section presents detailed mathematical formulation of the model used to find the optimal scaling and operation of the DG systems in an isolated MG.

In order to better understand this problem, it could be expressed as the following optimization problem:

$$\forall i \begin{cases} Minimize\ PlCost(X) + OpCost(X) \\ \quad st: \quad G(X) \geq 0\ :\ \lambda \\ \qquad\qquad H(X) = 0\ :\ \mu \end{cases} \tag{4}$$

$$X = \{GES_{i,m,h}, GEB_{i,m,h}, BET_{i,m} \ldots\}$$

$$\sum_{i=1}^{I} GES_{i,m,h} = \sum_{i=1}^{I} GEB_{i,m,h} \qquad \forall m, h \tag{5}$$

where λ and μ are dual variables of the non-equality and equality constraints presented above. This problem seeks to minimize the operational costs (*OpCost*) and installation costs (*PlCost*) which are defined as:

$$\begin{aligned} OpCost(X) = \sum\nolimits_{h} &\left[(sellCost - price_{h}) \cdot GES_{i,h} + lDiesel_{i,h} \cdot dieselCost \right. \\ &\left. + price_{h} \cdot GEB_{i,h}\right] + \sum\nolimits_{d} costET \cdot BET_{i,d} \end{aligned} \tag{6}$$

$$\begin{aligned} PlCost(X) = costPV \cdot powerPV_{i} + costHP \cdot powerHP_{i} + costES \\ \cdot batCapacity_{i} \end{aligned} \tag{7}$$

As mentioned, this kind of problem can also be formulated using an MCP. MCP problems are used to solve single-level investment and operation equilibriums. This process is explained in the literature in specific cases such as [27] or in deeper theoretical background in [28]. In our case, eq. (8)-(11) represents the KKT conditions of the model (4)-(5):

$$\nabla_{X}\big(PlCost(X) + OpCost(X)\big) + \lambda^{T}\nabla_{X}G(X) + \mu^{T}\nabla_{X}H(X) \geq 0 \perp X \geq 0 \tag{8}$$

$$\lambda \geq 0 \qquad \mu = free \tag{9}$$

$$\lambda \perp G(X) \qquad \mu \perp H(X) \tag{10}$$

$$\sum\nolimits_{i=1}^{I} GES_{i,h} = \sum\nolimits_{i=1}^{I} GEB_{i,h} \qquad \forall h \quad \perp \quad price_{h} \geq 0 \tag{11}$$

Where derivatives of the Lagrangian (8) are:

$$\frac{\partial \mathcal{L}}{dGES_{i,h}} = sellCost_{i} + \theta_{i} \cdot GES_{i,h} - price_{h} + \mu_{(43)} \geq 0 \perp GES_{i,h} \tag{12}$$

$$\frac{\partial \mathcal{L}}{dGEB_{i,h}} = price_{h} - \mu_{(43)} \geq 0 \perp GEB_{i,h} \tag{13}$$

$$\frac{\partial \mathcal{L}}{dlDiesel_{i,h}} = dieselCost + \big(\lambda_{(34)} - \mu_{(43)}\big) \cdot dieselRatio \geq 0 \perp lDiesel_{i,h} \tag{14}$$

$$\frac{\partial \mathcal{L}}{dBET_{i,d}} = costET - \mu_{(44)} \geq 0 \perp BET_{i,d} \tag{15}$$

$$\frac{\partial \mathcal{L}}{dcharge_{i,h}} = \mu_{(42)} \cdot effBat + \mu_{(43)} \geq 0 \perp charge_{i,h} \tag{16}$$

$$\frac{\partial \mathcal{L}}{ddischarge_{i,h}} = \lambda_{(33)} - \mu_{(42)} - \mu_{(43)} \geq 0 \perp discharge_{i,h} \tag{17}$$

$$\begin{aligned} \frac{\partial \mathcal{L}}{dHPtherm_{i,h}} = \mu_{(43)} + \lambda_{(35)} - \mu_{(45)} \cdot COP \cdot (1 - lossesHP)\{h \in d\} \geq 0 \\ \perp HPtherm_{i,h} \end{aligned} \tag{18}$$

$$\begin{aligned} \frac{\partial \mathcal{L}}{dHPtemp_{i,h}} = \mu_{(48)} \cdot {}^{UA}/_{2} \cdot COP \cdot (1 - lossesHP) - \mu_{(48)}\{h+1\} \\ \cdot \left(-{}^{2}/_{C} + {}^{UA}/_{2}\right) \cdot COP \cdot (1 - lossesHP) + \mu_{(43)} \\ + \lambda_{(35)} \geq 0 \perp HPtemp_{i,h} \end{aligned} \tag{19}$$

$$\begin{aligned} \frac{\partial \mathcal{L}}{dACInput_{i,h}} = \mu_{(43)} - \mu_{(48)} \cdot {}^{UA}/_{2} \cdot {}^{COP}/_{1.12} + \mu_{(48)}\{h+1\} \\ \cdot \left(-{}^{2}/_{C} + {}^{UA}/_{2}\right) \cdot {}^{COP}/_{1.12} \geq 0 \perp ACInput_{i,h} \end{aligned} \tag{20}$$

$$\frac{\partial \mathcal{L}}{dGastherm_{i,d}} = \mu_{(44)} - \mu_{(45)} \geq 0 \perp Gastherm_{i,d} \tag{21}$$

$$\begin{aligned} \frac{\partial \mathcal{L}}{dGastemp_{i,h}} = +\mu_{(48)} \cdot {}^{UA}/_{2} - \mu_{(48)}\{h+1\} \cdot \left(-{}^{2}/_{C} + {}^{UA}/_{2}\right) + \mu_{(44)}\{h \in d\} \\ \geq 0 \perp Gastemp_{i,h} \end{aligned} \tag{22}$$

$$\frac{\partial \mathcal{L}}{dTind_{i,h}} = -\mu_{(48)} - \left(1 - {}^{2}/_{C \cdot UA}\right)\mu_{(48)}\{h+1\} + \lambda_{(37)} - \lambda_{(36)} \geq 0 \perp Tind_{i,h} \tag{23}$$

$$\begin{aligned} \frac{\partial \mathcal{L}}{dSOC_{i,h}} = \lambda_{(32)} - \lambda_{(33)} + \mu_{(42)}\{h+1\} - \mu_{(42)} + \mu_{(41)(43)}\{h = final\ h\} \\ - \mu_{(41)}\{h = 1\} \geq 0 \perp SOC_{i,h} \end{aligned} \tag{24}$$

$$\frac{\partial \mathcal{L}}{dnewDem_{i,h}} = -\lambda_{(40)} + \mu_{(43)} - \mu_{(46)} - \mu_{(47)} \geq 0 \perp newDem_{i,h} \tag{25}$$

$$\frac{\partial \mathcal{L}}{dincDem_{i,h}} = \lambda_{(38)} + \lambda_{(39)} + \mu_{(47)} \geq 0 \perp incDem_{i,h} \tag{26}$$

$$\frac{\partial \mathcal{L}}{ddecDem_{i,h}} = -\mu_{(47)} \geq 0 \perp decDem_{i,h} \tag{27}$$

$$\frac{\partial \mathcal{L}}{dENS_{i,h}} = costENS + \mu_{(43)} \geq 0 \perp ENS_{i,h} \tag{28}$$

$$\begin{aligned} \frac{\partial \mathcal{L}}{dpowerPV_{i}} = costPV \cdot (1 + MCost) \\ - \sum\nolimits_{h} \mu_{(43)} \cdot DNI_{h} \cdot 0.001 \cdot (1 - lossesPV) \geq 0 \perp powerPV_{i} \end{aligned} \tag{29}$$

$$\frac{\partial \mathcal{L}}{dpowerHP_{i}} = costHP \cdot (1 + MCost) - \sum\nolimits_{h=1} \lambda_{(35)} \geq 0 \perp powerHP_{i} \tag{30}$$

$$\frac{\partial \mathcal{L}}{dbatCapacity_{i}} = costES - \sum\nolimits_{h} \lambda_{(32)} \geq 0 \perp batCapacity_{i} \tag{31}$$

Non-equality constraints, $G(X)$, are:

$$batCapacity_{i} \geq SOC_{i,h} \quad \forall i, h \tag{32}$$

$$SOC_{i,h-1} \geq discharge_{i,h} \quad \forall i, h \tag{33}$$

$$dieselCapacity_{i} \geq lDiesel_{i,h} \cdot dieselRatio \quad \forall i, h \tag{34}$$

$$powerHP_{i} \geq HPther_{i,h} + HPtemp_{i,h} \quad \forall i, h \tag{35}$$

$$Tind_{i,h} \geq 15 \quad \forall i \notin 4, h \tag{36}$$

$$25 \geq Tind_{i,h} \quad \forall i \notin 4, h \tag{37}$$

$$demandShift \cdot \sum\nolimits_{h \in d} demand_{i,h} \geq \sum\nolimits_{h \in d} incDem_{i,h} \quad \forall i, d \tag{38}$$

$$demand_{i,h} \geq incDem_{i,h} \quad \forall i, h \tag{39}$$

$$newDem_{i,h} \geq 0.01\, demand_{i,h} \cdot \quad \forall i, h \tag{40}$$

And equality constraints, $H(X)$, are:

$$SOC_{i,1} = SOC_{i,228} \quad \forall i \tag{41}$$

$$SOC_{i,h} = SOC_{i,h-1} + charge_{i,h} \cdot effBat - discharge_{i,h} \ \forall i, h \tag{42}$$

$$GEB_{i,h} - GES_{i,h} = newDem_{i,h} - DNI_h \cdot powerPV_i \cdot 0.001 \cdot (1 - lossesPV) + charge_{i,h} - discharge_{i,h} + ENS_{i,h} + HPther_{i,h} + HPtemp_{i,h} + ACInput_{i,h} - lDiesel_{i,h} \cdot dieselRatio \quad \forall i,h \tag{43}$$

$$BET_{i,d} = Gastherm_{i,d} + \sum_{h\in d} Gastemp_{i,h} \quad \forall i,d \tag{44}$$

$$Gastherm_{i,d} = {demandThermAnnual_i}/{365} \cdot demMens_d + \sum_{h\in d} HPther_{i,h} \cdot COP \cdot (1 - lossesHP)/0.8 \quad \forall i,d \tag{45}$$

$$\sum_{h\in d} newDem_{i,h} = \sum_{h\in d} demand_{i,h} \quad \forall i,d \tag{46}$$

$$newDem_{i,h} = demand_{i,h} + incDem_{i,h} - demDem_{i,h} \quad \forall i,h \tag{47}$$

$$\begin{aligned} Tind_{i,h} = Tout_{i,h} - {}^{2}/_{C \cdot UA} \cdot (Tind_{i,h-1} - Tout_{i,h}) \\ + \Big(Gastemp_{i,h} - ACInput_{i,h} \cdot {}^{COP}/_{1.12} \\ + HPtemp_{i,h} \cdot COP \cdot \frac{1 - lossesHP}{0.8}\Big) \cdot {}^{UA}/_{2} \\ + \Big(Gastemp_{i,h-1} - ACInput_{i,h-1} \cdot {}^{COP}/_{1.12} \\ + HPtemp_{i,h-1} \cdot COP \cdot \frac{1 - lossesHP}{0.8}\Big) \\ \cdot \left({}^{-2}/_{C} + {}^{UA}/_{2}\right) \end{aligned} \tag{48}$$

IV. SCENARIOS AND CASE STUDIES

In this first approach, a small district has been modeled, including the geographical characteristics of Madrid, Spain. Conventional battery systems have been considered as energy storage.

The case developed considers 12 days (each one represents a month) to simulate the behavior of a year. In addition, this case takes into account an MG which consists of eight end-users and a generator. This generator was modeled as a diesel generator.

As mentioned above, there are several profiles required as input for the model: DNI_h, $demandCurve_{h,t}$, $demMens_d$ and $Tout$. The data considered is shown in Figure 5 - Figure 9.

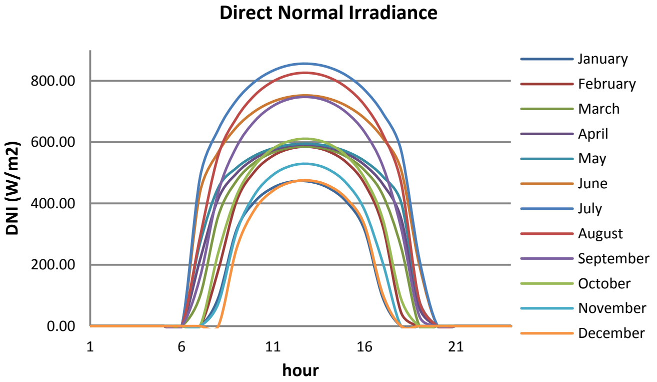

Figure 5: DNI profiles per month in Madrid obtained from [24].

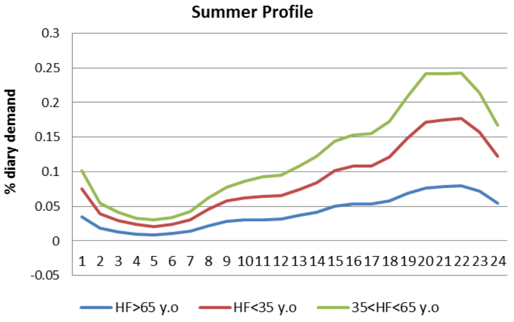

Figure 6: Normalized summer electric profiles applied for months ∈ [4,9] from [25].

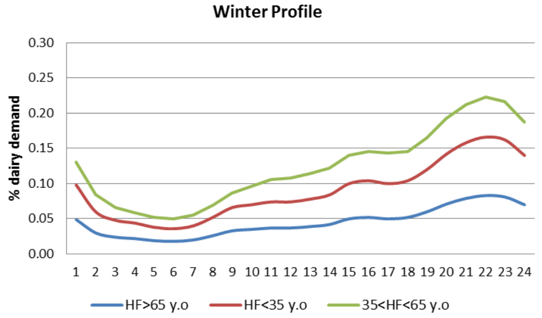

Figure 7: Normalized winter electric profiles applied for months ∉ [4,9] from [25].

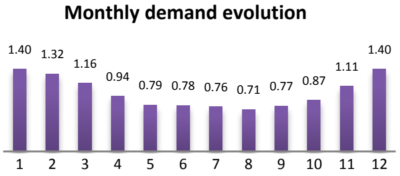

Figure 8: Monthly demand evolution along the year [25]

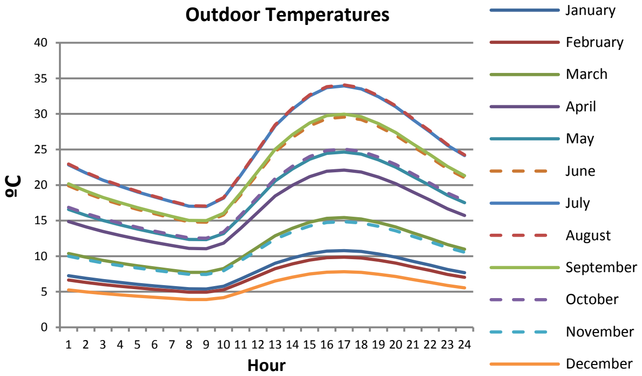

Figure 9: Average outdoor temperatures profiles in Madrid obtained from [26]

Table 2 Scalar Values

Parameter	Value
lossesPV (%)	24
lossesHP (%)	15
MCost (%)	7
costPV (USD/kW)*	5.7534
costHP (USD/kW)*	4.9315
*costsES** (USD/kW)*	2.054
costET (USD/kWh)	0.44
costENS(USD/kWh)	0
WACC(%)	3
Cost Increment rate(%)	5
COP (-)	2.5
effBat(%)	0.9
demandElecAnnual (kWh)	3698.1315
dieselRatio (kW/Liters)	3.5
dieselCost (USD/Liters)	1.048
demandShift (%)	0.15
UA(ºC/kW)	20
C(kW/ ºC)	1
θ_i *[(USD /kWh)/kW]* ∀*i*	0

**Cost in 20 years(USD/kW)·12/(20·365)*
***Cost in 8 years(USD/kW)·12/(8·365)*

As previously stated, perfect competition is considered in this model, in other words, the conjecture price-response parameter, θ_i , is 0 for all the agents i. Table 2, Table 3 and

Table 4 shows the value of the other parameters used in the scenarios presented below. Installation costs have been obtained using the cost of their lifespan (20 years or 8 years in the case of the batteries) divided by the number of days and then multiplied by the number of days considered (12 days, one per month).

Table 3 Parameters Values I [23], [25]

Agent	demandThermAnnual$_i$(kWh)	dieselCapacity$_i$ (kWh)
1	2018.3249	-
2	2018.3249	-
3	2290.5682	-
4	0	300
5	2290.5682	-
6	1724.79873	-
7	1724.79873	-
8	2290.5682	-
9	2290.5682	-

Table 4 Parameters Values II

Agent	sellCost$_i$(USD /kWh)	clientType$_i$
1	0.01	1
2	0.03	1
3	0.02	2
4	0.01	-
5	0.02	2
6	0.05	3
7	0.04	3
8	0.06	1
9	0.06	3

A base case which considers the current situation is developed. Then, four planning scenarios have been studied as shown in Table 5. Firstly, a scenario without DR, solar panels and storage is developed. Secondly, solar panels and storage are introduced. Then, scenario III introduces DR that allows shifting 15% of the electrical demand. Finally, houses 2 and 9 are not allowed to install PV and ES in scenario IV in order to demonstrate that order houses can sell their extra power production.

Table 5 Scenarios' definition

Scenario	DR	PV	ES	HP
Base				
I				✓
II		✓	✓	✓
III	✓	✓	✓	✓
IV	✓	✓*	✓*	✓

*except house 2 and 9

V. RESULTS

The current situation, where none of devices is deployed and where there is no DR, is taken as base case. The installation of PV and ES is not allowed in scenario I, therefore, the final price will be fixed by the marginal cost of the generator. This can be seen in Figure 10 and Figure 11 which represent the behavior of house 1. Cost comparison between Scenarios I and the Base case shows the effect of including the synergies between thermal and electric energy since HP consumes electric energy to supply thermal requirements.

In scenarios II and III solar panels are introduced in the model and their behaviors are shown in Figure 12 and Figure 13. The main difference between both scenarios is that in the last one, the consumption is moved to the hours where there is solar production, obtaining a better profit. In both cases, solar panels are oversized in summer months in order to obtain the best result during winter months, where the solar irradiance is lower. This fact can be seen in Figure 14 which corresponds to January in scenario III and where the ENS is null.

Installation and operation costs per scenario are presented in Table 6. The price in scenario I is not a surprise since it is fixed by the marginal cost of the diesel generator. Solar panels and batteries cause an important decrease in costs because prices are fixed among the agents whose costs are zero for their produced energy. However, they introduce a cost in order to express their willingness to sell energy among them.

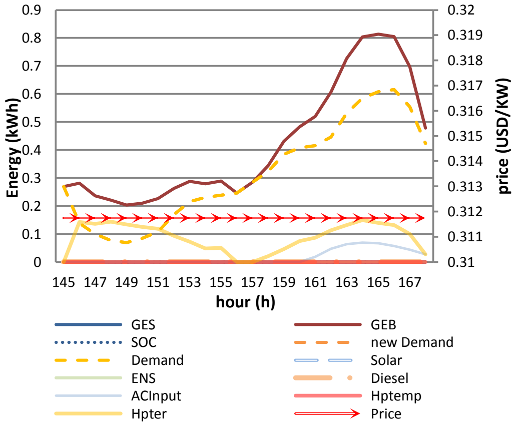

Figure 10 Consumption profile of house 1 in month 7 at scenario I

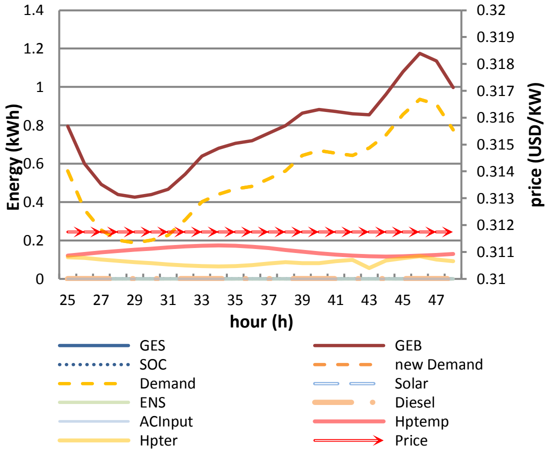

Figure 11 Consumption profile of house 1 in month 2 at scenario I

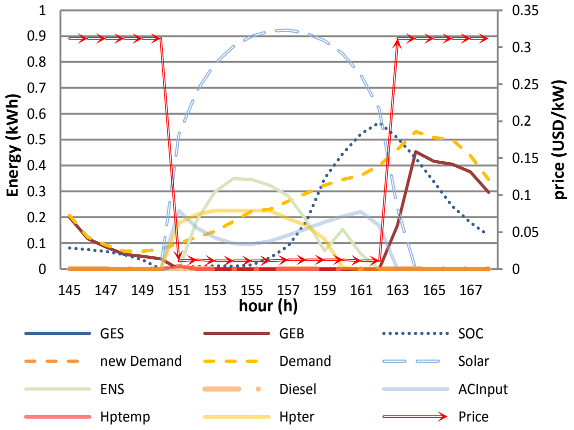

Figure 12 Consumption profile of house 6 in month 7 at scenario II

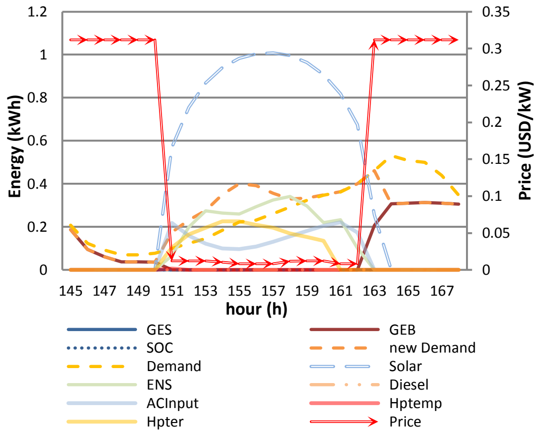

Figure 13 Consumption profile of house 6 in month 7 at scenario III

Table 6 Costs per Agent (USD in 20 years)

Scenario	Base	I	II	III	IV
1	49524.04	30242.88	22321.05	21452.52	20844.88
2	49524.04	30242.88	22468.83	21527.68	22615.72
3	54919.720	33916.94	25646.35	24427.31	24449.62
4	0	0.00	0.00	0.00	0.00
5	54919.72	33916.94	25646.35	24427.33	24449.62
6	43701.70	26276.75	19668.42	18794.40	18782.49
7	43701.70	26276.75	19667.97	18782.33	18780.07
8	51919.78	30917.00	22842.43	21774.58	21761.64
9	48680.47	27677.69	20257.39	19452.82	20493.93
Total	396891.17	240045	178894	171032	172670

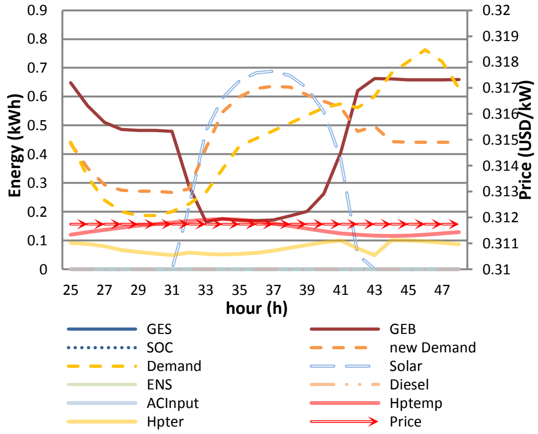

Figure 14 Consumption profile of house 6 in month 2 at scenario III

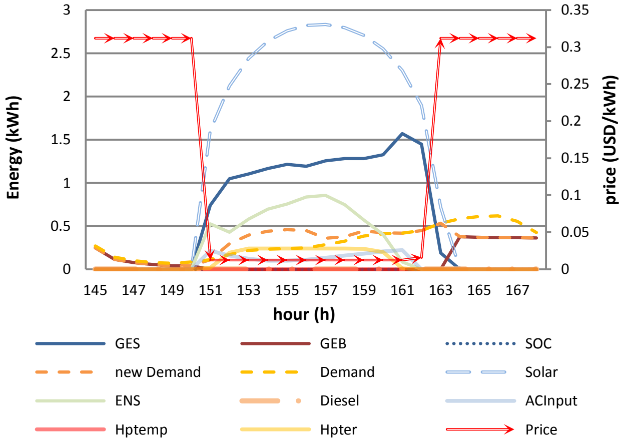

Figure 15 Consumption profile of house 1 in month 7 at scenario IV

In fact, when a home is not able to install solar panels, scenario IV, the rest of end users install higher capacities. End-users whose selling price is lower will install more in order to take advantage of it. In this case, house 1, which is the most willing to sell, taking into account Table 4, obtains the higher decrement in cost with respect to scenario III since it sells almost all the energy produced as shown in Figure 15.

Other interesting results are the benefits of the retailer's generator. In all scenarios, its profit is null since there are no other generators or agents whose production costs are greater. This fact means that a fixed cost should be paid to this agent in order to guarantee its services in the case that only a generator was available.

Finally, a temperature model has been developed in this paper in order to simulate the behavior of a smart thermostat. Indoor temperature has been limited to the interval [15º,25º] throughout the day. An example of the behavior of the temperature is shown in Figure 16.

Table 7 Installed capacity (kW)

Scenario	Base & I		II		III		IV	
	PV	**ES**	**PV**	**ES**	**PV**	**ES**	**PV**	**ES**
1	0	0	1.74	1.04	1.86	0.16	4.36	0.00
2	0	0	1.67	0.87	1.81	0.08	0.00	0.00
3	0	0	1.74	0.89	1.96	0.18	2.31	0.00
4	0	0	0.00	0.00	0.00	0.00	0.00	0.00
5	0	0	1.74	0.89	1.96	0.18	2.31	0.00
6	0	0	1.42	0.57	1.55	0.00	1.57	0.01
7	0	0	1.42	0.57	1.57	0.01	1.57	0.01
8	0	0	1.70	0.87	1.89	0.23	1.89	0.25
9	0	0	1.56	0.78	1.67	0.12	0.00	0.00

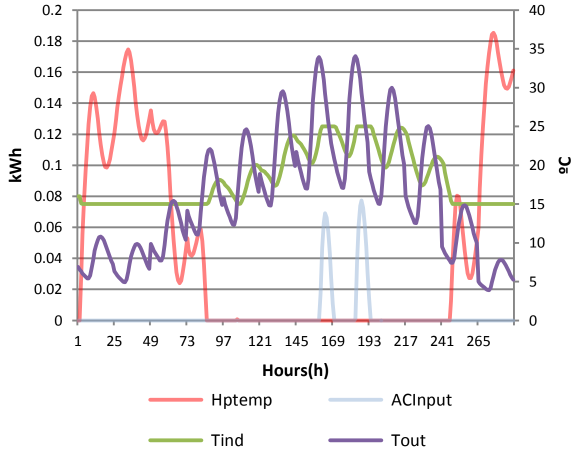

Figure 16 Temperatures House 1 Scenario I

VI. CONCLUSION

This paper presents a Market approach for the operation of an MG in islanded mode. Common distributed generation and storage systems are taken into account in planning and operating the system. The market equilibrium inside the MG has been solved using an MCP, considering solar and energetic demand characteristics in Madrid, Spain. This case study has been validated using a business model, a market approach and an indoor temperature behavior model presented above.

As a result, optimal scaling and operation scheduling were found under different scenarios. When there is no DER, consumers accept prices imposed by the generators in the MG, in this case, the marginal cost of the diesel generator. HP can take advantage of the energy synergies and save around 40% of the total cost. In the second scenario, where all the end users can install PV and ES systems, they can reduce their cost by around 25% regarding the first scenario and achieve around 30% if DR is added. In the case where some of the end-users cannot install PV and ES, those who are more willing to sell energy can increase these percentages.

In a future step, more energy resources such as combined heat and power will be introduced. Further work regarding combining isolated and connected mode of operation should be done in order to discover under which circumstances MGs are profitable.

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