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Holonic Self-Sustainable Systems for Electrical Micro Grids

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Abstract— **The self-sustainability of micro grids is an important challenge in the smart grids field due to the need to balance the fast growing energy consumption, reduce greenhouse gas emissions and increase energy independence by using renewable resources. The use of decentralized paradigms, and particularly multi-agent systems and holonic control, enable to face this challenge by implementing intelligent mechanisms that allow an efficient management of the power flow. In this paper, a holonic based model is introduced, considering load scheduling and forecast mechanisms to improve the micro grids self-sustainability, and consequently reduce the energy cost and the energy dependency from the main utility. The designed holonic based model and strategies were developed by using the agent technology, and particularly the JADE framework, showing important improvements in the self-sustainability of micro grids working in different operating modes.**

I. Introduction

The control and management of electrical power systems represents a big challenge not only due to its complexity but also due to its heterogeneity. As the world is moving towards a more resilient and sustained power supply, a need to follow the path of smart technologies is required. Smart grid technologies, such as advanced metering interfaces, distribution grid management (Automated re-closers, remote controlled distributed generation and storage), Wide-area monitoring and control (sensor equipment) or Customer-side systems (Smart appliances, building automation systems, smart thermostat) have the capability to support the integration the grow of heterogeneous devices within the distribution system and are essential move to reduce the overall greenhouse gas (GHG) emissions and push forward the energy efficiency [1]. When referring to smart technologies, besides the smart-meters or bidirectional communication networks, it is also considering smart/intelligent software applications that play a key role within the control and management of power and electrical devices forming the new generation of electrical energy systems. Clearly, the combination of smart appliances/devices with intelligent software will ease the appearance and propagation of smart grids.

Although smart grids also have to accommodate the electricity market liberalization and the large scale integration of distributed generation units (DG) and renewable energy sources (RES) that lead to topology changes within the power grid structure [2], [3]. However, smart grids have associated a complexity growing, particularly in large scale systems, requiring the need to manage the behavioral autonomy within the smart grids components in an individual manner but also the cooperation processes that emerges from the interaction among the smart grid components.

Smart grids, being large-scale networks can be composed by several autonomous and coordinated micro grids, that are low-voltage distribution grids comprising small power generation units. Micro grids represent an operation, security and control challenge due to its heterogeneous content nature. Therefore, a proper integration of new micro sources, such as RES, combined with intelligent strategies for efficient power flow, rational power utilization and proper management of storage devices represents an important issue in the deployment of micro grids. The complexity, diversity and intelligence shown within the smart grids, and particularly in micro grids, combined with emergent technologies and automation functions, namely demand response, real-time pricing, RES and intelligent control, allow to achieve optimization in smart electrical grids towards economics and sustainability.

Multi-agent systems (MAS) and holonic principles show high potential to face the challenges posed by the smart grids since they present decentralization of control over distributed structures, modularity, scalability, autonomy and reusability. In particular, based on their flexibility, robustness and mostly to their distributed nature, they are well placed to observe and explore the emergence of such complex systems [4].

The objective of this paper is to describe a holonic solution that enhances the balance between the production and consumption of energy in a micro grid working in different operating modes. The proposed solution enables the reduction of cost and dependency from the main utility through the usage of dynamic forecasting and scheduling algorithms, and is tested using an experimental micro grid case study.

The paper is organized as follows: Section II overviews the application of decentralized approaches to smart grids, and particularly MAS, holonics and IEC61499. Section III describes the proposed holonic approach for managing the self-sustainability in electrical micro grids and Section IV describes the developed experiments, namely by introducing the case study and discussing the experimental results. Finally, Section V rounds up the paper with the conclusions and points out the future work.

II. Decentralized Perspective for Smart Grids

A. Overview of the decentralized principles

MAS paradigm [5], [6] has its roots in distributed artificial intelligence field and constitutes an alternative way to design large-scale distributed control systems based on autonomous pieces of software, called agents, which are able to co-operate with each other to achieve their individual and global system objectives.

This innovative paradigm and technology offers decentralization, modularity, flexibility, robustness and parallel execution of activities, and is being applied to a wide range of application, from the electronic commerce and scheduling, passing by industrial domains such as manufacturing and lately in traffic control and energy systems.

MAS alone cannot provide the high level of abstraction to cope with the different entities present in the multiple application domains. In order to deal with the different entities, although at the same time similar or even equal in the way of management and control, the ideal combination is MAS with the holonic paradigm.

Holonic control is essentially based on the same basic MAS concepts, namely the society of autonomous and cooperative entities, in this case the holons. According to Arthur Koestler, a holon can be simultaneously a part and a whole (e.g., the entire system), allowing to use recursivity to design complex large scale systems. Holons can be part of a system and still preserve its autonomy and identity, having also the ability to dynamically belong to multiple holarchies [7]. An holarchy can be composed by several other holarchies although being can be conceived and handled by a single holon that abstracts its internal composition.

The flexibility provided by the holonic paradigm has attracted the attention of research community, especially in the manufacturing field through the Intelligent Manufacturing Systems (IMS) consortium that has established the Holonic Manufacturing System (HMS) framework to support the next generation of manufacturing systems.

MAS solutions are mostly developed to work at an intermediary level where they can introduce intelligence, adaptation and re-configurability. At lower control level, the state-of-the-art Programmable Logic Controllers (PLCs) are used to ensure the real-time constraints, which usually is not provided by MAS applications. The solution comes through the combination of the IEC 61499 standard, working at the lower control level, with agents, working at the higher control level [8].

The IEC 61499 function block architectures an extension of the IEC 61131-3 function block diagrams and defines a new way to model the control and execution of algorithms in distributed control systems, by encapsulating and reusing software modules [9]. This standard follows the multilayered architecture of IEC 61850, opening a pathway to deploy multi-agents on networked embedded control devices. Such combination paves the way to the industrial adoption and the ability to cope with real-time constrains and at the same time integrate highly flexible and adaptive control.

B. Existing applications

The referred decentralized approaches are being applied in several domains and particularly in power energy systems.

Several projects using MAS principles in smart grids can be found in the literature. For instance, [10] presents the EcoGrid project to implement a real-time energy market and in [11] an intelligent control of smart grid loads through a selective shedding of non-priority loads. A mode deeply analysis can be found in the survey [12].

The holonic principles are being applied to power energy systems, trying to capitalize the intrinsic characteristics into potential benefits. In [13] it is proposed an architectural model based on holonic multi-agent systems that structures software entities into the information and technology (IT) infrastructure of the smart grid, being the whole network assumed as holon that consists of some domain holons. In [14], it was introduced an holonic approach to power system automation that is based on distributed intelligence, combining application functions of IEC 61850-compliant devices with the IEC 61499-compliant “glue logic” using the communication services of IEC 61850-7-2. An holonic approach to structure and organize the smart grid into autonomous prosumers, recursively clustered at multiple aggregation layers, is presented in [15]. The control holons as they named them, form a complete control holarchy of the smart grid, being organized in a bottom-up structure. Functions such as environment state acquaintance, state analysis, database management, forecasting and scheduler are included in the holon structure.

In [16] the authors applied model driven engineering to smart grid automation using IEC 61499 and IEC 61850.

Frey et al. propose a holonic control architecture that addresses the requirements presented by smart grids such as control a wide variety of heterogeneous end-users while taking into account local objectives and private interests [17]. For this purpose, three integration patterns for conflict resolution in self-managed systems, namely hierarchic, collaborative and stigmergic where identified [18].

Pahwa et al. introduced an holonic multi-agent system architecture that is capable of adaptively control electrical power distribution systems, e.g. enabling operation of distribution systems when forced to islanding due to external factors such as environmental events or main grid failure [19].

These different works show the advantages of using decentralized structures and particularly holonic principles in defining the smart grid structure. However, there is room for improvement in several areas, such as sustainability in micro grids, which combining holonic principles with weather and power/consumption forecast or load and production scheduling will allow to enhance the smart grid management and control.

III. Holonic approach to Self-Sustained Micro grids

The proposed holonic architecture takes advantage of the recursive property inherent to holonic systems to naturally match the smart grid recursive structure. As shown in Fig. 1, it is clear that a holon can be divided into several other holons, meaning that the holon can be any device, i.e. producer, consumer, prosumer (producer/consumer), storage or even the micro grid itself, without being necessary to change its internal architecture. This flexibility enhances the cooperation, not only, in horizontal way (i.e. among holons of the same level, e.g., interaction among several photovoltaic (PV) units and battery banks) but also in the vertical way (i.e. between holons present in different levels, e.g., PV units and the overall micro grid). However, there are some components (modules) that can be present in the majority of the holons and other that are only present in a few of them as stated in the next section.

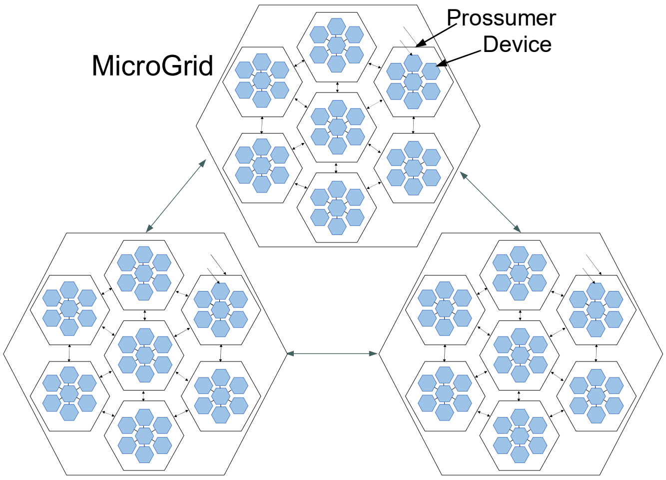

Fig. 1. Recursive micro grid holonic architecture.

Having this in mind, the holonic architecture considers 3 types of holons, that represent the different types of entities presented within the power grid system, namely:

- Consumer holon (CH), representing the controllable loads, is responsible for the management of the consumption of its entity according to its needs, priorities and state of the grid.
- Producer holon (PH), representing the producers, e.g., wind generators and non-renewable generators, is responsible to manage the produced power.
- Storage holon (SH), responsible for the management of the storage units and electric vehicles and providing a dynamic coordination of the state of charge as well as the charging and discharging cycles.

The rest of this section will detail the internal architecture and behavior of the holons, as well as the forecast and scheduling mechanisms that will support the micro grids self-sustainability.

A. Internal Holon Model

The internal holon architecture assumes a crucial importance in the specification of the proposed holonic architecture since it will enable the inter-holon and intra-holon communication. As illustrated in Fig. 2, the generic holon is composed by several functions part of the intelligent management component, complemented by the learning and context aware modules.

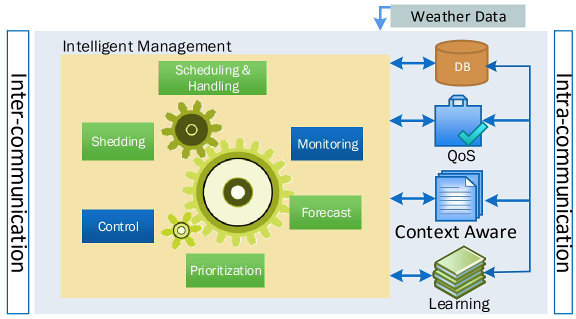

Fig. 2. Holon internal architecture.

The *monitoring function* is responsible for the detection and analysis of the power grid situation and pricing in order to detect when is the correct time to disconnect from the main grid and also to implement adaptive procedures, such as the need to charge batteries at lower price or start scheduling and prioritization of controllable loads. The load and production balancing is issued by the *control function* that ensures a proper and stabilized management of the power flow. The *scheduling and handling function* is responsible for the allocation of load and production (if possible and depend of the type of producer) for each time slot and time horizon. The *shedding funtion* is responsible for the identification and disconnection of loads as well as weighing the shedding for each controllable load. The *forecast function* provides forecasting information, namely related to the energy production and consumption depending on the type of holon, to other modules based on the weather (current and forecast) and on the current status of the holon. The load prioritization is performed by the *prioritization function* that is issued with the task of identifying what are the most important and critical loads fort each time slot and time horizon.

The *learning module* is responsible for the continuous adjustment of the holon behavior aiming to have a continuous improvement in the holon's performance. The major output of this module is the assistance in tuning the parameters of each one of the other modules taking into account the historic events, data stored into the DB and the context provided by the context aware module. The *context aware module* is responsible to analyze the current state of each module and incite each module to adapt to the current context of the power grid. The *QoS (quality of service) module* aims to help minimizing the impact on the user's quality of service and provides to the other modules a level of impact of the action being made. The.

Each agent's behaviors can comprise several modules specified in the internal holon architecture, but some of these modules are specific for some agents, e.g. the prioritization module is specific for the consumer agents.

B. Individual Agent's Behaviors

The behaviors of each individual holon were specified tacking into consideration the monitoring, management, rationalization and production, consuming and storage coordination capabilities. In this work, the Petri nets formalism [20] was used to specify the individual holon's behaviors due to its powerful capability for formally describe, analyze and validate complex event-driven systems.

As example, Fig 3 illustrates the Petri net model for the consumer holon behavior.

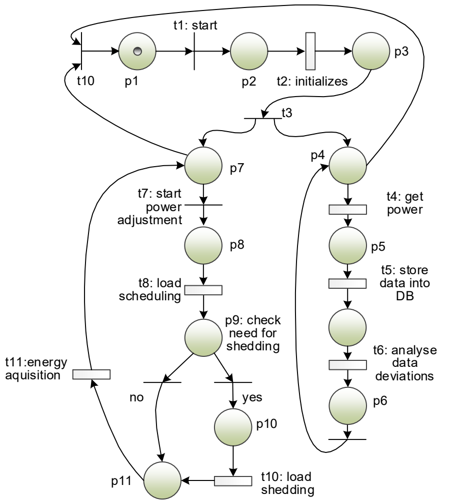

Fig. 3. Behavior model for the consumer agent.

The initialization procedure, represented by the transition *t2*, comprises the loading of the holon profile and the launching of two sub-behaviors that runs in parallel:

- One managing the power demand (*p7*), being responsible to execute the load scheduling and shedding and the negotiation with producer and storage holons aiming to fulfill the required demand.
- The second one (*p4*) has a direct connection to the physical device allowing to gather the consumption data and to detect failures on the equipment.

Each behavior model contains several transitions that can be exploded into more detailed sub-Petri net models to provide further logic control details. As example, transition *t8* executes a set of actions to schedule the power consumption profile in order to take advantage of the low prices of certain periods of time during the day. In case of a failure of the energy supplier stakeholder, a load shedding is executed (transition *t9)*.

Similar Petri net models were designed to other holons.

C. *Interactions and Communication Protocols*

The interaction between the distributed holons, combined with their local knowledge, leads to the emergence of the global system behavior. The cooperation mechanism illustrated in Fig. 4 describes the interaction between consumers, producers and storage holons during the process of buying energy according to the consumer holons needs. An important point to consider is that all holons involved in this negotiation are able to decide when, which quantity and to whom will sell/buy their energy (e.g., consumer holons decide which proposal will better fit its needs taking into account the price and power proposed from the other holons).

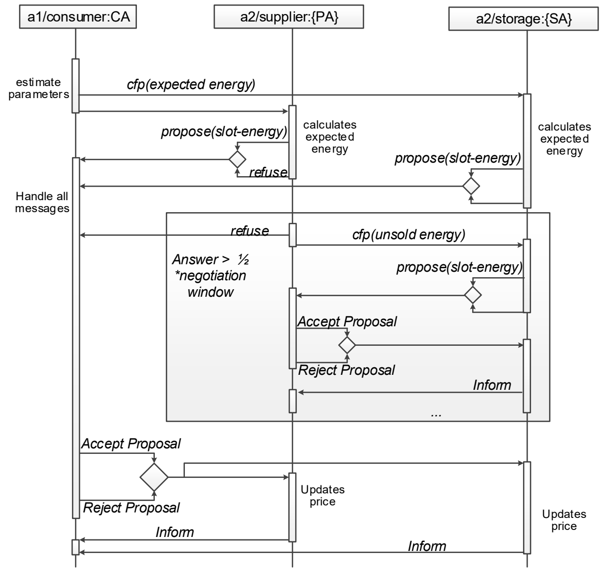

Fig. 4. Interaction protocol for the process of buying energy to satisfy consumers demands.

After a proposal has been sent by the producers they will only wait a given amount of time equal that is equal to half of the negotiation window. This will start a call for proposals to store power into the battery banks. In each call for proposals interaction, the price will always be the key to seal the deal between the participants.

IV. Intelligent Mechanisms for Forecasting and Scheduling

An important issue in the proposed holonic solution is the consideration of intelligent mechanisms to enhance the self-sustainability of the micro grids, namely related to dynamic scheduling, shedding, prioritization and forecasting. In this work, the scheduling and forecasting mechanisms, embedded in the distributed holons, will be detailed. The transition *t8* of behavior model illustrated in Fig. 3 comprises mechanisms that are responsible to perform the forecasting and scheduling of the demand.

A. *Forecasting Mechanisms*

The forecasting mechanism play a key role in this work by enhancing the holons' behavior to take proper and adaptive measures in advance, anticipating the occurrence of expected or unexpected events. Examples of these events are the forecast of load demand, energy produced (based on renewable sources) and cost of the supplied energy. This mechanism is embedded in several other mechanisms such as scheduling (described in the next sub-section) and shedding.

Several qualitative and quantitative methods to forecast data is available in the literature. Qualitative methods are based on opinion and judgments of the intervenient being more appropriate when past date is not available, methods such as sales force polling or consumer surveys are often used. In the case of quantitative methods, the forecast is based upon past data and when there are defined patterns making-it easier to identify future data [21]. Examples of quantitative methods are the Linear Prediction (LP), Simple Moving Average (SMA) or even Weighted Moving Average (WMA).

In this work, the option was to use one quantitative method due to the existence of past data, and the well-defined pattern of consumer's profiles. In particular, the Exponential Moving Average (EMA) was selected since it is more flexible than SMA or WMA, and it enables a better and faster response to changes in the consumption profile.

The load demand, price and energy produced parameters are forecasted using a one-day time window, taking into account the historical data from previous day and to weather forecasting (e.g. provided by the OpenWeatherMap). The one day ahead forecast was used due to the necessity of more recent values to the changes imposed by the introduced algorithms.

The forecast is done individually by each consumer, producer and storage holon, which provides a sufficient level of anticipation to prepare controllable loads to be scheduled, shed or eventually switched off.

B. Scheduling Mechanisms

The scheduling of controllable loads is also a crucial mechanism to ensure the self-sustainability of micro grids, enabling the reallocation of loads depending on their consumption profiles, energy production profiles and market prices (e.g., moving some loads to period with lowest price in a bi-timely market situation). The scheduling algorithm embedded in each consumer holon, extended the timed transition t8 of Fig 3, is illustrated in Fig 5.

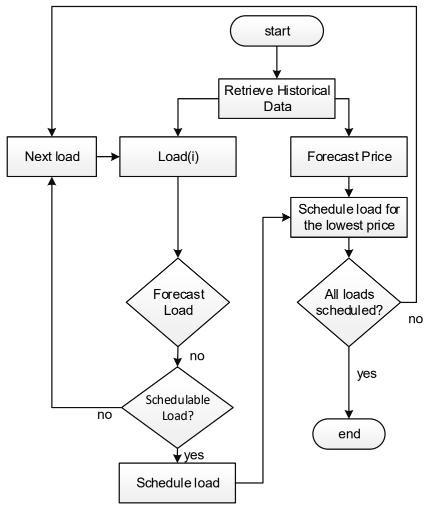

Fig. 5. Model of the scheduling mechanism.

The scheduling of each load is an iterative process that comprises the execution of two set of actions in parallel: in one side is checked if the load is schedulable, and if so which time window will better fit the load characteristics. In the other side, the lower price windows are checked. At the end, the results coming from the two parallel sides meet together in other to find an ideal time window to schedule the load. The load will only be scheduled if the load fits the consumer's profile and if no change is introduced into the user's usability.

V. EXPERIMENTAL RESULTS

The proposed holonic model considering the designed intelligent strategies for scheduling and forecasting aiming the electrical micro grids self-sustainability, was implemented using multi-agent systems technology, and particularly, using the agent development framework JADE [22].

A. Description of the Case study

In this work, a small low-voltage micro grid was considered to test the proposed approach, as illustrated in Fig. 6, containing 13 houses, 10 PV units (approx. 5 KWp each) and 6 battery banks of 225 AH each. The houses are fully independent, which means that there is no restriction on the purchases as long as the proposal is the cheaper. In the case of producers, they try to sell to whom offers the beast deal. In case of the battery banks, they are more passive only dealing with the left-overs.

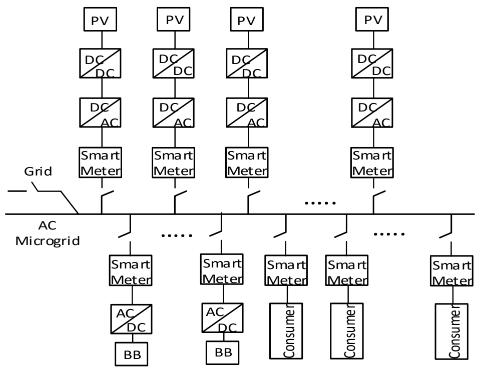

Fig. 6. Electric schema of the micro grid use case.

The profiles for the consumption and production of energy were considered for the winter and summer time, being simulated using the GridLab-D power simulation software [23], considering a weather profile in the latitude of 41.816667.

The case study was simulated considering 3 different scenarios:

- Basic: no intelligent mechanism for scheduling or forecasting is considered and the PV power surplus is sold to the utility grid.
- Intermediary: similar to the basic profile but now considering the intelligent control for the battery banks (i.e., the power surplus will be allocated into the battery banks).
- Intelligent: Similar to the intermediary profile but adding now the intelligent mechanisms, namely forecasting and scheduling.

B. Analysis of results

As stated before, the case study was tested under three different scenarios aiming to reduce the energy costs without affecting the end-users. The following table summarizes the experimental results for the simulation of 7 days, stating the costs with buying/selling power (*Cost* in €), the total power consumed (P_{cons} in KW/h), the power requested to the utility grid (P_{req} in KW/h), the power sold to the utility grid (P_{sold} in KW/h) and the percentage of P_{req} over P_{cons} (α).

TABLE 1. SIMULATION RESULTS FOR SUMMER SEASON

Scenario	Cost	P_{cons}	P_{req}	P_{sold}	α (%)
Basic	41.4	1265,2	961.4	2504.4	75.8
Intermediary	39,9	1135.7	825.5	1314.4	72.7
Intelligent	30.5	1035.3	716.3	1221.1	69.2

The analysis of the experimental results allows to verify that the use of more sophisticated and intelligent strategies leads to a reduction in costs and power requested to the utility grid. This happens since the power being sold during the period of low demand is now sent to the battery banks to later be used by the consumers. It is noticed that the power sold to the main utility grid has a small effect in the costs rebalance. In fact, since the electric supplier companies tend to pay-it cheaper and cheaper, the benefits of storing, in an intelligent manner, this power are clear. This way the intelligent battery charging enabled a better power balance leading to savings in power expenses.

The next table summarizes the experimental results for the winter season where the differences are more pronounced due to fact of less power provided by the PV units.

TABLE 2. SIMULATION RESULTS FOR WINTER SEASON

Scenario	Cost	P_{cons}	P_{req}	P_{sold}	α (%)
Basic	79.1	1241.6	1087.9	819.9	87.6
Intermediary	57.6	1224.5	986.6	261.7	84.1
Intelligent	43.8	1142.3	906.9	258.4	79.4

This simulation shows that the load scheduling clearly affects the costs and consumption levels. In some cases, like in water heater, the power and costs savings can be achieved by a proper schedule of the loads, e.g., adjusting the periods of switch on/off.

The difference between summer and winter rely mostly on the amount of power that was sold to the main utility grid during summer. Also the difference between the loads types (e.g. air conditioning) increased the demand slightly as this types of loads are un-schedulable during hours that could affect the users free will of usage.

It is clear that the usage of intelligent mechanisms and strategies enables a better management of the controllable loads, improving the efficiency and costs savings. It also enables a better management of the available power in the micro grid, reducing the wasted energy and concentrating it in the moments of higher demand needs.

VI. CONCLUSIONS

Self-sustained micro grids require an efficient management of their internal energy resources to face the energy demands. Managing the micro grids self-sustainability, without affecting the end-user way of life, represents a challenge especially when the resources are scars.

The proposed holonic model considers intelligent mechanisms for the scheduling of controllable loads, complemented with forecasting mechanisms, to increase the self-sustainability of micro grids.

A case study micro grid was used to test the proposed holonic solution, incorporating these intelligent mechanisms, and developed using multi-agent system technology. The achieved experimental results clearly show a decrease of the cost paid to the utility grid, which means a better management of the internal energy resources.

Future work is related to the refinement of the internal holon modules, and particularly the shedding and load prioritization.

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