Holonic Energy Management Systems: Towards Flexible And Resilient Smart Grids*

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Abstract. The increasing global warming and soaring fossil fuel prices have made energy generation minimization a crucial objective. As a result, the relevance of smart grids has significantly grown, especially in the context of regulating energy demand based on available resources. This necessitates the implementation of Demand Side Management (DSM) tools for effective regulation. While various models and architectures have been developed for smart grids, the utilization of holonic architectures remains limited in existing literature. In this paper, we propose a holonic architecture specifically tailored for smart grids, which proves to be highly advantageous. Holonic architectures are particularly valuable in smart grids as they enable seamless operation among different actors, even during technical challenges. Our proposed model consists of interconnected agents forming holons, with five agents working in tandem to ensure flexibility across multiple aspects. We have tested this model in three different scenarios. The first scenario represents a healthy grid. The second scenario simulates a grid with production mismanagement. Lastly, the third one simulates a grid experiencing a region-specific blackout. Results show how the grid distributes the available energy depending on the available production, storage (if any) and the assurance of the distribution across the various requesting holons.

Keywords: Smart Grid · Holarchy · Holon · Multi Agent System (MAS) · Energy Management System (EMS).

1 Introduction

In 2015, the Paris Agreement was accepted by 196 countries as a commitment to limit global climate change resulting from global warming to be less than 2°C, primarily through the reduction of fossil fuel usage [29]. In line with this, the European Union is funding projects aimed at developing solutions to mitigate greenhouse gas emissions. One such project is MAESHA, which includes

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the contributions discussed in this article, focusing on decarbonizing the French island of Mayotte.

Energy production infrastructures play a significant role in climate change, and early projects have revealed that relying on natural gas for electricity production is not an ideal solution. Firstly, natural gas is a fossil fuel, meaning its energy generation still contributes to pollution. Secondly, the availability of natural gas is not uniform across all countries, and transportation issues, whether due to accidents or political conflicts, can lead to dramatic price increases.

Consequently, it is essential to explore alternative solutions that are more accessible and manageable. To this end, transition policies away from coal and other fossil fuels have been discussed in [26], proposing an increased integration of Renewable Energy Sources (RESs) such as Photovoltaic (PV) panels. Although RES installations are currently more costly compared to conventional energy sources, the study in [4] estimates that the Return Of Investment (ROI) will improve over time, eventually matching that of fossil fuels. However, a significant challenge associated with RESs is their dependency on weather parameters like sunlight, temperature, and wind, making it difficult to control energy generation.

Another challenge arises from the increasing number of Electric Vehicles (EVs) and the subsequent higher demand for charging, which increases the risk of grid instability and potential blackouts [12]. Nevertheless, with proper control over EVs charging processes (such as delaying or advancing the charging time) and utilizing their batteries for discharging when necessary, it becomes possible not only to prevent blackouts but also to leverage these batteries as energy storage units during peak hours—a concept known as Vehicle to Grid (V2G) [13, 18]. Given the uncontrollable nature of energy generation and the controllable aspects of EVs charging and discharging, demand becomes the only parameter that can be managed through Demand Side Management (DSM). DSM aims to delay, flatten, or plan energy demand and utilize battery storage during periods of high demand and excess energy production [16]. Therefore, upgrading traditional Electrical Grids (EGs) to Smart Grid (SG) is necessary to enable intelligent energy usage and efficient energy routing, thereby maximizing the benefits of DSM.

The concept of SGs as known today was defined by Amin and Wollenberg [2]. It represents an upgraded version of traditional EGs that aims to enhance various aspects such as measurements, predictions, data registry and analytics, control, and communication. SGs address a wide range of challenges and requirements within the grid system, including consumers, producers, energy distribution, and blackout management. By improving communication and distributed control among different actors, including consumers, producers, storage facilities, EVs, and the emergence of prosumers [8], SGs facilitate the integration of RESs. Prosumers, who can generate energy using RES, contribute to the grid by either satisfying or supplementing their own energy demands based on factors like weather conditions (sun radiation) and the energy availability on both the grid and EV side.

To fully utilize RESs, batteries, and EVs, SGs necessitate bidirectional energy routing, enabling users to not only consume but also produce and feed surplus energy back into the grid during peak hours [25]. However, to optimize the performance of prosumers, accurate measurements and predictions for the near future are crucial. Predictive capabilities allow SG actors to plan their energy demands or offerings in advance, enabling more effective energy routing with reduced losses and lower transmission costs. It also allows for the possibility of delaying certain demands before peak hours occur. Several deep learning methods have been proposed for energy demand prediction in a flexible and reusable manner. Studies such as [6, 15] have introduced deep learning models for demand prediction in different regions, while [15, 22] have focused on different time ranges. Additionally, [27] has proposed a flexible deep learning approach that ensures adaptability to both time ranges and regional domains.

Numerous architectures and models have been proposed for SGs. However, one architecture that remains insufficiently tested and defined in the domain of SGs is the holonic architecture. This paper aims to address this gap by introducing a holonic SG architecture, in response to the suggestion put forth by Howell et al.[14].

The holonic architecture is characterized by the aggregation of a universal entity known as a holon. A holon possesses the ability to function autonomously as a whole entity while also being part of a larger entity of the same type [20]. In the context of a holonic SG, a holon can be conceptualized as the aggregation of multiple microgrids, each of which is further comprised of smaller microgrids, ultimately extending to the level of individual houses or electric devices.

The proposed model in this paper aims to simulate the behavior of holons within the SG framework. Holons encompass a variety of agents that can be modified to simulate diverse scenarios. For instance, the model can incorporate different energy pricing schemes (e.g., flat prices, dynamic prices, carbon-based prices) and energy management strategies (including load curtailment, peak and load reduction, peak clipping, valley filling, etc.), as well as encompass various technologies. Scenarios within the model encompass a wide range of disturbances that can affect the grid, including those related to its structure, behaviors, or external factors.

By adopting the holonic architecture, the proposed model presents a novel approach to SGs, allowing for the exploration of complex interactions and behaviors within the system. It provides a platform to study and evaluate different energy pricing strategies, energy management techniques, and the impact of disturbances on the grid. Through this holistic approach, the holonic SG architecture holds promise for enhancing the efficiency and resilience of future SGs.

In this paper, we present an extended version of the paper [28]. The present version contains a mathematical model that includes costs, energy storage via Battery Energy Storage System (BESS) and the concept of energy curtailment. It also distinguishes between the Energy Management System (EMS), that is, the root holon (the deciding holon) and the aggregator holons that can play the role of EMS in case of grid faults to prevent blackouts. The paper starts with a literature review of holons and Holonic Multi-Agent System (HMAS) in Section 2. Section 3 describes the proposed model as both a single holon model, a holarchic model, as well as a control method based on cost optimization. In Section 4, the materials and methods used for the simulations are discussed, along with the three test cases used on the proposed model. Conclusion and future work are given in Section 5.

2 Literature Review And Gaps

The concept of holons and holarchy, where holons are organized in a hierarchical architecture, was first introduced by Arthur Koestler in his book ”The Ghost in the Machine” in 1967 [17]. The concept of HMASs was then introduced by Gerber, Siekmann, and Vierke [10], where an agent can be an aggregation of multiple lower domain agents. This concept has been applied to various domains, including automation, manufacturing, and transportation systems [19].

While different architectures have been proposed for SGs, the most interesting ones are based on holarchies as they provide greater flexibility to the different actors within the grid, such as consumers, producers, prosumers, storage facilities, and distribution points [21]. These architectures benefit from both decentralized decision-making and a top-down hierarchical organization or surveillance. [11] has proposed to compose the SG of two layers: physical layer where all the connections to all physical devices happen, and aggregation layer where all holons from the first layer merge or aggregate to form the SG. [3] has defined their SG based on low and medium voltages: a first level designs smart homes and energy resources, than the higher levels are for low voltage feeders, medium voltage feeders, medium voltage substations, etc. up to the highest level that contains the EMS holon that is responsible for managing the whole system.

Many papers have discussed the various control methods and architectures for EMSs. However, the most relevant architectures and solution are the ones that focus on hierarchical EMSs and EMS aggregators [7]. Indeed, EMS aggregators have been discussed for different objectives and in different roles such as demand response aggregators [5], load aggregators [24], and microgrid aggregators [23].

In terms of holonic architecture, Ferreira et al. [9] introduced the concept of single holon modeling, where a holon can manage anything from a physical device to an apartment, building, or even micro-grids. They also proposed a multi-threaded holon, with separate threads for negotiation with peers, negotiation with children, and local behaviors. The application of holonic SGs for self-healing purposes has been discussed in [1], highlighting the potential, challenges, and requirements of SGs in a holonic architecture. Another framework based on holonic architectures has been proposed, consisting of historical data collection, prediction (Forecasting of Resources for Dynamic Optimization - FRODO), and decision or strategy selection (Optimal Load and Energy Flow - OLAF) [30].

The existing modeling of SGs has some limitations and challenges. One of the main drawbacks is the lack of flexibility in the architecture, which often leads to rigid and centralized control systems. This limits the ability of different actors within the grid to make autonomous decisions and adapt to changing conditions. Additionally, traditional SG models often struggle to handle the complexity and scalability of large-scale systems, making it difficult to incorporate diverse energy sources, accommodate fluctuations in supply and demand, and ensure efficient grid operation.

This is where the holonic model can provide significant benefits. The holonic architecture offers a more flexible and decentralized approach to SG modeling. By organizing the SG as a hierarchy of holons, where each holon can function as an autonomous unit while being part of a larger entity, the holonic model enables more distributed decision-making and control. This allows for greater adaptability, resilience, and self-organization within the SG.

Furthermore, the holonic model supports modularity and reusability. Holons can be easily composed and recomposed to form different configurations of the SG, accommodating various energy sources, devices, and actors. This modularity facilitates system expansion, integration of new technologies, and easier maintenance and upgrade processes.

The holonic model also addresses the challenge of scalability. By breaking down the SG into smaller holonic units, such as microgrids, and then aggregating them into larger holonic structures, the model can effectively manage the complexity of large-scale SGs. This hierarchical organization allows for efficient coordination and communication between different levels, ensuring smooth operation and effective resource management.

Overall, the holonic model overcomes the limitations of traditional SG modeling by offering greater flexibility, decentralization, modularity, and scalability. It empowers individual actors within the grid while enabling coordinated behavior and optimal system performance.

In the next sections we will discuss a new proposed single holon model that is composed of multiple agents. The main goal of this model is to provide the highest possible flexibility in terms of the definition of the SG architecture, its reuse and blackouts avoidance.

3 The Proposed Model

In this section, we propose a holonic architecture that is composed of flexible and resilient holons, organized as a hierarchical bidirectional rooted tree. Holons represent their connected actors and their subholons, they are able to control them or to communicate with upper level entities that take care of the control and they are composed of five interconnecting agents: measurement agent, data agent, prediction agent, control agent and communication agent. These holons, their functionality, as well as their composing agents will be discussed in details in the following subsections.

3.1 Holarchic Architecture

A holarchy, or holarchic architecture, is a hierarchical arrangement of holons. Unlike traditional hierarchies where parts rely on the whole and cannot function individually, holons are autonomous units that can operate both independently or as a part of their corresponding roots.

The proposed holarchic architecture offers flexibility in three aspects: control and communication, space, and time. It allows holons to represent and control various actors in the SGs, such as physical devices, storage facilities, EVs, or even micro-grids. The measurement agent facilitates communication with different devices or smart meters, while the communication agent enables interactions with other holons representing smaller or larger micro-grids. This ensures the flow of data from devices and other holons to the control agent.

Holons are created and distributed on different levels based on regional considerations. For example, the top-level holon represents an entire country or an island. The second level consists of holons representing regions or actors with similar power demand or generation capacity, like a thermal power plant. The third level represents villages or equivalent actors involved in power trading, such as renewable energy, facilities or storage units. This architecture can extend to lower levels, depending on the configuration, reaching down to simple smart devices like heating devices. At each time step, holons check for connections to physical devices or subholons to provide or obtain the required energy.

Holons should also be capable of providing predictions at different regional scales, whether for a large region, a small group of buildings, or even a single device. In this paper, holons are connected only to their upper holon, lower holons, and associated devices. They do not communicate directly with other holons at the same level but rely on feedback from their upper holon, which has broader information.

Furthermore, holons need to adapt to various time ranges depending on their level and the physical actors and holons they interact with. A data agent stores relevant data for future steps, including predictions and decision-making, while a prediction agent generates predictions for multiple time ranges according to the control agent's requirements.

Figure 1 shows an example of how a holarchy looks like for the SG while Figure 2 shows a sequence diagram for the five agents of a holon, with social agents of its connected holons.

3.2 The Holon: Composition And Functionality

In this subsection we will discuss the details of the main element of the holarchy: the holon. Holons in the proposed model can have two different roles. The first role is the global EMS (called root holon) and the second role is the aggregator role.

Holons Roles

Aggregator Holons represent a part of the EG, a region or a micro-grid. They apply basic control algorithms only to provide the necessary data and information to the root holon (or EMS). They also take care of forwarding or sending

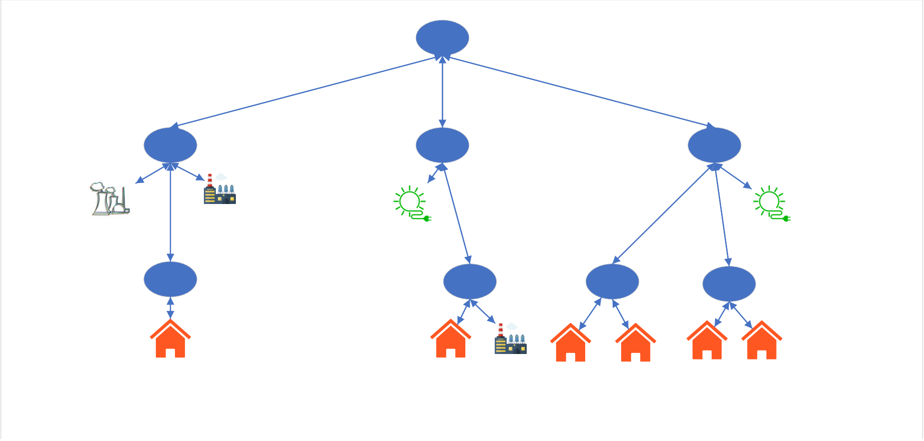

Fig. 1. The holarchic architecture. In this image, we can see that the holarchy is composed of three levels whereas it can be extended to as many levels as needed [28].

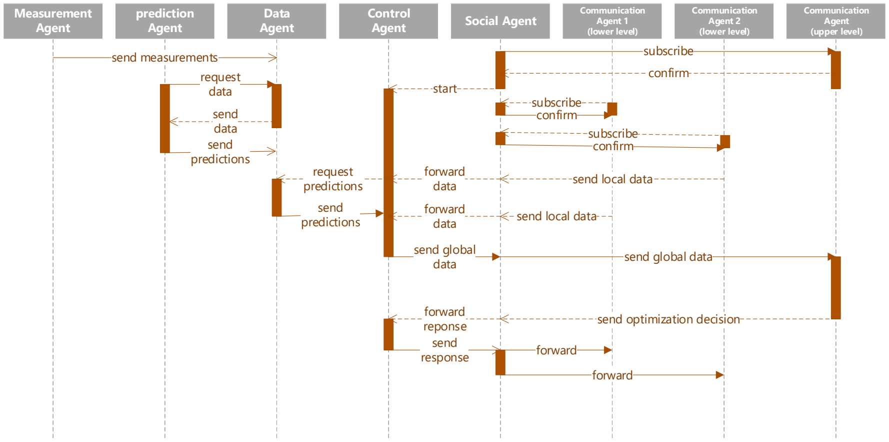

Fig. 2. The interaction between the various agents of the holon and the social agents of their connected holons. In this diagram, we considered that the holon is connected to only 2 subholons while this number can be less or more in other cases [28].

the result of the decision that they receive from their upper holon. In case of grid faults or disturbance, in order to ensure the highest resilience possible, aggregator holons can temporarily play the role of a root holon in their local holarchy, and thus act as a separate holarchy until the grid problems get fixed.

Root Holon is the highest level holon that has a global reach to all its subholons demands, generations, available BESS and possible charging. It applies a relatively complicated algorithm that aims to ensure a global convergence while ensuring the priority of RESs and cost minimization. Section 3.3 provides more details on how this holon performs its optimization.

It is worth mentioning that while the architecture proposed in this paper is similar to the original paper [28], the main difference, in addition to introducing BESS and load curtailment and generation and demand costs, is in the behaviours or roles of the various holons, namely: the aggregator and the root roles. The advantage of having these two roles compared to the original paper is that in the first proposition, subholons could prioritize their self consumption and do not send their generation information to higher levels, while in the current version aggregator holons should declare or inform the root holon which can take decisions considering the global interests of the grid. This helps to avoid any conflict of interest between the local decisions and the global decision.

Composing Agents The previously mentioned holon, is composed of five agents that are similar to the original proposition of the [28], except for the control agent which has different behaviours that can change depending on the needs of the grid. They are shown in Figure 3, and are defined as follows:

Measurement Agent handles the data and the measurements by handling the communication with physical devices (IoT devices, smart meters, etc.) and the transmission of these data to the Data Agent.

Prediction agent handles the forecasting the energy generation and/or demands using historical data that is stored in the data agent and other data like holidays and weather forecasts. In this paper, prediction agent implements the hybrid deep learning algorithm described in [27], which is able to make flexible predictions on both time scale and spatial scale. For the spatial scale, this method can provide predictions on a whole island scale as well as on the scale of a small group of buildings without the need of any modifications in the method. On the time scale, this method can also provide predictions on different time ranges (real-time, daily and weekly predictions) with minor changes in the preprocessing phase.

Data agent is the agent that handles and stores the data sent by data agent to provide them later to the prediction agent. The data agent also stores the energy forecasts made by the prediction agent to be sent for control agent upon request.

Communication agent is the agent responsible for the communications with other holons via their respective communication agents, it uses the Agent Communication Language (ACL) specifications for the communications with other agents. It also ensures that lower holons are in synchronization with its current time-step.

Control agent is the decision making unit inside the holon in the case of decentralized or distributed decisions (in the case of the original proposition), and it is the representative of the interests of its lower holons and itself in the case of centralized control systems that implements the concept of centralized EMS (in the case of the current proposition). It takes its decision depending on two flows of information. The first is the prediction data made by prediction agent and stored with data agent. The second is the ensemble of requests and/or offers sent from lower holons and the feedback received from the upper holon (in a holarchic architecture). Details about the control algorithm are provided in Section 3.3.

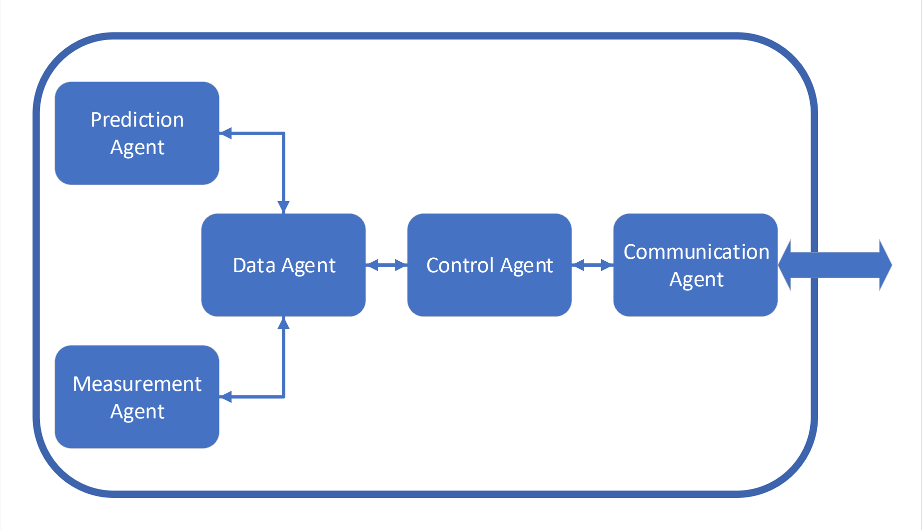

Fig. 3. The structure of the proposed holon, composed of five interconnecting agents as defined in [28].

3.3 Control Method

In this section , we will discuss the algorithm and behaviour of the control agent in more details. The first part of this section will discuss the algorithm of this agent, while the second part will discuss the details of the mathematical representation and the optimization model proposed for the decision making in the control agent of the root holon.

Control Algorithm Control agent is the brain of its corresponding holon. It takes the role of the root or aggregator holon depending on its position in the holarchy and on potential problems in the SG. It also takes care of informing and of decision making for the demands, generation and storage. Algorithm 1 shows the steps followed by this agent in order to ensure the well functionality in the holon.

Algorithm 1 Control Algorithm.

```
$T \leftarrow T_{max}$
$UPPER\_HOLON$ = READ_UPPER_INFO()
$HOLON\_STATE$ = READ_HOLON_STATE()
while $T \leq T_{max}$ do
    RECEIVE_DATA_FROM_LOWER_LEVELS()
    RECEIVE_LOCAL_PREDICTIONS()
    CHECK_AVAILABLE_STORAGE()
    CHECK_AVAILABLE_THERMAL_GENERATION()
    if $UPPER\_HOLON \neq NUll$ & $CHECK\_UPPER\_CONNECTION() = True$ then
        SET_STATE(Aggregator)
        SEND_AGGREGATION_TO_UPPER_HOLON()
        WAIT_FEEDBACK()
        RECEIVE_FEEDBACK()
    else if $UPPER\_HOLON \neq NUll$ & $CHECK\_UPPER\_CONNECTION() = False$ then
        SET_STATE(EMS)
        PSO()
    else if $UPPER\_HOLON = NUll$ then
        PSO()
    end if
    SEND_FEEDBACK_TO_LOWER_HOLONS()
    $T \leftarrow T + 1$
end while
```

The PSO() method is Particle Swarm Optimization (PSO) that has been applied to the optimization algorithm described in Section 3.3.

Mathematical Model In this paper, we represent the smart grid as a holarchy, which can also be viewed as a rooted tree structure where each node is connected to a single parent node. A smart grid can be described using a tuple (V, E, r), where V represents the set of nodes, E denotes the communication links between holons, and r is the root node that represents the entire island and that plays the role of the EMS. The links between holons symbolise the bidirectional communication for exchanging data and decisions between lower and upper holons. While r plays the role of EMS, other nodes are considered as aggregation holons that can play the role of EMS in case of need (grid fault, communication problems, etc.). Holons, or nodes, within the smart grid handle specific segments of the grid, such as regions. They encompass themselves, their subholons (representing villages within the region), and any actor directly associated with them (such as a solar park). Therefore, a holon h can be associated to a 3-tuple (G_h, S_h, H_h), where G_h denotes the subset of generation points, S_h represents the subset of battery energy storage systems (BESS), and H_h represents the subset of subholons connected to holon h.

Let $G_{h,g}(t)$ be the energy generated in the holon h, by the generator g, at the period of time t. Let $S_{h,s}(t)$ be the amount of energy stored in holon h, inside the BESS s, at time t. $\delta S_{h,s}(t)$ is the amount of energy charged or discharged from time t to $t+1$. Let D_h is the amount of energy demanded or needed by the holon h from the grid.

$$Minimize \sum_{g \in G} C_{h,g} G_{h,g}(t) + \sum_{s \in S} C_{h,s} \delta S_{h,s}(t) + \sum_{h} C_D D_h(t) + \sum_{h} C_{LC} LC_h(t) \qquad \forall h \in H, t \in T \tag{1}$$

subject to:

$$\sum_{g \in G} G_{h,g}(t) + \sum_{s \in S} \delta S_{h,s}(t) + \sum_{h} D_h(t) + \sum_{h} LC_h(t) = 0 \qquad \forall h \in H, t \in T \tag{2}$$

and

$$\delta S_{h,s}(t) = S_{h,s}(t+1) - S_{h,s}(t) \qquad \forall h \in H, s \in S, t \in T \tag{3}$$

and

$$S_{h,s}^{Min} \leq S_{h,s}(t) \leq S_{h,s}^{Max} \qquad \forall h \in H, s \in S, t \in T \tag{4}$$

and

$$G_{h,g}^{Min} \leq G_{h,g}(t) \leq G_{h,g}^{Max} \qquad \forall h \in H, g \in G, t \in T \tag{5}$$

where T is the hourly index in the simulation, H is the set of holons (nodes in the rooted tree), G is the set of generation points (generators), S is the set of BESS, D is the total energy demand needed for the holon (energy consumption).

$LC_h(t)$ is the load curtailment required to ensure the satisfaction of the clients. It is the result of the energy demand that could not be satisfied with the generated energy or with the stored energy in the BESS, during the time period t, and that has been delayed for later hours.

$G_{h,g}$, $S_{h,s}$, D_h and LS_h are all positive variables while $\delta S_{h,s}$ can be positive (recharging) or negative (discharging).

$C_{h,g}$, $C_{h,s}$, C_D, C_{LS} are the respective costs for the generation for each generator g that belongs to the holon h, energy storage for each BESS s that belongs to the holon h, the demand tariff and the load curtailment cost. In the proposed model, we estimate that battery charging and discharging is always more costly that energy production while it is always less costly that load curtailment.

4 Model Validation

The simulation has been made using JAVA as a programming language and JAVA Agent DEvelopment Framework (JADE) for the development of holons and their composing agents. It exploits the optimization method proposed in Section 3.3.

4.1 Data And Approach

In this paper, the data used for the simulations are for the island of Mayotte, and it has been provided by the MAESHA project. The simulation utilized weather forecasts, holiday data, and historical data on energy demand and renewable energy production with a time granularity of 60 minutes. Mayotte's energy landscape comprises two thermal power plants, various renewable energy sources (PV parks) and two BESS. The simulation implemented a 3-level holarchy architecture, with the root holon representing the entire island at the first level and playing the role of the EMS, the 17 regions at the second level, and the villages within each region at the third level playing the role of aggregator holons.

In this simulation, second-level holons represent their corresponding regions and encompasses the thermal power plants, renewable energy facilities (PV parks), energy demands of big consumers and BESSs. Third-level holons represent the villages, each responsible for initiating energy demands (excluding big consumer demands, that are represented by second level holons), that will then propagate to the second level. Second-level holons aggregate the data from third-level holons with its own demands (big consumers), generation, and energy storage offers and demands. The aggregated data will be then sent to first-level holon or the EMS. The EMS applies the control method defined in Section 3.3, and provides its feedback to lower level holons, this feedback propagates until it reaches the specific holons responsible for the demands. The proposed control method ensures the use of BESS for discharging during peak-hours and for charging during off-peak hours, as well as the stability in case of grid faults.

The architecture described in Section 3 was tested in three scenarios. We have applied the PSO algorithm on the optimization method of Section 3.3. The cost of RES has been considered as only O&M costs (without installation costs, to ensure the low cost for RES and thus to give it a higher priority in the optimization algorithm). The cost for energy storage has been considered as a very low cost to ensure that the BESS will be properly charged when grid faults happen. The cost for diesel is the average cost for the year 2020 in the island of Mayotte. Finally, to ensure that the model will only resort to load curtailment when needed (in case it is impossible to deliver energy during grid faults), we have considered that the cost of load curtailment is very high compared to other costs. This can be justified by the fact that not providing energy can have bad effects on the economy.

Due to the large number of holons on the island, the simulation results were presented for one specific holon, Mamoudzou, representing a region in the island that has its own PV park and BESS ensuring that even in the case of disconnection (as demonstrated in Section 4.4), it could still demand energy from its region's holon (its own) and compensate its lack of sufficient generation with the energy that is already stored in the BESS. Regions or villages capable of either producing their own energy or requesting energy from connected holons should exhibit similar behavior as demonstrated in the second scenario. However, it should be noted that holons or groups of holons that are disconnected from the grid with zero production or energy storage will be unable to satisfy their demands due to the lack of energy availability. It is worth mentioning that the simulation scenarios in this paper are similar to those in [28]. However they have been applied to another control algorithm that provides more flexibility and introduces the aspects of energy costs, energy storage and load curtailment.

4.2 Standard Scenario

In the standard scenario, all holons across the three levels described in Section 4.1 are properly connected, and thermal production operated optimally to meet all energy demands throughout the grid while BESSs have all the needed energy to stay charged during the simulation. Energy requests and availability propagate from the third level (lowest level) to higher levels. Once the highest-level holon (EMS) received all the requests, it provides its feedback for the demands ranging from 0 (no available energy) to 1 (the full demanded energy can be fulfilled), as well as feedback for the storage ranging from -1 (to discharge all the energy that is stored and available with respect to the batteries characteristics into the grid) to +1 (to charge the batteries to the maximum that is possible during the one hour time-step). Figure 4 illustrates that the energy demanded by Mamoudzou was successfully received in this standard scenario.

4.3 Disrupted Plant

This scenario considers the case where a thermal power plant (a large energy provider) experiences disruptions or undergoes maintenance, leading to its temporary shutdown. In this test case, the power plant located in **Koungou** stops working between the time-step 5 and 14, leading to a decrease in the energy generation while only the second thermal power plant located in **Badamiers** is working along side the PV parks and BESSs. Figure 5 shows that the energy received is higher than the energy demanded in the beginning of the simulation

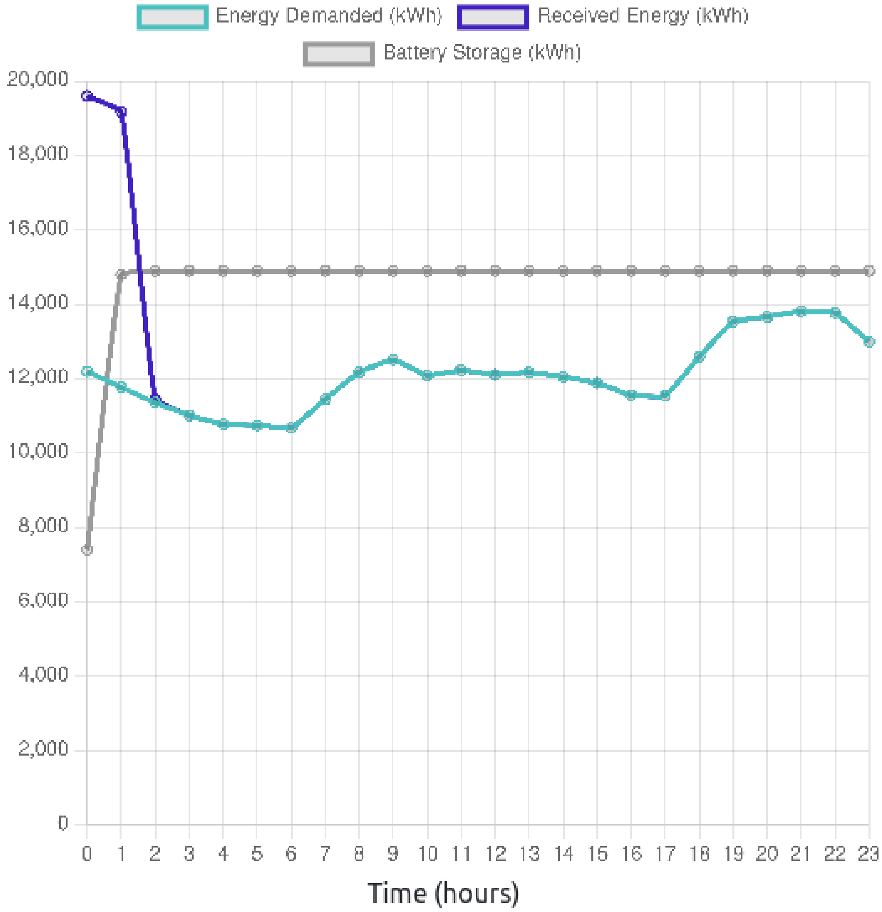

Fig. 4. Energy received by a holon representing a region in the island, in the standard scenario where all the holons and actors across the whole grid are properly connected.

due to the charging of the BESS. Between time steps 5 and 10, even though the thermal power plant has been shut down, the region still received all its requested energy because the PV generation with the other power plant was still enough to satisfy all demands. Starting from time-step 10 up to time step 13, BESSs starts discharging to compensate the insufficiency of energy generation compared to the peak in the demand side. After energy generation in the **Koungou** plant restarts, energy demands start to be fully received in the grid and BESSs start receiving energy for recharging. It is worth mentioning that in this scenario all holons keep their respective role as aggregators with the root holon plays the role of the EMS.

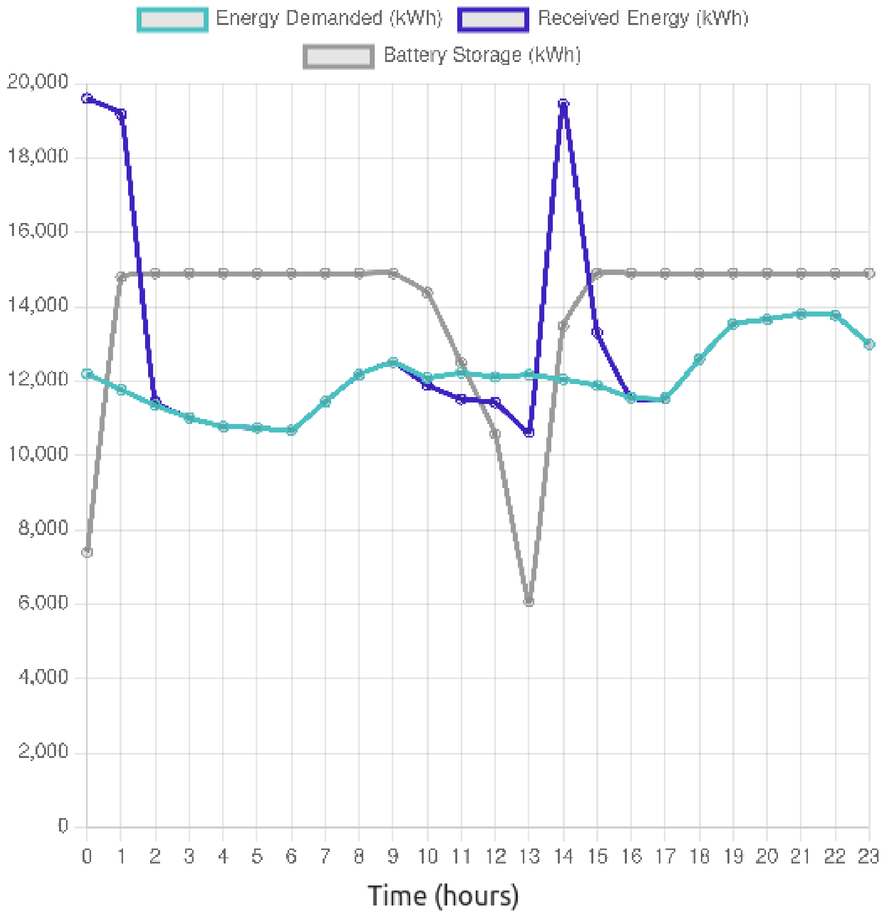

Fig. 5. Energy received by a holon representing a village on level 3, in a scenario where only one thermal power plant is operating.

4.4 Disconnected Region

In this section, the simulation explores the effects of a grid fault that causes a disconnection between the region of **Mamoudzou** and the rest of the grid. In this case, the grid functions normally until time-step 5, when the grid fault occurs. After that, the representing holon of this region starts acting as its own EMS, separately from the rest of the grid, while relying solely on available energy generation sources, namely photovoltaic (PV) generation and energy storage in the BESS. Any unsatisfied energy demand during this period is treated as load curtailment. Subsequently, at time-step 14, the grid recovers from its fault, the holon reestablishes its connection with the rest of the grid and it goes back to playing the role of an aggregator. Consequently, the region regains access to the grid generation, starting to recharge its batteries and to fulfill its demands. Figure 6 shows the results of this simulation test.

5 Conclusion and Future Work

In this paper, we proposed a holonic smart grid architecture following the concept of single holon modelling, where holons can take the role of an EMS or an aggregator. Holons represent geographical zones starting from small villages up to the whole grid as a whole thanks to its flexibility on the regional, spatial and functional aspects. In this paper, we have discussed the composing components (agents) of this holon, the interactions between the agents in the same holon, and between the various connected holons as well as the optimization and control method applied at the highest level holon (the EMS) and the role of other holons as aggregators. We then applied this architecture to the French island of Mayotte, forming a 3 levels holarchy. The first level consists of the highest holon which represents the island. The second level represents the 17 regions of the island and the third level (the lowest level in the holarchy) is composed of 72 holons. Each of these holons is connected to its respective upper holon. We then tested this holarchy on three test scenarios. The first one is a standard scenario where the energy flow and the connection between holons are working as supposed to be. The second scenario is a test where a thermal power plant is disconnected from the grid due to disruption or maintenance problems. The third scenario is a disconnection scenario where a holon is disconnected from the main grid and it has to deal with the energy generation and storage that it has without going into a blackout. The simulations have proven this architecture to be flexible and resilient in the three tested scenarios. Finally, the paper has focused mainly on the proposition of this new architecture, its feasibility and its flexibility in all aspects, while introducing the EMS element, the aggregator holon that can change to EMS depending on the needs, the energy storage using BESSs and load curtailment to ensure the well functioning of the grid in all situations while aiming to the highest satisfaction of the clients. In future works, more advanced control and communication algorithms will be introduced to get the most benefits of the available resources like generation and storage while introducing the concepts of Virtual Power Plants (VPPs) and load shifting.

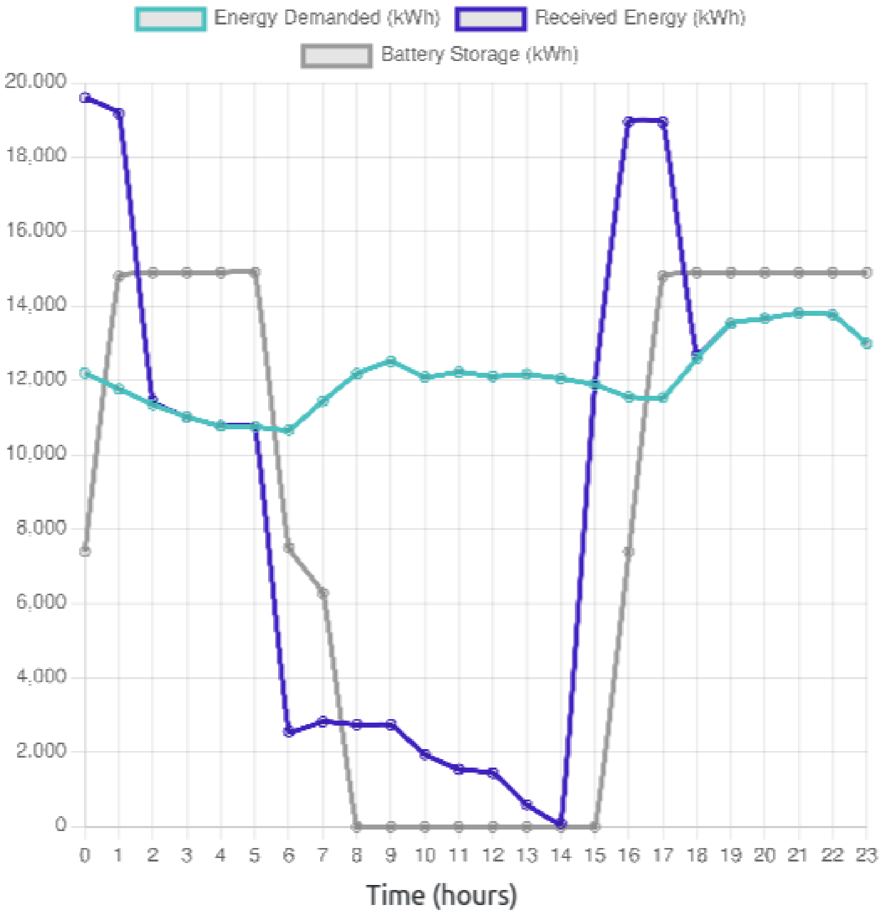

Fig. 6. Energy received by a holon representing region in the island, in a scenario where it is disconnected from the grid and the only energy and storage available are the energy produced and the storage available locally in the region.

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