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Smart Transactive Energy Framework in Grid-connected Multiple Home Microgrids under Independent and Coalition Operations

Mousa Marzband^{a,b}, Fatemeh Azarinejadian^b, Mehdi Savaghebi^d, Edris Pouresmaeil^c, Josep M. Guerrero^d, Gordon Lightbody^{e,f}

^aFaculty of Engineering and Environment, Department of Maths, Physics and Electrical Engineering, Northumbria University Newcastle, Newcastle upon Tyne NE1 8ST, UK

^bDept. of Electrical Engineering, Lahijan Branch, Islamic Azad University, Lahijan, Iran

^cDept. of Electrical Engineering and Automation, Aalto University, 02150 Espoo, Finland

^dDept. of Energy Technology, Aalborg University, DK-9220 Aalborg East, Denmark

^eControl and Intelligent Systems Group, Department of Electrical and Electronic Engineering, UCC, College Rd., Cork, Ireland

^fSFI Research Centre for Marine and Renewable Energy, MaREI, Ireland

Abstract

This paper presents a smart Transactive energy (TE) framework in which home microgrids (H-MGs) can collaborate with each other in a multiple H-MG system by forming coalitions for gaining competitiveness in the market. Profit allocation due to coalition between H-MGs is an important issue for ensuring the optimal use of installed resources in the whole multiple H-MG system. In addition, considering demand fluctuations, energy production based on renewable resources in the multiple H-MG can be accomplished by demand-side management strategies that try to establish mechanisms to allow for a flatter demand curve. In this regard, demand shifting potential can be tapped through shifting certain amounts of energy demand from some time periods to others with lower expected demand, typically to match price values and to ensure that existing generation will be economically sufficient. It is also possible to obtain the maximum profit with the coalition formation. In essence the impact of the consumption shifting in the multiple H-MG schedule can be considered while conducting both individual and coalition operations. A comprehensive simulation study is carried out to reveal the effectiveness of

Email address: mousa.marzband@northumbria.ac.uk Corresponding author (Mousa Marzband)

the proposed method in lowering the market clearing price (MCP) for about 15% of the time intervals, increasing H-MG responsive load consumption by a factor of 30%, and promoting local generation by a factor of three. The numerical results also show the capability of the proposed algorithm to encourage market participation and improve profit for all participants.

Keywords: Coalition formation, demand side management, electricity market, home energy management system, home Microgrid, profit allocation, Transactive Energy.

Nomenclature

Acronyms

ABC	artificial bee colony
CHP	combined heat and power
EB	electrical boiler
EHP	electrical heat pump
ES+/ES-	energy storage (ES) during charging/discharging mode
GB	gas boiler
UG+/UG-	buying/ selling power from/to H-MG i / the upstream grid (UG)
MCP	market clearing price
RLD+, RLD-	amount of responsive load demand (RLD) that goes/come from/to other time period to/from t
STP	solar thermal panel
TES	thermal energy storage
WT	wind turbine

Symbols

@	the coalition formation among the H-MGs i and j ($j \neq i$)
$\{A@B\} \equiv \{AB\}$	coalition formation between H-MGs A and B
$\{A\}$	H-MG A is in individual operation
$k \mapsto i$	distributed energy resource (DER) k installed in H-MG i

Indices

$i+, i-$	buying/ selling power from/to H-MG j /H-MG i
$e/h/D$	electrical/ thermal/ non-responsive load demand
$i \in \{ES-, WT, CHP, GB, STP, EH, EB, TES-, UG-\}, \{i, j, k\} \in \{1, 2, \dots, n\}, j \neq i$	
j	all H-MG except H-MG i

Constants

α, β	amount of demand that will be added/subtracted to/from the primary demand forecast for relevant hours
$\zeta_e^{k,i}, \zeta_h^{k,i}$	electrical/ thermal efficiency of the thermal DER k in H-MG i (%)
$\bar{P}_e^{k,i}, \bar{P}_h^{k,i}$	maximum electrical/thermal power generated by dispatchable/non-dispatchable DER k in H-MG i (kW)
π^{ng}	natural fuel price offer (£/kWh)
ζ^{TES}	heat loss efficiency value (%)
$\underline{SOC}^x, \overline{SOC}^x$	the lower/ upper limit of state-of-charge (SOC) in x ($x \in \{ES, TES\}$) (%)
$SOC_{INI}^{ES,i}, SOC_{INI}^{TES,i}$	the initial value of ES/TES SOC in H-MG i (%)
S	the collector surface area
α_1, α_2	the first/ second order thermal loss coefficients (kWm ² /k ⁰)
η_0	the zero thermal loss efficiency
κ	part of excess/ shortage power generated/ required by H-MG i / upstream grid

Parameters

$\tilde{P}_{t,h}^{STP,i}$	the predicted generated thermal power by STP at time t in H-MG i (kW)
$\tilde{P}_{t,e}^{WT,i}$	the predicted generated power by WT at time t in H-MG i (kW)
$\tilde{P}_{t,e}^{D,i}, \tilde{P}_{t,h}^{D,i}$	the predicted consumed electrical/thermal load demand at time t in H-MG i (kW)
$\tilde{\lambda}_{t,e}^{MCP}, \tilde{\lambda}_{t,h}^{MCP}$	the electrical/thermal of MCP at time t (£/kWh)

G_t^*	the solar radiation (kW/m ²)
Tem_t^c, Tem_t^a	the collector mean/ ambient temperature
Decision variables	
$P_{t,e}^{k,i}, P_{t,h}^{k,i}$	thermal/electrical power generated/ consumed by dispatchable/non-dispatchable DER k in H-MG i (kW)
$\pi_{t,e}^{k,i}, \pi_{t,h}^{k,i}$	electrical/ thermal price bids of dispatchable/non-dispatchable DER k in H-MG i (£/kW)
$X_t^{CHP,i}$	binary variable, 1 means CHP on, otherwise CHP off
$FU_t^{k,i}$	fuel consumption rate of dispatchable DER k in H-MG i at time t (kW)
$P_{t,e}^{RLD+,i}, P_{t,e}^{RLD-,i}$	the value of added RLD consumed load in time interval t (RLD+) and shifted load to another time interval (RLD-)
$\lambda_{t,e}^{MCP}, \lambda_{t,h}^{MCP}$	the electrical/thermal of MCP calculated by <i>ABC-1 unit</i> at time t (£/kWh)
$\lambda_{t,e}^{MCP}, \lambda_{t,h}^{MCP}$	the electrical/thermal of MCP calculated by <i>ABC-2 unit</i> at time t (£/kWh)
$P_{t,e}^{i+j}, P_{t,h}^{i+j}, P_{t,e}^{i-j}, P_{t,h}^{i-j} \forall j \neq i$	the electrical/ thermal power sold/bought from/to H-MG i/H-MG j at time t (kW)
$P_{t,e}^{UG+,i}, P_{t,e}^{UG-,i}$	the value of power sold/ bought from/to upstream grid/ H-MG i at time t (kW)

1. Introduction

While smart grids are known as the future of power systems, home Microgrids (H-MG) can be considered as a vital technology to deliver the functional blocks of smart grid on a local scale. In developing this system, a large number of elements, currently just passively connected to the grid, will become actively involved in negotiation and complex coordination tasks [1–3]. The big challenge for executives is how to handle an unbounded number of intelligent elements, each with their own objectives and perspectives, into a cohesive and efficient system [4–6]. In this context, Transactive energy (TE) concepts and adaptation into the distribution-level of

10 the electricity grid can be profoundly effective; thus, is considered as an area of
11 recent research interest [7]. Indeed, TE is facilitated by a set of intrinsically trans-
12 ferable and shared economic and control mechanisms that guarantees equilibrium
13 between supply and demand among trading partners in the entire electrical infras-
14 tructure [8, 9].

15 In addition, clusters of actively managed H-MGs may be grouped together into
16 so-called energy coalitions in the multiple H-MG [10–13] for participation in local
17 or system-wide energy and power system services markets. Formation of such coal-
18 tions may be beneficial for operators of the multiple H-MG. As a result, they may
19 reduce transaction costs of participation in such markets, reduce uncertainty (given
20 the benefits from aggregation and diversity in energy demand and supply, especially
21 in the presence of variable renewables) and avoid the grid usage fees through lo-
22 cal energy trading [14–17]. For society as a whole, formation of such coalitions
23 can also be beneficial as day-ahead coordinated market participation of H-MGs can
24 reduce price volatility and average price levels through increased market liquidity,
25 improved reliability and reduced peaks in demand from the upstream grid; thus,
26 potentially expensive investment can be avoided [18–21].

27 Coalitions may be formed or broken depending on the conditions of the mo-
28 ment [22]. For example, a group of H-MGs may conclude they can achieve more
29 profit at a particular moment through cooperation and hence form a coalition. At
30 a future time, H-MGs may decide that higher profit may be achieved by breaking
31 the coalition and forming an alternative coalition, or possibly even by operating in-
32 dependently. Assuming that the considered H-MGs are rational economic entities,
33 cooperation can only be implemented if each rational player can expect to obtain a
34 higher profit by joining the coalition. A crucial consideration in the decision to join
35 a coalition is therefore the mechanism through which coalition profit is allocated,
36 once the coalition can extract value from market participation. If the mechanism
37 employed by a coalition for allocating profit is perceived to be unfair, the result of
38 the coalition forming process may be sub-optimal, for both individual H-MG and
39 the coalition as a whole. Hence, it is necessary to find a way to fairly allocate the
40 profit obtained from the coalition among all players. In the method proposed in

41 this paper, it is shown that because of the ineffectiveness of the independent de-
42 cisions, H-MGs may have interest in cooperating with each other by coordinating
43 their energy supplies and the demand rate consumption, which leads to an increase
44 in their aggregated utilities. As a result, the pay-off of each H-MG can be increased
45 by cooperation. In this context, it is worth mentioning that since some players may
46 contribute more to the coalition than others or may exhibit different bargaining
47 power exchange methods for transactive energy balance etc. This raises the follow-
48 ing key questions:

- 49 1. How should the generated surplus be distributed among the players (i.e. each
50 H-MG) for any particular coalition?
- 51 2. How important is each player to the overall cooperation?

52 Furthermore, it is important to consider responsive load demand (RLD) in H-MG
53 which can be defined as the change in electric usage by a customer from the normal
54 consumption pattern in response to the electricity price variations over time, or to
55 the incentive payments designed to induce lower electricity use at times of high
56 wholesale market prices [10, 23]. RLD models presented in the literature generally
57 refer to the quantification of the RLD potential with highly increasing penetration
58 rate of renewable energy sources and load demand into the electrical power grids
59 [24, 25]. However, the methodology proposed in this paper goes further on mak-
60 ing possible for the consumers to participate in the consumption shifting scheme
61 under coalition formation in multiple H-MG systems. It also allows H-MGs to ade-
62 quately manage the coalition formation process together with RLD programming.
63 In addition, the characteristics of distributed energy resource (DER) with RLD re-
64 sources integrated inside each H-MG are taken into account, respectively as input
65 parameters and technical constraints of the optimization model. It is developed to
66 perform a joint between both H-MG and RLD resources scheduling under coalition
67 formation, in a multiple H-MG architecture.

68 In this paper, a multi-stage stochastic programming based on artificial bee colony
69 (MSSP-ABC) algorithm is applied for multiple H-MG applications, to simulate the
70 formation of possible coalitions. A local home energy management system is im-
71 plemented in the control centre by using an MSSP-ABC algorithm. According to

72 the several advantages of ABC such as simplicity, accuracy and short calculation
73 time [26–28], it is applied in this paper for the optimization of the multiple H-MG
74 operation in terms of performance, generation scheduling, and economic power
75 dispatch. This can provide economic results with excellent reliability because of its
76 high convergence speed and ability of finding general optimum solution compared
77 with other innovative optimum methods (e.g. gravitational search algorithm, ant
78 colony optimization, imperialist competition algorithm) [26]. The total profit of
79 each possible coalition from participation in a distributed energy market is also
80 calculated. Subsequently, the cooperation of H-MGs is discussed and an algorithm
81 based on MSSP-ABC is implemented for deciding coalition formation. The proposed
82 algorithm is then used for logical and grid-wise distribution of profits for each of
83 the H-MGs in the coalition.

84 With regards to the proposed approach, H-MGs are able to reasonably predict
85 in advance that how much gain they can obtain from participating in a coalition. In
86 order to do that, each H-MG seeks to calculate its contribution of expected marginal
87 value to the coalition. This value can then be used to assess the profitability of avail-
88 able coalitions and inform the decision to join a coalition or not. Furthermore, a
89 group of H-MGs can cooperate and form a larger coalition if this formation increases
90 the pay-off of at least one of the H-MGs without decreasing the pay-off of any of the
91 others involved in the coalition. In an analogous manner, a coalition can decide to
92 split and divide itself into smaller coalitions if splitting is preferred by H-MGs.

93 The main contribution of this paper is the development of a modeling frame-
94 work for profit allocation across H-MG participating in HM-MG coalition which can
95 answer the question of what a “fair” distribution of profit should be, and which
96 coalitions are likely to form. Applications of the proposed concepts are various,
97 from H-MG portfolio design to optimal contract design by aggregators, H-MG oper-
98 ators and energy service companies.

99 An illustrative grid connected case study application with three electrical/thermal
100 coupled H-MGs is presented here to demonstrate the models introduced. The differ-
101 ent coalition formation rules are then compared with each other in order to evaluate
102 the profit that each H-MG that can be obtained by joining the coalition. The results

show that the disconnection of H-MGs resulting from pricing decisions allows them to collaborate together to achieve higher profits due to excess production and avoid penalties due to production shortages. It is also demonstrated that significant increase in the profit may persuade H-MGs to form a coalition.

In summary, the main contributions in this work are as follows:

1. The formulation of a particular coalition formation strategy combined with RLD programming based on framework of TE;
2. The formulation of a special demand side management (DSM) strategy based on solving optimization problem for maximizing the total profit of a multiple H-MG system by taking into account the variable uncertainties;
3. The development of a modeling framework for profit allocation across H-MG participating in multiple H-MG coalition to have a “fair” profit distribution.

This paper is organized as follows:

The proposed algorithm is developed and explained in Section 2 while conceptual design of the proposed problem is outlined in Section 3. Simulation results and discussions are presented in Section 4. Finally, the paper is concluded in Section 5.

2. Proposed MSSP-ABC algorithm

A general picture of the multiple H-MG connected to the several conventional building (CB) is shown in Figure 1. Multiple H-MG is designed as an active cluster of H-MGs and each of them is configured by dispatchable/non-dispatchable DER resources, storage devices and associated RLDs. Non-dispatchable DERs (such as wind and photovoltaic resources) are based on renewable energy resources which inherently suffer from a lack of the dispatch capability due to inherent stochastic behaviours of these resources. Under these conditions, each H-MG having an aggregator has the ability of supplying its power shortage from other H-MGs. CBs are the buyers of power from multiple H-MG and/or upstream grid and their consumed loads are uncontrollable. When an H-MG has the excess generation, it has the ability of selling power to other H-MGs within multiple H-MG system, the upstream grid and CBs connected to this system. This excess power can be allocated to sup-

ply each of them according to the terms of their bids. Otherwise, when an H-MG has the generation shortage, it means that it does not have the ability of supplying its internal demand and must import power from other H-MGs and the upstream grid and/or possibly shift the loads. The operation and management of the corresponding H-MG can be controlled and monitored by a control centre as shown in Figure 1. A control strategy is developed in the control centre for coordinated operation of networked H-MGs in a multiple H-MG distribution system. The control centre is considered as a distinct entity with individual objectives to maximize the profit for all H-MGs taking into account the possibility of coalition formation between them.

The flowchart of the proposed algorithm is shown in Figure 2. Various parameters such as load demand, renewable power generation, and MCP are treated as uncertainties in the proposed structure. In order to handle the uncertainties, Taguchi's orthogonal array testing (TOAT) approach is utilized which enhances a trade-off between the accuracy of the solution and the computational burden [10, 29, 30]. The TOAT method selects the minimum number of scenarios while preserving the main statistical information of the entire dataset. More details on the stochastic framework of this study can be found in [31–34]. As observed in Figure 2, this structure is made up of *TOAT*, *ABC-1*, *DSM-ABC*, *ABC-2* and *MCP units*. Since the *TOAT* and *MCP units* are explained in detail in [10], only the *ABC-1*, *DSM-ABC* and *ABC-2 units* are discussed in the following. At first, the rated capacity of the existing DERs and their operational constraints will be required to exhibit ABC algorithm. Then, prediction data including solar radiation, wind speed, electrical/thermal load demand and the electricity price will be sent to the *TOAT unit*. Then, *ABC-1 unit* is executed for determining the value of MCP-1. After calculating the MCP-1 value, demand side management is again conducted to deliver both energy efficiency gains and peak demand reductions based on the objective function defined in *ABC-2 unit*. After levelling the load demand curve and assuring the MCP reduction due to implementation the RLD program, MCP-2 is calculated and is declared to the market operator.

In Figure 2 the solid black lines show the execution trend of *ABC-1 unit* and

163 dashed grey lines state the execution of *ABC-2 unit* for determining MCP-2 ¹.

164 2.1. *ABC-1 unit*

165 **Input information:** $\tilde{P}_{t,h}^{STP,i}$, $\tilde{P}_{t,e}^{WT,i}$, $\tilde{P}_{t,e}^{D,i}$, $\tilde{P}_{t,h}^{D,i}$, $\tilde{\lambda}_{t,e}^{MCP}$, $\tilde{\lambda}_{t,h}^{MCP}$.

166 **Variables:** Produced electrical/thermal power by the generation resources, ES
167 and TES charge/discharge power, electrical/thermal power exchanged between H-
168 MGs and upstream grid, all the buying/selling offers related to DERs, H-MGs and
169 the consumers, binary variables, $\lambda_{t,e}^{MCP}$, and $\lambda_{t,h}^{MCP}$.

170 **Objectives:** Determining the electrical/thermal optimum values of the gener-
171 ated power such that the profit obtained by these resources becomes maximum.
172 The defined objectives in this unit are to maximize the profit, resulting from the
173 H-MGs individual operation or interactive performance under different coalition
174 formation patterns, to achieve electrical/thermal balance, as well as to improve the
175 SOC condition in ES/ TES.

176 2.2. *DSM-ABC unit*

177 **Input information:** $P_{t,e}^{D,i}$, $\lambda_{t,e}^{MCP}$.

178 **Variables:** $P_{t,e}^{RLD+}$, $P_{t,e}^{RLD-}$.

179 **Objectives:** to smooth demand curve applying a strategy that considers the
180 shifting of certain amounts of energy demand from some time periods (with higher
181 MCP) to other time periods with lower expected demand (lower MCP), typically in
182 response to price signals.

183 2.3. *ABC-2 unit*

184 **Input information:** $P_{t,h}^{STP,i}$, $P_{t,e}^{WT,i}$, $P_{t,e}^{D,i}$, $P_{t,h}^{D,i}$, $P_{t,e}^{RLD+,i}$, $P_{t,e}^{RLD-,i}$, $\lambda_{t,e}^{MCP}$, $\lambda_{t,h}^{MCP}$.

185 **Variables:** $P_{t,e}^{k,i}$, $P_{t,h}^{k,i}$, $\pi_{t,e}^{k,i}$, $\pi_{t,h}^{k,i}$, $X_t^{CHP,i}$, $FU_t^{k,i}$, $P_{t,e}^{RLD+,i}$, $P_{t,e}^{RLD-,i}$, λ_t^{MCP} , λ_t^{MCP} ,
186 $P_{t,e}^{i+j}$, $P_{t,h}^{i+j}$, $P_{t,e}^{i-j}$, $P_{t,h}^{i-j}$, $P_{t,e}^{UG+,i}$ and $P_{t,e}^{UG-,i}$.

¹The solid black lines demonstrate the execution trend of Stage 1, the solid gray lines indicate Stage 2 and dashed grey lines state the execution of Stage 3.

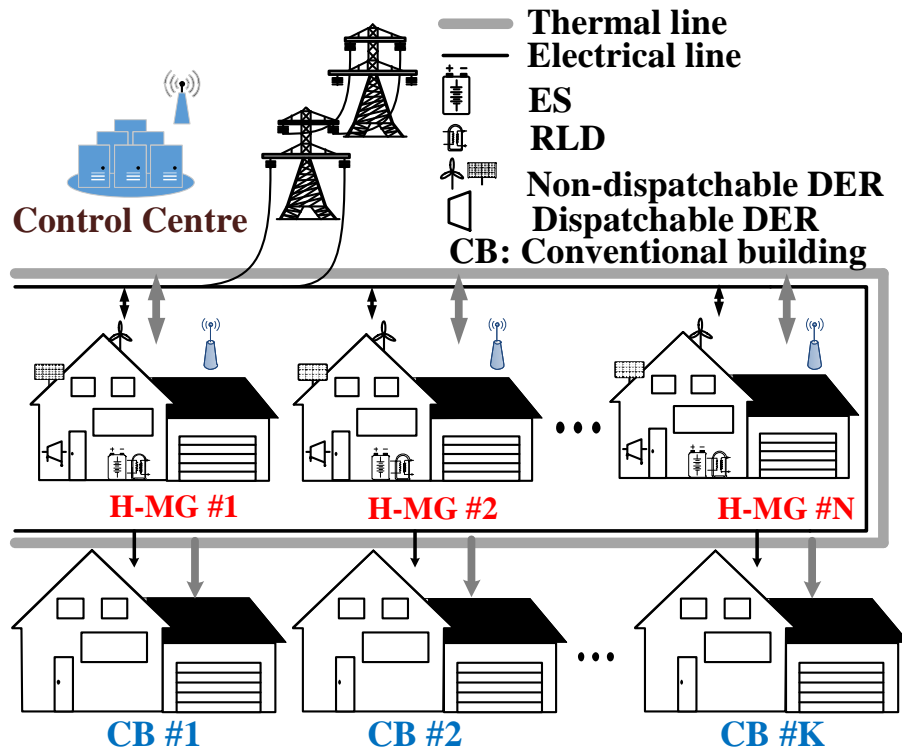


Figure 1: General structure of multiple H-MG

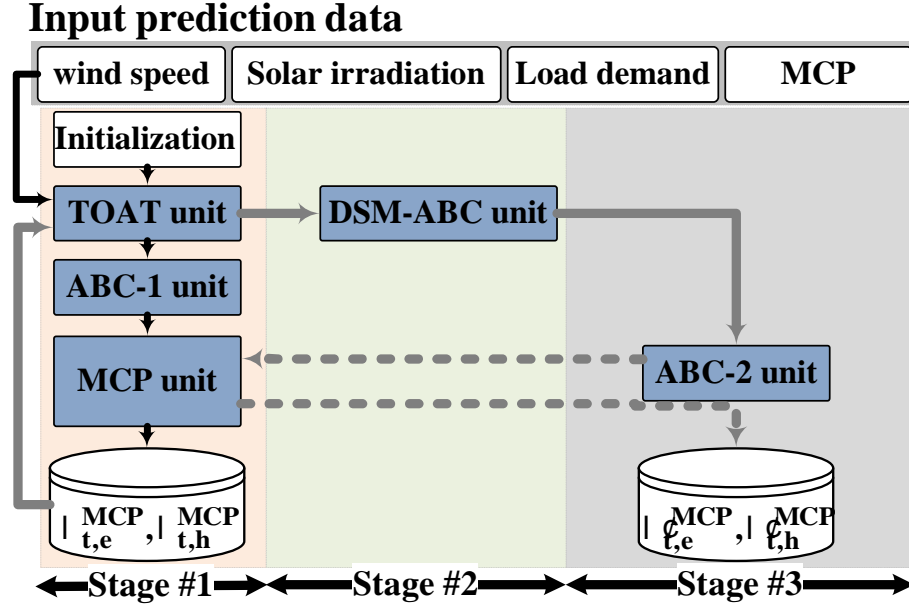


Figure 2: Proposed MSSP-ABC algorithm

187 **Objectives:** Determining the amount of consumers participation of in RLD pro-
 188 gram and the value of the power produced by generation resources such that their
 189 profit becomes maximum.

190 To achieve these objectives, load demand profile improvement is considered by
 191 using $\lambda_{t,e}^{\text{MCP}}$ and $\lambda_{t,h}^{\text{MCP}}$. Under these conditions, shifted load demand (i.e. RLD-) from
 192 time interval with higher MCP (peak hours) is evenly distributed among lower MCP
 193 (off-peak hours) by using *ABC-2 unit*. In addition, the quantity of shifted load at
 194 each hour is proportional to the demand at that hour.

195 The performance of demand side management proposed by *ABC-2 unit* has been
 196 shown in Figure 3. As it can be seen, when the MCP value goes up to a certain limit,
 197 *ABC-2 unit* could reasonably assume that further optimization efforts with a demand
 198 shifting rate would improve the load demand profile while all the constraints of the
 199 system are satisfied.

200 To achieve these objectives, the active participation of consumers in total load
 201 demand profile improvement is increasingly seen politically desirable, especially

any voluntary RLD program taking $\lambda_{t,e}^{MCP}$ and $\lambda_{t,h}^{MCP}$ into consideration. For this implementation, *ABC-2 unit* is developed to shift load demand from time period t to sometime before and/or after time t . It can be a way to induce lower electricity consumption at times of high MCP, during peak electricity demand, in a cost-effective manner or when system reliability is jeopardized.

On the other hand, a certain RLD amount income is verified by *ABC-2 unit* in period t , shifted from other periods. At the end, in period t , considering the consumption shifting (incoming: RLD+/outgoing: RLD-) and the consumption reduction, the final consumption can be lower or higher than the initially expected demand depending on the objective. It is important to keep in mind that the total consumption can be dropped to less than the initially expected demand. This case will occur if the appliance electricity consumption cannot be shifted from other periods to this period.

In essence, the proposed MSSP-ABC algorithm with the novel RLD criterion consisting of *ABC-1* and *ABC-2 units* will be found to be reliable, efficient and cost-effective.

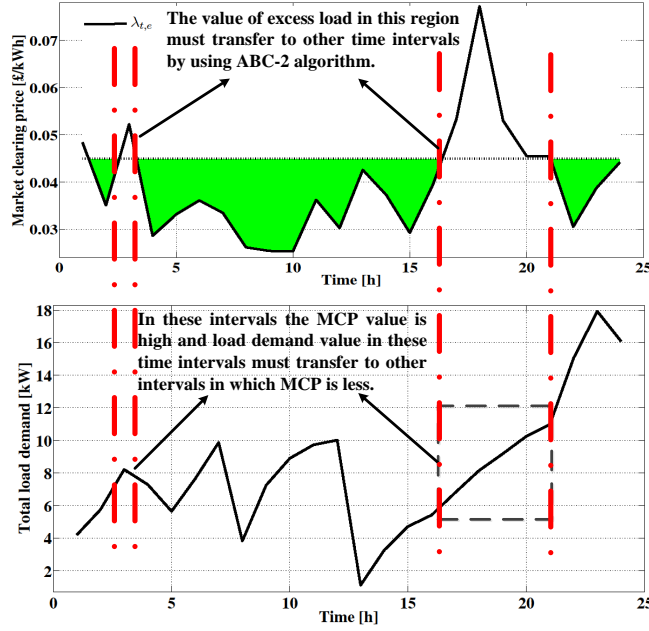


Figure 3: Method of demand side management based on MCP in the ABC-2 unit

218 2.4. MCP unit

219 In this unit, the MCP is calculated based on the schedules obtained from ABC-
 220 1 and ABC-2 units and the supply and demand bids submitted by the participants
 221 using forward market with double-side auction [35–38]. Supply and demand bids
 222 as well as optimal schedules of the participants are the parameters given to the
 223 MCP unit. The forward market aggregates supply and demand in the merit order as
 224 price-quantity pairs. The quantities are the optimal schedules obtained from ABC-
 225 1 and ABC-2 units, and the prices are the supply and demand bids submitted by
 226 the participants. As expected, the aggregated supply and demand quantity-price
 227 are monotonically increasing and decreasing step-wise curves, respectively. Then,
 228 the MCP will be the point of aggregated supply and demand curves intersection.
 229 Subsequently, the value of the payoff function for each participant can be computed
 230 using the MCP unit.

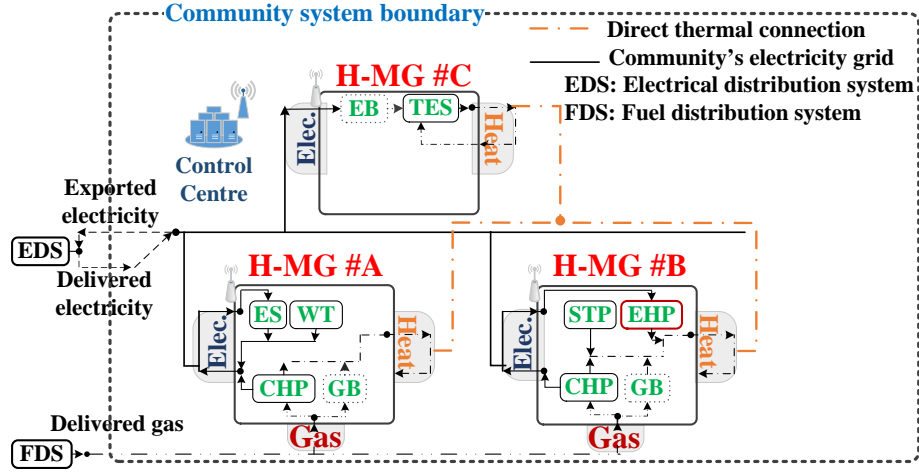


Figure 4: schematic of the system under study

3. Problem formulation

To illustrate how the proposed method works, it is applied to a case study for the multiple H-MG depicted in Figure 4. As shown in this figure, multiple H-MG comprises three different H-MGs A, B and C with various dispatchable/non-dispatchable DER resources. As observed in this figure, the resources storing electrical/thermal power are included in A and B for storing provided excess electrical/thermal power. At the beginning of the planning horizon, each H-MG decides whether to operate individually or in coalition with other H-MGs, and determines the selling price offered to the consumers to be used during the planning horizon. After fixing the H-MGs operation status as individual (i.e. $\{A\}, \{B\}, \{C\}$ and $\{UG\}$) or coalitional (i.e. $\{AB\}, \{AC\}, \{BC\}$ which are double coalition and $\{ABC\}$ which is a triple coalition) and the buying/selling prices, each H-MG decides the amount of energy purchased/sold in the pool to/from other H-MGs to supply the demand of all its consumers during each period (e.g. one hour) over along the planning horizon (e.g. 24 hours). All other information about the capacity of equipment installed in each H-MG are presented in [10] in detail and therefore not repeated in this paper. At first, the objective functions for the case study are described and then the main results of applying the proposed algorithm are presented and discussed.

249 3.1. Objective functions

250 The objective functions defined in both *ABC-1* and *ABC-2 units* are based on
251 decision making problem related to maximizing solitary profit of each H-MG in
252 independent working conditions or the profit resulting from their participation in
253 coalitional cooperation among each other. With this difference that the value of
254 the profit resulting from the participation of the consumers in the RLD program has
255 been included in the objective function of problem *ABC-2 unit*. In the following
256 paragraphs, the mathematical model of the discussed problem has been presented
257 in this paper.

258 An multi-stage decision-making problem with the defined objective functions in
259 both *ABC-1* and *ABC-2 units* is employed in MSSP-ABC algorithm. This problem
260 is constrained by a collection of market clearing problems representing pool trad-
261 ing, and its individual objective functions corresponding to profit maximization. To
262 reach this aim, an MSSP-ABC algorithm is developed to include additional profit for
263 the players who are involved in a deregulated power market environment. In this
264 direction, the mathematical model represents the equilibrium of a pool-based mar-
265 ket taking into account the outcomes on the spot market based on expected profit
266 maximization for H-MGs; and the anticipation of the upstream grid or H-MGs for
267 achieving success and earning more profit under collation formation. The demand
268 is considered exogenous but supply bids and the power generation of DERs are
269 obtained as endogenous variables of the model. The optimization problem of this
270 model seeks maximum profit for H-MGs considering coalition formation between
271 them and contains H-MGs, DERs and RLD scheduling constraints, when the day-
272 ahead energy market [39] can be cleared under different operating conditions to
273 deal with profit maximization problems of all H-MGs. The proposed structure pro-
274 vides a procedure to derive the optimal offering strategy of all players including H-
275 MGs, DERs of them and upstream grid. In this direction, an H-MG can decide about
276 its level of involvement in the future pool markets as well as the selling/buying price
277 offered to/from other H-MGs with the goal of maximizing the expected profit. The
278 mathematical formulation of the optimization problem is presented as follows.

279 3.1.1. Objective function in ABC-1 unit

280 Different scenarios which have been considered for defining objective functions
281 are as follows:

283 • Profit resulting from H-MG i under individual operation

$$\text{Profit}^i|_{\forall i} = \max \sum_{t=1}^{24} \left(\begin{aligned} &\sum_{\forall k \rightarrow i} (P_{t,e}^{k,i} \times \pi_{t,e}^{k,i} + P_{t,h}^{k,i} \times \pi_{t,h}^{k,i}) \\ &+ \sum_{\forall j \neq i} \left(\begin{aligned} &P_{t,e}^{i-j} \times \pi_{t,e}^{i-j} + P_{t,h}^{i-j} \times \pi_{t,h}^{i-j} \\ &-(P_{t,e}^{i+j} \times \pi_{t,e}^{i+j} + P_{t,h}^{i+j} \times \pi_{t,h}^{i+j}) \end{aligned} \right) \\ &+ P_{t,e}^{UG+,i} \times \pi_{t,e}^{UG+,i} - P_{t,e}^{UG-,i} \times \pi_{t,e}^{UG-,i} \\ &- \sum_{\forall k \rightarrow i} FU_t^{k,i} \times \pi^{ng} \end{aligned} \right) \times \Delta t \quad (1)$$

284 The first right side term of Eq. 1 states the income value resulting from the
285 production of electrical/thermal powers produced by the DER k existing in
286 H-MG i . The right side term section is equivalent to the value of paid cost
287 for supplying the fuel required by thermal resources. Section three states the
288 income from selling electrical/thermal powers sold to other H-MGs minus the
289 cost of buying electrical/thermal powers from other H-MGs for the completion
290 of its function of the power required in the H-MG i . The last term of the
291 equation shows the value of electrical power bought from the upstream grid
292 for supplying the H-MG i load demand.

293 • Profit resulting from H-MG i and H-MG j ($j \neq i$) considering coalition for- 296 mation between them

$$\sum_{\forall t} \text{Profit} = \sum_{\forall t} \text{Profit}^i @ \sum_{\forall t} \text{Profit}^j, \quad \forall j \neq i \quad (2)$$

299 • Profit resulting from upstream grid

$$\text{Profit}^{UG} = \sum_{\forall i,t} (P_{t,e}^{UG+,i} \times \pi_{t,e}^{UG+,i} - P_{t,e}^{UG-,i} \times \pi_{t,e}^{UG-,i}) \quad (3)$$

298 3.1.2. Objective function in ABC-2 unit

299 The objective functions defined in this part of simulation problem are exactly
300 similar to objective functions defined for ABC-1 unit with this difference that
301 profit value resulting from the consumer's participation in RLD program must

also be considered. Because of this, the following expression must be added to all the Eqs. 1-3:

• **Profit resulting from RLD program**

$$\text{Profit}_t^{\text{RLD}} = P_t^{\text{RLD},+,i} \times \pi_t^{\text{RLD},+,i} - P_t^{\text{RLD},-,i} \times \pi_t^{\text{RLD},-,i} \quad (4)$$

3.2. *Technical and economic constraints*

• **Supply bids**

$$\underline{\pi}_{e/h}^{k,i} \leq \pi_{t,e/h}^{k,i} \leq \bar{\pi}_{e/h}^{k,i} \quad (5)$$

where $\underline{\pi}_{e/h}^{k,i}$ and $\bar{\pi}_{e/h}^{k,i}$ are respectively the minimum and maximum offer of the electrical/thermal price in the i^{th} H-MG. $\bar{\pi}_e^{k,i}$ can be considered the equivalent of the value of predicting electrical MCP of the day before implementing uncertainty. $\underline{\pi}_e^{k,i}$ can be considered zero for renewable resources and for resources which consume fuel, can be estimated by calculating electrical marginal cost value (MC_e) of the desired resource. MC_e for fuel consuming resource is calculated from the following equation:

$$MC_{t,e}^{k,i} = \frac{P_{t,e}^{k,i}}{\zeta_{e,i}^{k,i}} \times \pi^{\text{ng}} \quad (6)$$

Also, $\underline{\pi}_h^{k,i}$ can be considered the equivalent of thermal marginal cost value (MC_h) and can be calculated by

$$MC_{t,h}^{k,i} = \frac{P_{t,h}^{k,i}}{\zeta_h^{k,i}} \times \pi^{\text{ng}} \quad (7)$$

• **ES and TES constraints [26]**

For modelling ES and TES constraints such as stored energy limitations, maximum power charge/discharge limitations and power equilibrium have been considered.

$$P_e^{\text{ES}} \leq P_{t,e}^{\text{ES},i} \leq \bar{P}_e^{\text{ES}} \quad (8)$$

$$\underline{\text{SOC}}^{\text{ES}} \leq \text{SOC}_t^{\text{ES},i} \leq \overline{\text{SOC}}^{\text{ES}} \quad (9)$$

$$\text{SOC}_t^{\text{ES},i} = \text{SOC}_{t-1}^{\text{ES},i} + \frac{P_{t,e}^{\text{ES},i}}{\bar{P}_e^{\text{ES}}} \quad (10)$$

$$\text{SOC}_{t=1}^{\text{ES},i} = \text{SOC}_{\text{INI}}^{\text{ES}} \quad (11)$$

$$P_h^{\text{TES}} \leq P_{t,h}^{\text{TES},i} \leq \bar{P}_h^{\text{TES}} \quad (12)$$

$$\underline{\text{SOC}}^{\text{TES}} \leq \text{SOC}_t^{\text{TES},i} \leq \overline{\text{SOC}}^{\text{TES}} \quad (13)$$

$$\text{SOC}_t^{\text{TES},i} = \text{SOC}_{t-1}^{\text{TES},i} + \frac{P_{t,h}^{\text{TES},i}}{\bar{P}_h^{\text{TES}}} \quad (14)$$

$$\text{SOC}_{t=1}^{\text{TES},i} = \text{SOC}_{\text{INI}}^{\text{TES}} \quad (15)$$

• **CHP constraints** [40]

$$\underline{P}_e^{\text{CHP},i} \leq P_{t,e}^{\text{CHP},i} \leq \bar{P}_e^{\text{CHP},i} \quad (16)$$

$$P_{t,e}^{\text{CHP},i} = \text{FU}_t^{\text{CHP},i} \times \zeta_{t,e}^1 + X_t^{\text{CHP},i} \times \zeta_{t,e}^2 \quad (17)$$

$$P_{t,h}^{\text{CHP},i} = \text{FU}_t^{\text{CHP},i} \times \zeta_{t,h}^1 + X_t^{\text{CHP},i} \times \zeta_{t,h}^2 \quad (18)$$

where the coefficients $\zeta_{t,e}^1$ and $\zeta_{t,e}^2$ can be determined as $f(\underline{P}_e^{\text{CHP},i}, \bar{P}_e^{\text{CHP},i}, \zeta_{t,e})$ and $\zeta_{t,h}^1$ and $\zeta_{t,h}^2$ can be calculated as $f(\underline{P}_h^{\text{CHP},i}, \bar{P}_h^{\text{CHP},i}, \zeta_{t,h})$ from interpolation of manufacturers' curves of efficiency with respect to loading level and considering the full load electrical efficiency (i.e. $\zeta_{t,e}$) and thermal efficiency (i.e. $\zeta_{t,h}$).

• **EHP constraints** [26]

$$P_{t,h}^{\text{EHP},i} = P_{t,e}^{\text{EHP},i} \times \text{COP}_t \quad (19)$$

where COP_t is coefficient of performance.

$$0 \leq P_{t,h}^{\text{EHP},i} \leq \bar{P}_h^{\text{EHP}} \quad (20)$$

• **GB constraints** [26]

$$0 \leq P_{t,h}^{\text{GB},i} \leq \bar{P}_h^{\text{GB}} \quad (21)$$

$$P_{t,h}^{\text{GB},i} = \zeta_h^{\text{GB},i} \times \text{FU}_t^{\text{GB},i} \quad (22)$$

• **STP constraints** [26]

$$P_{t,h}^{\text{STP},i} = S \cdot G_t^*(\eta_0) - \frac{\alpha_1(\text{Tem}_t^c - \text{Tem}_t^a)}{G_t^*} - \frac{\alpha_2(\text{Tem}_t^c - \text{Tem}_t^a)^2}{G_t^*} \quad (23)$$

where S is the collector surface area (corresponding to efficiency parameter) (m^2), G^* is the solar radiation ($\frac{\text{kW}}{\text{m}^2}$). α_1 and α_2 are the first order and second order thermal loss coefficients ($\frac{\text{kWm}^2}{\text{K}^0}$), Tem_t^c is the collector mean temperature, η_0 is the ambient temperature and is the zero thermal loss efficiency.

354 • WT constraints

$$0 \leq P_{t,e}^{WT,i} \leq \bar{P}^{WT,i} \quad (24)$$

355 • Upstream grid constraints [10]

$$0 \leq P_{t,e}^{UG+} \leq \kappa \times \sum_{\forall i} P_{t,e}^{UG+,i} \quad (25)$$

357

$$0 \leq P_{t,e}^{UG-} \leq \kappa \times \sum_{\forall i} P_{t,e}^{UG-,i} \quad (26)$$

358 where κ is part of excess/ shortage power required by the H-MG i or upstream
359 grid.

360 • Electrical/thermal power balance in H-MG i

$$\begin{aligned} & P_{t,e}^{D,i} + P_{t,e}^{ES+,i} + P_{t,e}^{EHP,i} + P_{t,e}^{EB,i} + \sum_{\forall j \neq i} P_{t,e}^{i+j} \\ & + P_{t,e}^{UG-,i} = \sum_{\forall j \neq i} P_{t,e}^{i-j} + P_{t,e}^{UG+,i} + P_{t,e}^{CHP,i} + P_{t,e}^{WT,i} \end{aligned} \quad (27)$$

362

$$\begin{aligned} & P_{t,h}^{D,i} + P_{t,h}^{TES+,i} + \sum_{\forall j \neq i} P_{t,h}^{i+j} = \sum_{\forall j \neq i} P_{t,h}^{i-j} + \\ & P_{t,h}^{CHP,i} + P_{t,h}^{GB,i} + P_{t,h}^{EHP,i} + P_{t,h}^{EB,i} + P_{t,h}^{TES-,i} \end{aligned} \quad (28)$$

363 • Electrical/thermal power balance in multiple H-MG

$$\begin{aligned} & \sum_{\forall i} (P_{t,e}^{D,i} + P_{t,e}^{ES+,i} + P_{t,e}^{EHP,i} + P_{t,e}^{EB,i} + P_{t,e}^{UG-,i}) \\ & = P_{t,e}^{CHP,i} + P_{t,e}^{WT,i} \end{aligned} \quad (29)$$

365

$$\begin{aligned} & \sum_{\forall i} (P_{t,h}^{D,i} + P_{t,h}^{TES+,i}) = \\ & \sum_{\forall i} (P_{t,h}^{CHP,i} + P_{t,h}^{GB,i} + P_{t,h}^{EHP,i} + P_{t,h}^{EB,i} + P_{t,h}^{TES-,i}) \end{aligned} \quad (30)$$

366 • RLD constraint

$$P_{t,e}'^{D,i} = \tilde{P}_{t,e}^{D,i} + P_{t,e}^{RLD+,i} - P_{t,e}^{RLD-,i}, \quad \forall P_{t,e}'^{D,i} > 0 \quad (31)$$

368

$$P_{t,e}^{RLD-,i} \leq \alpha \times \tilde{P}_{t,e}^{D,i}, \quad P_{t,e}^{RLD+,i} \leq \beta \times \tilde{P}_{t,e}^{D,i} \quad (32)$$

369

$$\sum_{\forall i,t} P_{t,e}^{RLD+,i} = \sum_{\forall i,t} P_{t,e}^{RLD-,i} \quad (33)$$

370 4. Result and discussion

371 This section presents an illustrative scenario to which the proposed MSSP-ABC
372 algorithm has been applied under the possibility of individual operation and coali-
373 tion formation of distributed H-MGs. The H-MGs schedule performed by a control
374 centre which maximizes their own profit under individual operation or coalition
375 formation, taking into account the resources' constraints for each period.

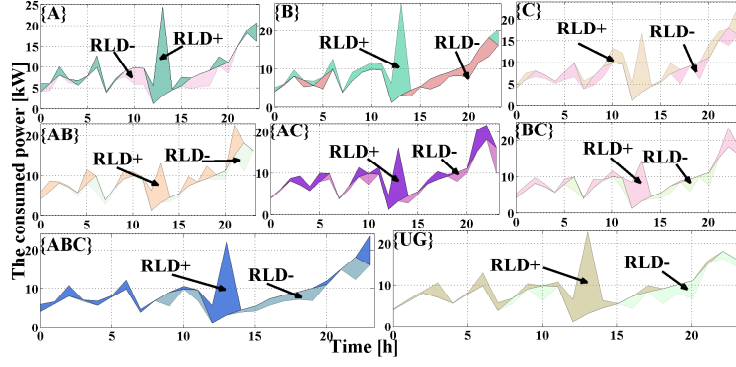
376 For demand side, the power consumption profile of each H-MG under different
377 scenarios are shown in Figure 5(a) where the consumption load demand profiles
378 are completely different in H-MG A during planning period under each scenario.
379 There are foreseeable conditions in which could be possible that RLD+ might ex-
380 ist in one scenario while RLD- can occur under another scenario during the same
381 time interval around the daily peak consumption periods. For each RLD+ or RLD-
382 event, the control centre has previously established the consumption reduction and
383 shifting available in each consumption cluster, according to the chosen objective
384 function (i.e. individual operation or coalition formation). It is also considered to
385 allocate or maybe distribute the corresponding profit to each H-MG and upstream
386 grid under different scenarios. The maximum consumption and shifting capacity
387 can also be seen, so one can have an idea on how much consumption shifting could
388 be additionally scheduled. As shown in Figure 5(a), the maximum value of RLD+
389 is achieved at 13:00 o'clock because of the severe impact of purchasing power from
390 upstream grid when MCP is cheap as shown in Figure 5(a). Under this condition,
391 in addition to earning higher profit associated with DER resources in H-MG A, con-
392 sumers in this H-MG have been increasingly getting benefited from having a role
393 relating to RLD program during daily operation of the network. From Figure 5(a),
394 the total amount of RLD+ consumption is seen to be more than 43% of the total
395 amount of RLD- under all scenarios. In addition, its maximum value is about 53%
396 while the scenario {AC} could have taken place during 24 hours of operation as
397 seen in Figure 5(a). In this scenario, the necessary power needed to supply the
398 consumers in H-MG C can be met by the DER resources existing in H-MG A. The
399 excess generation in H-MG A can also be spent for feeding RLD+ in that or selling

400 to the upstream grid.

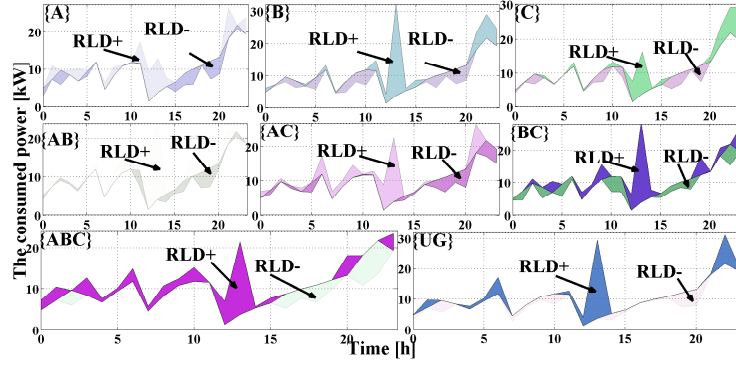
401 The increase of RLD+ and RLD- in the H-MG *B* along the 24h of the day is al-
402 most the same (about 41%), however, the maximum value of the difference between
403 RLD+ and RLD- is about 51% when scenario {C} has occurred, because, in this sce-
404 nario, the purchasing power from upstream grid by H-MGs *B* and *C* has increased
405 significantly. While this is true for all scenarios, except for {UG} which shows a
406 reduction around 21% relative to {C} as seen in Figure 5(b) and 5(c). In this case,
407 the load is shifted from time periods when higher prices are expected, for instance
408 the end of the day, to time periods with lower expected prices, e.g. night and some
409 afternoon time periods. Thereby, when H-MGs tried to exchange power with each
410 other while upstream grid is responding to hourly prices scheduling, *ABC-2 unit* has
411 also performed at the same time to reduce more the peak load demand and flattens
412 the total aggregated load curve of all H-MGs as seen from Figure 5(b). Another fea-
413 ture of the effective coalition formation is also the management of energy balance,
414 for scenarios where a limited and/or restricted electrical power is purchased from
415 the upstream grid. For instance, as it can be seen in Figure 5(a), shifting a part of
416 consumption to the night hours when prices are more favourable for H-MG *A* and *B*
417 coalition formation leads to the reduction of RLD+ value relative to RLD- (around
418 37%), although trend is reversed in H-MG *C* as seen in Figure 5(c) which shows
419 the capability of the proposed algorithm to regulate energy balance feature under
420 coalition formation processes.

421 Analyzing load demand daily operation profiles provides insight into under-
422 standing market behaviour of each H-MG, interactions between different H-MGs
423 under different scenarios of individual operation and coalition formation, and also
424 the arising flexibility. This is another key aspect/feature that are now about to
425 explain market conditions and load demand correlations change throughout the
426 day-ahead operation so the real value of flexible systems needs to be obtained by
427 performing multiple H-MG operation analysis. This also enables the consideration
428 for a distributed profit scenario for each H-MG under different conditions, and mon-
429 itor the maximum consumption and shifting capacity.

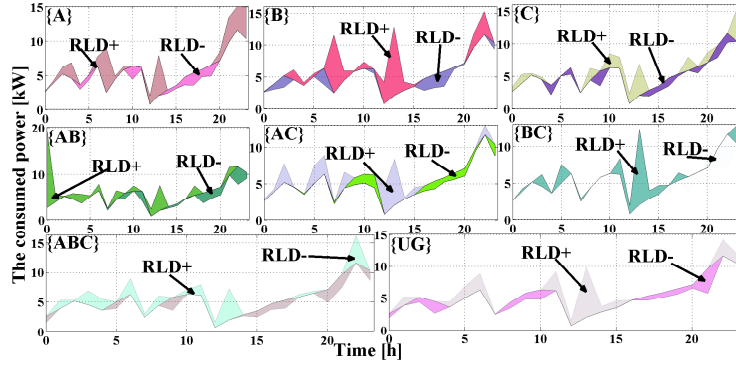
430 In the above, the values of $\lambda_{t,e}^{MCP}$ and $\lambda_{t,e}^{MCP}$ obtained by *ABC-1* and *ABC-2 units* are



(a) H-MG A



(b) H-MG B



(c) H-MG C

Figure 5: Load profile of H-MG A, B and C under individual or coalition inter-operating conditions

431 compared to address inter-operability between multiple-coalition in H-MGs. The
 432 demand side strategy applied in *ABC-2 unit* has had a significant effect in reducing
 433 the MCP value in all of the time intervals. As can be observed in Figure 6, that $\lambda_{t,e}^{MCP}$
 434 value is higher than $\lambda_{t,e}^{MCP}$ in more than 96% of time intervals when H-MGs operate
 435 independently without coalition. In particular, the difference between them under
 436 {AB} and {ABC} scenarios has respectively reached 79% and 92% of time intervals;
 437 considering that it has undergone even more intense reduction under {UG} scenario
 438 up to 33% of time intervals than any other scenario.

439 The maximum and minimum values of MCPs have also had significant reduction
 440 in all the possible scenarios as seen in Figure 6. This is while the maximum value
 441 of $\lambda_{t,e}^{MCP}$ unlike $\lambda_{t,e}^{MCP}$ is reached to a value between 4% to 28% of its initial value in
 442 all the possible scenarios. In addition, the minimum value of $\lambda_{t,e}^{MCP}$ has shown more
 443 reduction relative to $\lambda_{t,e}^{MCP}$ (between 17% and 96%) in all the possible scenarios. The
 444 double coalition formation among H-MGs undoubtedly had considerable effect in
 445 lowering the maximum values of MCP especially with respect to the case that H-MGs
 446 are allowed to work more independently. This is while the maximum value of MCP
 447 is negligibly increased under triple (grand) coalition, i.e. {ABC}, but its minimum
 448 value is significantly reduced under this scenario. This shows that grand coalition
 449 among H-MGs is a critical decision criterion which needs to be carefully idealized
 450 at all the times. For instance, comparison of values in Figs. 5 and 6 shows that
 451 when MCP has its maximum value under all scenarios, MSSP-ABC algorithm has
 452 tried to motivate the customers shift their energy demand to off-peak period when
 453 MCP is lower, and when it is more convenient for the H-MG to distribute electricity.
 454 The minimum values of $\lambda_{t,e}^{MCP}$ and $\lambda_{t,e}^{MCP}$ have occurred at the early hours of the
 455 day (except {AB}) and at the end of the day in all possible scenarios, respectively.
 456 The values of $\lambda_{t,h}^{MCP}$ and $\lambda_{t,h}^{MCP}$ obtained by *ABC-1* and *ABC-2 units* are compared in
 457 Figure 7 to address inter-operability between multiple-coalition in H-MGs.

458 The comparison of the profit profiles earned by each H-MG and upstream grid
 459 under different scenarios are shown in Figure 8. As observed, H-MG A has achieved
 460 its highest profit in an individual operation (i.e. {A}) and gained less profit under
 461 scenarios {AB} and {AC}, about 30% and 41%, respectively. This highlights that

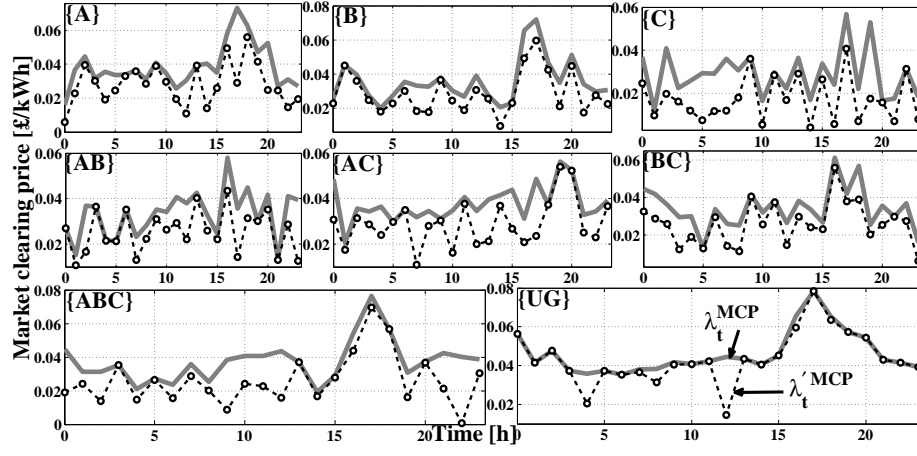


Figure 6: Electrical MCPs for mutual inter-operability schemes or independent function

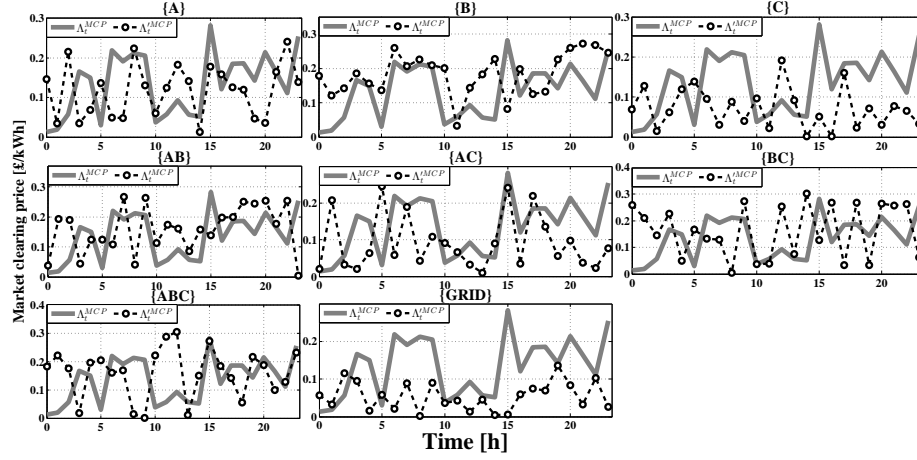


Figure 7: Thermal MCPs for mutual inter-operability schemes or independent function

462 even the sum of the profits of H-MGs A and B is reduced by 26% under {AB}, be-
 463 cause, forming the coalition {AB} not only has decreased the profit of each one of
 464 H-MGs A and B, but also has reduced the obtained total profit. This is while the
 465 value of MCP in more than 58% of the time intervals is significantly reduced rela-
 466 tive to the scenarios in which the H-MGs A and B operate as inter-operable parts. In
 467 fact, interoperability of the H-MGs is offered by the Proposed MSSP-ABC algorithm
 468 where the excess energy of one H-MG can be stored or momentarily consumed in
 469 another H-MG. On the other hand, although {AB} has had negative effect over the
 470 profit obtained from H-MGs A and B, it has had positive effect over the MCP value.
 471 In grand coalition schemes, similar conditions have occurred and a 57% decrease in
 472 the value of total profit has been obtained from forming coalition. However, in 50%
 473 of time intervals, the value of MCP in {ABC} is less than its value in the scenarios
 474 when H-MGs operate, independently. Regarding {BC} and {AC}, these results can
 475 also be reversed. It means that the total profit from {AC} and {BC} has respectively
 476 increased by 40% and 60% relative to the H-MGs operating completely indepen-
 477 dent. This is while the values of MCP after forming coalitions {AC} and {BC} have
 478 respectively reduced for about 46% and 58% of time intervals, relative to the H-MGs
 479 independent operation. In other words, forming coalition would not only increase
 480 the participation rate of H-MG owners and consumers in the deregulated market,
 481 but can also be considered to smooth the fluctuation of load demands. It is impor-
 482 tant to mention that the profit obtained from forming coalition by upstream grid
 483 has become less than the H-MGs in an individual operation which requires opti-
 484 mization for inter-operable routines. This means that during coalition formation
 485 among H-MGs, they have bought less power from the upstream grid and they have
 486 supplied their needed power from their partners as much as possible.

487 5. CONCLUSION

488 In this paper, an optimal, autonomous, and distributed bidding-based energy
 489 optimization scheduling algorithm is proposed in order to maximize the profit and
 490 energy balancing efficiency of H-MGs under residential loads, in specific when mul-

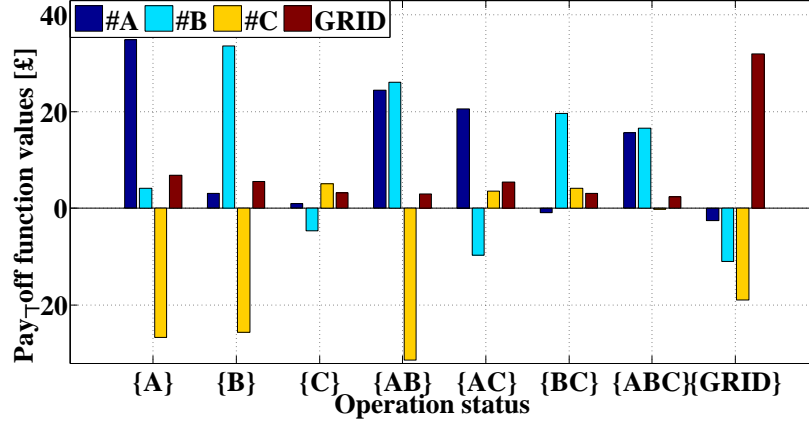


Figure 8: Obtained profit profiles by H-MGs and upstream grid under solitary or coalitional H-MGs

491 multiple H-MGs are trying to share their DER energy resources to create a reliable sup-
 492 ply of sustainable energy. Unlike most of the previous strategies that focus solely
 493 on the interactions between the utility companies and conventional buildings, the
 494 basis of the proposed design is the interactions among the H-MG to help increase
 495 their overall energy efficiency infrastructure, to reduce the energy costs as well as to
 496 improve the profit of both supplier and buyer. The proposed algorithm uses inter-
 497 active H-MGs communication which maximizes profits either operated separately
 498 or in a group. In order to encourage H-MGs to behave in a way consistent with the
 499 group's interests, (i.e., inter-operable coalition formation) a smart pricing tariff
 500 should be implemented such that the interactions among the H-MGs automatically
 501 lead to an optimal load profile with optimal DER scheduling and/or lower MCP.
 502 Some of the proposed algorithm advantages are:

503 1) to selectively identify within multiple H-MGs not only the amount of their
 504 energy consumption at each hour of the day, but also the portion of the energy
 505 desired to obtain from each available energy resource under individual operation
 506 or as coalition formation. 2) to facilitate influencing energy consumption levels
 507 in each H-MG through coalition formation. This support can be accomplished by
 508 introducing impetus energy cost functions. These energy cost functions depends on
 509 not only the energy production by DERs inside each H-MG, but also on the amount

510 of MCP, the energy consumption, and the energy production by other H-MGs in the
511 multiple H-MG systems.

512 Interoperability of the H-MGs is offered by the proposed market structure where
513 the excess energy of one H-MG can be stored in their ES/TES or momentarily con-
514 sumed/sold in another H-MG/ upstream grid when MCP is relatively high or during
515 coalition formation. In essence, it is proposed that MSSP-ABC algorithm is effective
516 in reducing the peak demand and the value of MCP while simultaneously contribut-
517 ing to gain a greater profit under coalition formation, in comparison with individual
518 operation of H-MG. The reduction is achieved in peak demand which depends on
519 the load participation in RLD operation during peak hours, the appropriate value
520 of MCP and the profit earned by H-MG under individual operation or as coalition
521 formation which is globally implementable for a range of energy management, op-
522 timization and trading applications in smart multiple H-MGs. The presented archi-
523 tecture and simulation results confirmed the applicability of the proposed algorithm
524 to power management and trading in smart multiple H-MGs.

525 In future work, the authors are planning to improve market operation by inte-
526 grating the possibility of coalition formation among consumers. Additionally, physi-
527 cal constraints of the network, such as voltage at different locations and power flow
528 through lines, will be formulated as an optimal power flow problem.

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