Optimal Real-time Dispatch for Integrated Energy Systems: An Ontology-Based Multi-Agent Approach

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***Abstract*— With the emerging of small-scale integrated energy systems (IESs), there are significant potentials to increase the functionality of a typical demand-side management (DSM) strategy and typical implementation of building-level distributed energy resources (DERs). By integrating DSM and DERs into a cohesive, networked package that fully utilizes smart energy-efficient end-use devices, advanced building control/automation systems, and integrated communications architectures, it is possible to efficiently manage energy and comfort at the end-use location. In this paper, an ontology-driven multi-agent control system with intelligent optimizers is proposed for optimal real-time dispatch of an integrated building and microgrid system considering coordinated demand response (DR) and DERs management. The optimal dispatch problem is formulated as a mixed integer nonlinear programing problem (MINLP) and solved through an agent-based approach. Several computer simulations are also presented to show the effectiveness of the proposed approach over the conventional methods.**

***Keywords*— Demand response, distributed energy resources, multi-agent system (MAS), smart microgrids.**

I. INTRODUCTION

By the emergence and deployment of small-scale integrated energy systems (IESs) in form of residential smart microgrids (SMGs), efficiency improvement of energy infrastructures is expected. More than half of potential reductions in greenhouse gas (GHG) emissions would be achieved, transmission losses would be reduced, peak-load would be managed and transparency in electricity prices would be increased [1]-[2]. Moreover, through integration of digital technologies to the modernization of many sectors of the economy, higher efficiency gains, new opportunities, and greater productivity can be also guaranteed [3]. The improved flexibility of the IESs permits high penetration of green and sustainable renewable energy sources (RESs) such as solar power and wind power, even without the addition of energy storage. However, the difficulties in dealing with intermittent power and the low utilization efficiency of conventional energy systems as well as dispatching power of the required quality in a reliable, clean and economical way appeared to be obstacles. To address these issues suitably, different approaches have been adopted in related literature [4]-[14]. For example, authors of [4] discussed the optimal operation of future distribution networks under assumption of multi-microgrids concept. They developed a stochastic and probabilistic model for distributed generations (DGs) as well as demand at each microgrid and determined economic operation of each microgrid thereafter. Authors of [6] also proposed a multi-objective optimal dispatching model for a microgrid considering a variety of DGs. They introduced operation cost, sewage treatment cost and comprehensive benefit cost as competitive objectives and solved the optimization problem by use of meta-heuristic approaches. In a same way, authors of [8] presented an efficient energy management architecture to solve the multi-objective operation and scheduling problem in a typical microgrid with regard to different energy resources, storage options and demand response (DR) programs. In [9] a mathematical formulation was developed for a microgrid energy management problem and model predictive control techniques were used to determine the optimal operation strategy. Likewise, a cost-efficient energy scheduling scheme was proposed in [10] for residential renewable-based smart grids so as to determine the optimal utilization of RESs and to achieve a meaningful tradeoff between the system-wide benefits from exploitation of renewables and the associated costs. Although most of the reviewed optimal dispatching models are considered in a centralized form [4]-[11], some are designed in a decentralized way utilizing distributed elements due to the specific characteristics of the studied environment [12]-[14].

This paper proposes a practical hybrid strategy for optimal dispatch of an IES based on the technology of the multi-agent system (MAS). With this approach, the energy scheduler is not seen as a global system to optimally manage power throughout the network, but as a collection of independent entities that nevertheless collaborate. The proposed MAS provides a flexible and reliable solution to optimally manage loads at demand-side and domestic controllable generation units at the supply-side considering energy cost minimization and user's comfort maximizations as objectives of the optimization problem.

This paper is structured as follows: section II deals with the system presentation and mathematical formulation of different components within the system. The case studies and simulation results are provided in Section III, whereas Section IV draws the paper's conclusions.

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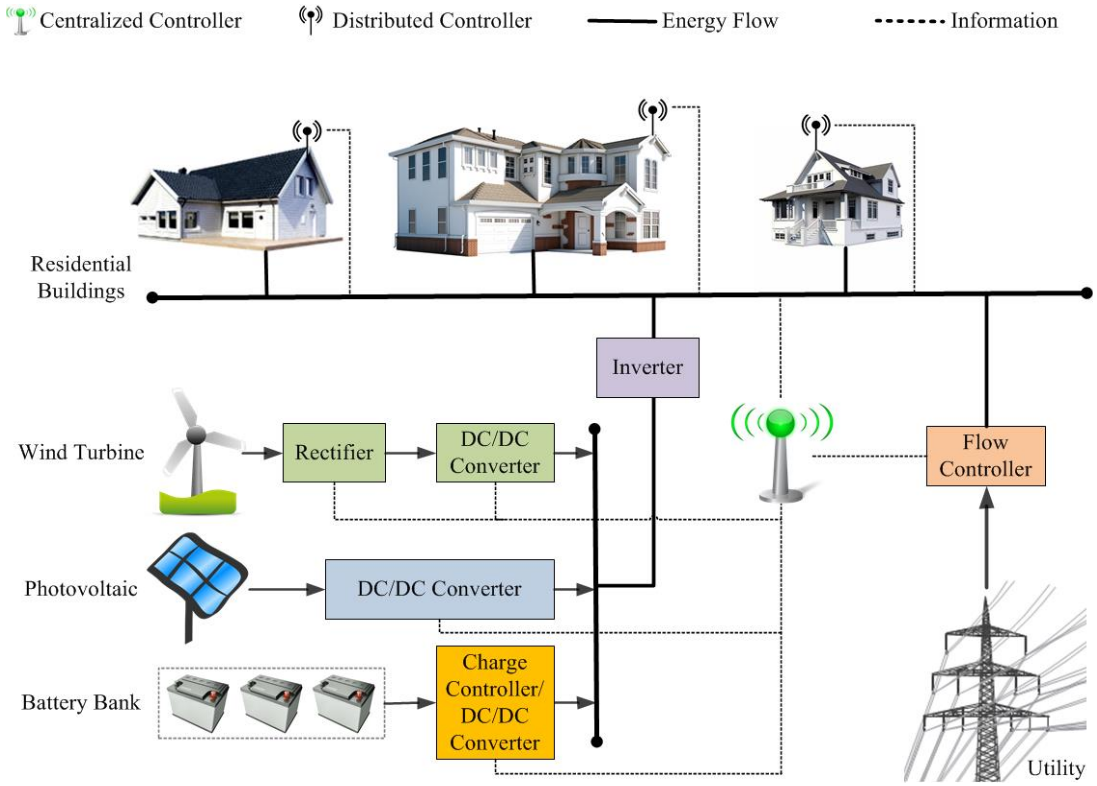


Fig.1. A typical LVAC IES including residential building and microgrid systems

II. SYSTEM PRESENTATION

As shown in Fig. 1, the case study includes a typical LVAC IES with several residential buildings, conventional/renewable energy sources and building-level DG units such as underfloor heating/cooling system (UFH/CS), micro-combined heat and power generator (micro-CHP), and means of energy storage.

A. *Proposed MAS Structure*

To optimally dispatch controllable devices both in supply and demand sides in a coordinated manner, a hybrid framework based on the technology of MAS is applied. Six types of agents including microgrid central coordinator agent (MGCC), distributed agents (DAs), RES agent (RESA), energy storage agent (ESA) and service agent (SA) are considered in the mentioned system. For the proposed MAS, the communication architecture and message passing hierarchy is implemented as depicted in Fig. 2. During each decision period, synergy is triggered by sending and receiving messages between MGCC and RESAs (messages M1-M4 in Fig. 2). Based on these messages, the amount of available power from renewable sources is reported to MGCC and sent to the DAs at residential buildings thereafter (message M5). Each DA manages energy consumption and generation units within a building based on the received information, pending tasks, operating status of in-home devices, usage requests and electrical/heat demands considering minimum energy consumption cost and maximum comfort level as competitive objectives (messages M6-M9). Then, the amount of power which is exchanged between the grid and the i^{th} building is reported to the MGCC by dedicated DA_i (message M10). Summing up all the power transactions with the utility, MGCC in connection with ESA would be able to dispatch the energy storage system based on couple of factors such as net power demand, energy prices and possibility of power exchange with the utility to fulfill the system's objective and constraints (messages M11-M14).

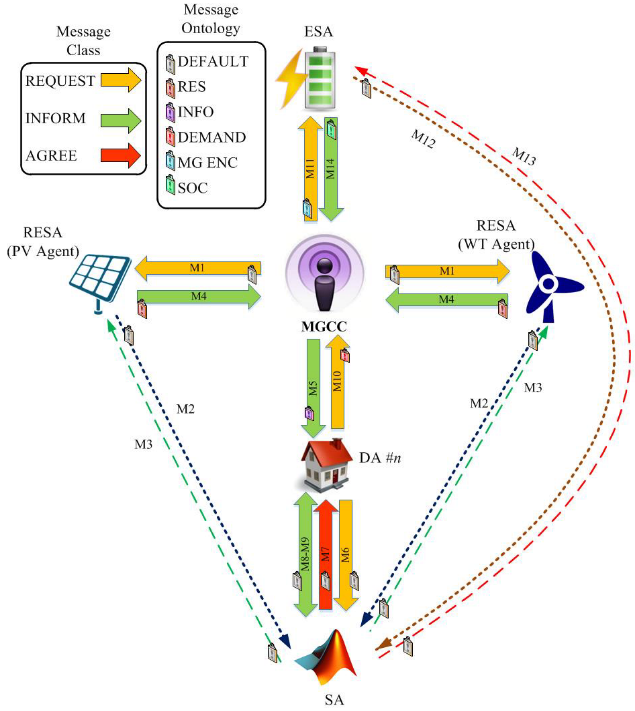


Fig.2. Communication architecture and message passing hierarchy

To deal with Agent Communication Language (ACL) in the proposed MAS as well as to define message exchange interaction protocols, and content language representations, an ontology-based FIPA-ACL structure is utilized as described in Table I.

TABLE I. FIPA ACL MESSAGE ELEMENTS [15]

Element	Description
Performative	Denotes the type of the communicative act of the ACL message.
Sender	Denotes the identity of the sender of the message.
Receiver	Denotes the identity of the intended recipients of the message.
Reply-to	Indicates that subsequent messages in this conversation thread are to be directed to the agent named in the reply-to element, instead of to the agent named in the sender element.
Content	Denotes the content of the message.
Language	Denotes the language in which the content element is expressed.
Encoding	Denotes the specific encoding of the content language expression.
Ontology	Denotes the ontology(s) used to give a meaning to the symbols in the content expression.
Protocol	Denotes the interaction protocol that the sending agent is employing with this ACL message.
Conversation-Id	Introduces an expression (a conversation identifier) which is used to identify the ongoing sequence of communicative acts that together form a conversation.
Reply-with	Introduces an expression that will be used by the responding agent to identify this message.
In-reply-to	Denotes an expression that references an earlier action to which this message is a reply.
Reply-by	Denotes a time and/or date expression which indicates the latest time by which the sending agent would like to have received a reply.

Within this framework, there is also a need to assign an Agent Identifier or AID to each node in the system. It is the information that identifies an agent and provides some information on how to communicate with it, i.e., its addresses. Every agent has a unique AID. In this work, that AID is composed of a unique name and a set of addresses and ontology which can be used to communicate with the agent.

B. Distributed Energy Sources

To shape an optimal management strategy for scheduling of demand/supply sides, models of different energy sources, storage options and schedulable loads should be defined and formulated based on the system's requirements. With regard to an IES, DERs can be exploited both in forms of conventional and renewables. Renewable-based energy technologies such and wind and solar are becoming a major part of future energy systems. The amount of power captured from such resources mainly depends on the local conditions as well as energy potentials and can be estimated based on a number of dominant parameters such as technical data and meteorological information. For example, the output power of wind-driven electric generator as shown in Fig. 3 can be determined as ([16]-[17]):

$$P_{WT} = \frac{1}{2}\left(C_p \cdot \rho \cdot A \cdot V^3 . \eta_g \cdot \eta_b\right) \tag{1}$$

where V is the wind velocity at the turbine site, ρ is the local air density, A is the rotor swept area, and η_g and η_b are the generator and gearbox efficiencies, respectively.

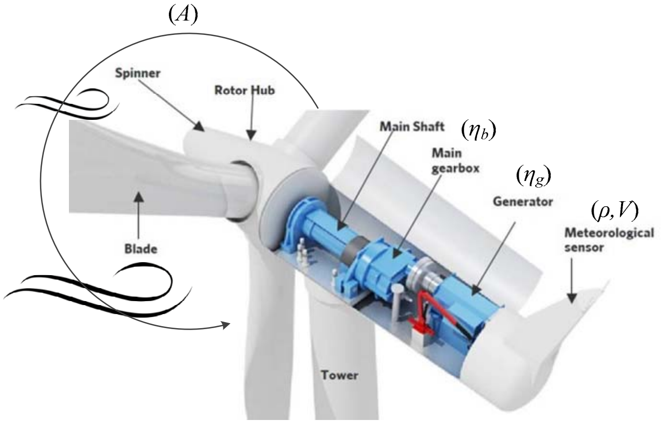


Fig.3. wind-driven electric generator

C_p is the power coefficient of the wind turbine (WT) which is a function of two parameters: pitch angle of the rotor blade and the tip speed defined as follows:

$$\lambda = \frac{\omega_m R}{V} \tag{2}$$

where ω_m is the angular velocity of the rotor and R is the length of the rotor blade. In a similar fashion, the behavior of a photovoltaic system (PV) can be described knowing some parameters such as nominal capacity of the PV array, its derating factor, and solar radiation incident on the PV array as discussed in [18]-[19]. Mathematical models of other building-level DG units such as micro-CHP system, UFH/CS, and battery energy storage system are also well-described and presented in [20]-[22].

C. Schedulable Tasks

Generally, in each residential section the household appliances are categorized into two: schedulable and non-schedulable appliances. Non-schedulable appliances are ones which their operation times are determined by the user and are not negotiable, but schedulable appliances are those that their usages can be postponed to later times during the period under consideration. As shown in Fig. 4, each schedulable task i has several characteristics that need to be defined by users for efficient scheduling.

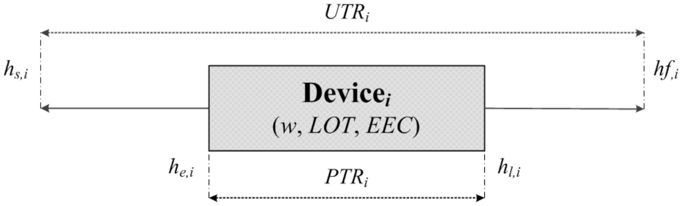


Fig. 4. Operating parameters of schedulable taks i: utilization time range (UTR=[$h_{s,i}$, $h_{f,i}$], desired time range (PTR=[$h_{e,i}$, $h_{l,i}$]), operation time requirement (LOT), energy demand (EEC) and task sigmificance (w).

Moreover, several constraints have to be met for operation of different schedulable household appliances. These include but are not limited to: successful completion of a task operation during a valid utilization time range, running in one-shot or consecutive operation mode, meeting the maximum allowed energy consumption [23].

D. System's objective

As mentioned before, a cooperative MAS structure is applied to optimally manage schedulabe loads at demand-side and domestic controllable generation units at the supply-side. Considering energy cost minimization and user's comfort maximizations as objectives in the studied IES, the mixed-objective function for the whole community can be derived as follow:

$$\text{Min}:\ Mobj = \sum_{i\in K}\sum_{h\in T} TIESC_{h,i}\cdot\left(\psi_{i,1}\cdot TSC_{h,i}+\psi_{i,2}\cdot TC_{h,i}\right)^{-1} \tag{3}$$

where $TIESC_{h,i}$ is the operation cost of the i^{th} building unit at hour h, and TSC_i and TC_i are the i^{th} user's convenience level about in-home task scheduling and his thermal comfort level, respectively. $TIESC_{h,i}$ is calculated based on the amount of power exchanged between the i^{th} building and the utility at hour h ($P_{grid,i}(h)$) and the amount of gas consumed by the micro-CHP unit (if exists in i^{th} house):

$$TIESC_i = \sum_{\substack{h\in T\\ i\in K}}\left(\rho_{grid}(h)P_{grid,i}(h)+\rho_{gas}\left(u_{CHP,i}(h)g_{CHP,i}(h)\right)\right) \tag{4}$$

where ρ_{grid} and ρ_{gas} are the electricity and natural gas prices, respectively, $g_{CHP,i}(h)$ is the total amount of gas consumed by the micro-CHP unit at hour h and $u_{aux,i}(h)$ is the on/off state of the corresponding unit. Likewise, T is the optimization time horizon and K is the set of all households in the IES. TSC_i and TC_i are also defined and quantified based on the following distribution functions:

$$TSC_i(h)=\begin{cases}1 & ;\ h\in PTR_i\\ \begin{pmatrix} H(h_{e,i}-h)\cdot\left(\xi_e\cdot EXP\left(h-h_{e,\text{i}}\right)\right)\\ +H(h-h_{l,i})\cdot\left(\xi_l\cdot EXP\left(h_{l,i}-h\right)\right)\end{pmatrix} & ;\ Oth.\end{cases} \tag{5}$$

$$TC_i(h)=\begin{cases}\xi_c\cdot EXP\left(T_{in,i}(h)-T_{s,i}+\Delta T_{th,i}\right)\\ \qquad ;\ T_{in,i}(h)-T_{s,i}<-\Delta T_{th,i}\\ 1 \qquad ;\ \left|T_{in,i}(h)-T_{s,i}\right|\leq\Delta T_{th,i}\\ \xi_h\cdot EXP\left(T_{s,i}+\Delta T_{th,i}-T_{in,i}(h)\right)\\ \qquad ;\ T_{in,i}(h)-T_{s,i}>+\Delta T_{th,i}\end{cases} \tag{6}$$

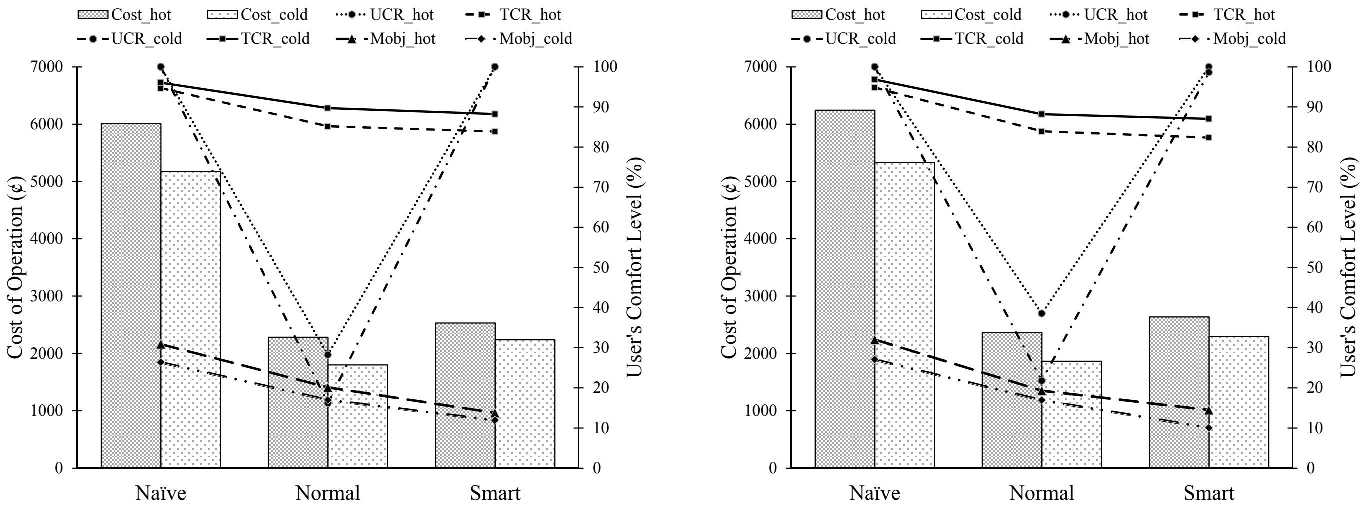
where, $H(\cdot)$ and $EXP\ (\cdot)$ denote Heaviside step and exponential functions, respectively, $T_{in,i}$ and $T_{s,i}$ are the actual temperature and the user-specified set-point for indoor temperature of i^{th} building unit and $\Delta T_{th,i}$ is the threshold temperature difference. ζ_e, ζ_l, ζ_c, and $\zeta_h \in R^+$ are also the leading coefficients of the natural exponential functions used for adjusting the penalty values. It must be noted that the described optimization problem should be solved taking into account demand-supply balance equation and all available technical constraints for generation units, storage devices and schedulable tasks.

III. SIMULATION RESULTS AND DISCUSSION

The case study is configured with a grid-tied IES and ten residential building units with similar constructional elements adopted form [24]. Different kinds of distributed heat and electricity generation units as well as schedulable tasks are considered for the case study. A fuel-cell based micro-CHP system with an electric power output range of 0.3-1.5 kW, thermal efficiency of 70% and a reference natural gas consumption rate of 92.4×10^{-3} m^3/h is considered as a co-generation system within each residential section. It is also assumed households own energy storage systems (either in form of static batteries or electric vehicles) with energy capacity of 24 kWh, nominal charging/discharging power of 3.3 kW and charging efficiency of 87%. For heating/cooling purposes, each building unit is equipped by a UFH/CS with nominal power of 2 kW and default set-point of 25 ^oC. The residential community is also powered by the centralized energy sources inside the IES considering user's subscription rates. These are including a wind generator with 20 kW rated power, a PV system with nominal power of 25 kW and a battery bank with energy capacity of 240 kWh.

To verify the effectiveness of our proposed methodology for coordinated energy and comfort management within the IES, several operating situations in different weather conditions (i.e., hot and cold), and time frames (i.e., weekdays and weekends) are considered. Moreover, low to high levels of intelligence for agents are also investigated. By the use of smart agents (i.e., agents with the highest intelligent level), a mixed objective function as stated in (3) would be fully addressed, while using of normal agents (i.e., agents with higher intelligent levels) will only result in a cost-effective operation. At the lowest level of intelligence, naïve agents neither consider energy consumption costs nor the user's convenience and comfort levels, however they meet the system's contraints. The proposed MAS structure is also implemented based on cooperation of different agents described earlier. In the MAS structure, agent actions are also specified through different behavioral classes and added to their life cycles. For MGCC, DAs, RESA and ESA that run their tasks periodically and execute some user-defined piece of code at regular intervals, *Ticker Behaviour* is adopted, while *Cyclic Behaviour* is applied for SA that stays active as long as it is alive and is called repeatedly after every event. The simulation platform is implemented in JAVA. Other third-party softwares such as MATLAB and GAMS are also incorporated as calculation engines where needed. Moreover, to facilitate the development of an agent-based environment in compliance with the FIPA specifications, Java Agent Development Framework (JADE) is utilized.

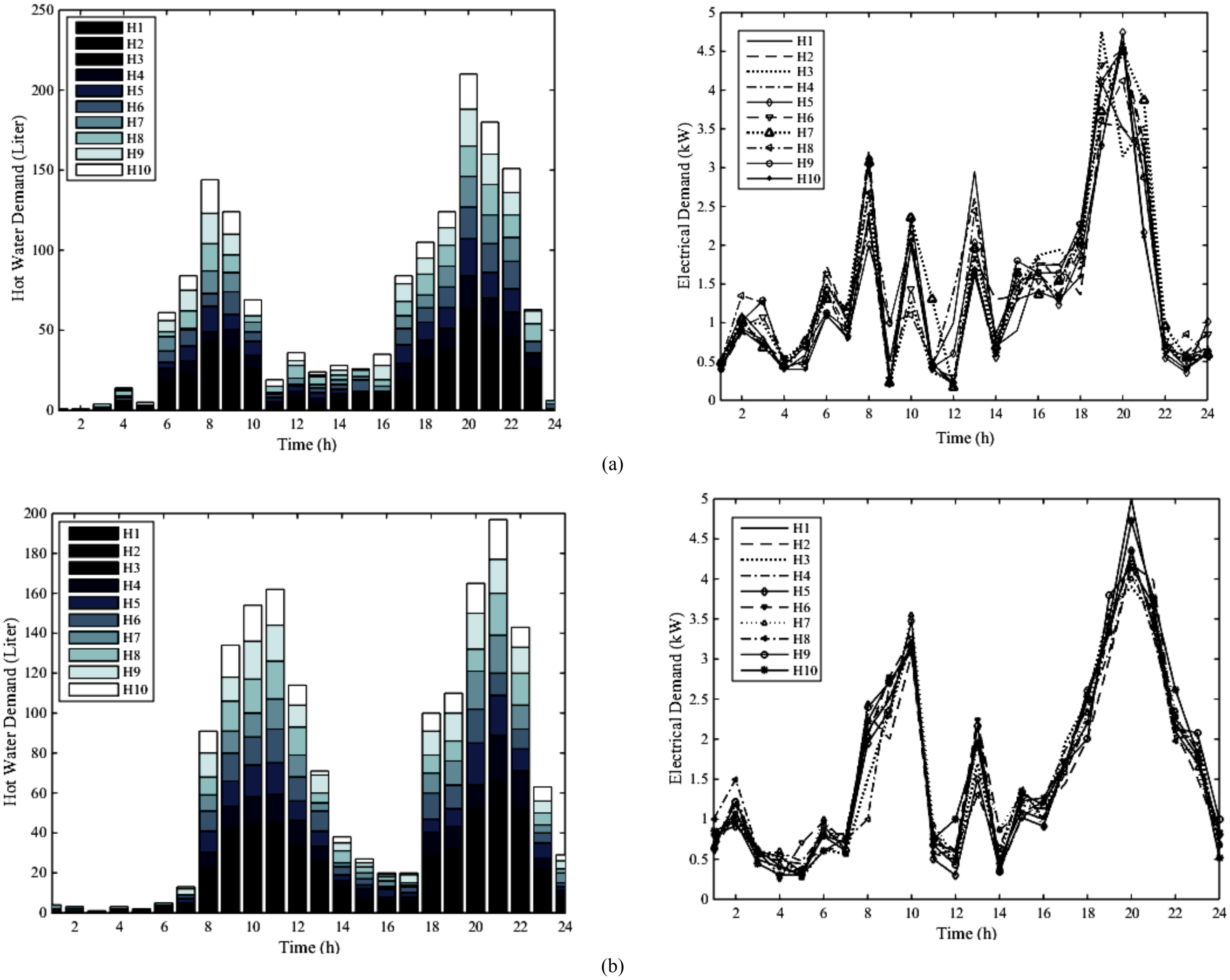
Figure 5 shows the simulation results for different case studies considering the hourly electricity demand and hot water usage profiles as illustrated in Fig.6, the meteorological information as depicted in Fig.7, and schedulable tasks as shown in Table II. Each subplot in Fig. 5, presents the total operation cost of the IES, average user's convenience and thermal comfort rates (UCR and TCR), and the hybrid index (Mobj) as defined in (3) for the examined scenarios.



a) weekday

b) weekend

Fig.5. Performance comparison of the proposed algorithms in different working scenarios



(b)

Fig.6. Hourly base-load electricity demand and hot water usage profiles: a) weekday, b) weekend

TABLE II. SCHEDULABLE TASKS DATA AND USER'S PREFERENCE

Appliance	UTR	PTR (Weekday)	PTR (Weekend)	LOT	EEC (kWh)	w_i
Washing Machine	07:00 21:00	08:00 14:00	13:00 19:00	2	1	1
Dishwasher	09:00 22:00	14:00 18:00	17:00 21:00	2	1.4	2
Dryer	09:00 21:00	11:00 17:00	16:00 21:00	1	1.8	1
Iron	01:00 13:00	05:00 07:00	08:00 11:00	1	1.1	2
Vacuum Cleaner	08:00 20:00	09:00 12:00	15:00 19:00	1	0.65	2
Microwave	08:00 19:00	11:00 14:00	13:00 16:00	1	0.9	3
Rice Cooker	10:00 20:00	14:00 17:00	16:00 19:00	2	0.6	3
Electric Kettle	04:00 12:00	06:00 07:00	08:00 10:00	1	1	3
Toaster	01:00 10:00	06:00 08:00	07:00 09:00	1	0.8	3

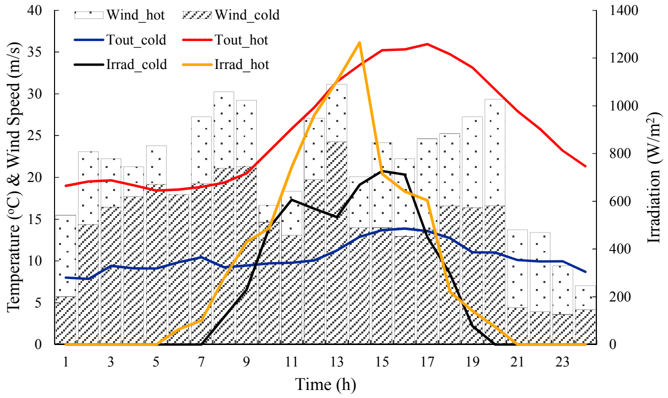


Fig.7. Meteorological data for the examined location [24]

It is clearly understood from the computer simulations that the proposed smart MAS approach has a superior performance compared to other MAS-based architectures in terms of the hybrid index improvement. Numerical results show that the *Mobj* is improved up to 57% and 23% with respect to the naïve and normal MAS-based approaches averaged over all scenarios. The results also demonstrate that using smart MAS-based control strategy not only provides an effective way to reduce energy consumption in buildings, but also ensures a comfortable life for inhabitants.

It can be also observed that the overall system behavior can be affected by different weather conditions or time frames. As an example, the operating cost of the community is higher in hot weather conditions due to the cooling load of the buildings, which necessitate further operation of UFH/CSs to fulfill user's needs. Likewise, the energy consumption cost of the IES is a little bit higher in weekends compared to the ones in weekdays.

To get more into details of the message passing structure for the proposed MAS, Fig. 8, summarizes a number of conversations between agents during the course of scenarios. At startup, all agents subscribe themselves into the Directory Facilitator (DF) as participants in the MAS structure to be informed every time an agent is born or dead, a container is created or deleted. To proceed with a new conversation, each agent needs to send a message based on FIPA-ACL to the target agent knowing the receiving AID which is provided by the Agent Management System (AMS). It should be noted that the AMS and DF are immediately created once a JADE platform is launched. Furthermore the messaging service is always activated to allow message-based communication.

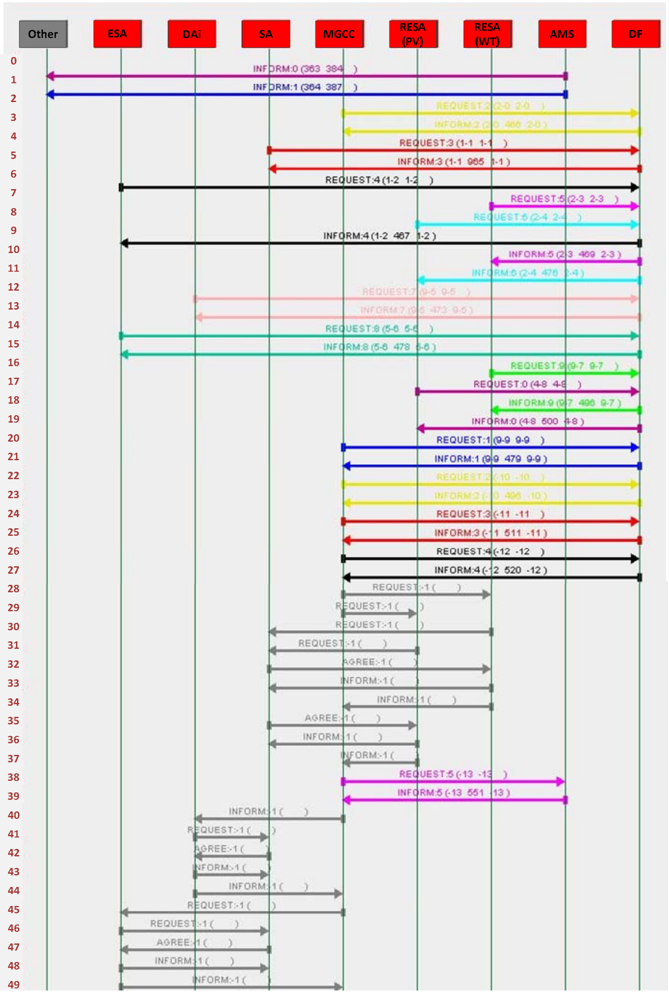


Fig. 8. Message passing hierarchy in the proposed MAS

IV. CONCLUSION AND FUTURE WORKS

An ontology-driven MAS-based dispatch strategy for applications in a residential IES was described, modeled and validated in different operating conditions. It was demonstrated through the computer simulations that the proposed approach has the capability to reduce domestic energy usage and improve the user's satisfaction degree and comfort level using coordinated demand response and distributed generation management strategy while considering system's constraints. Simulation studies also showed effectiveness of the proposed model over the conventional ones. Future efforts will be mainly aimed at improving the current MAS framework by taking into account more functionalities such as fault-tolerant and uncertainty handling capabilities.

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