A Holonic Multi-Agent Architecture For Smart Grids

Ihab Taleb[a], Guillaume Guerard[b], Frédéric Fauberteau[c] and Nga Nguyen[d]
Léonard de Vinci Pôle Universitaire, Research Center, 92 916 Paris La Défense, France

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Abstract: The global warming and the increase of fossil fuel prices make the minimization of energy generation an important objective. Thus, smart grids are becoming more and more relevant in a context where we want to regulate the demand according to the available energy. This regulation can be operated thanks to Demand Side Management (DSM) tools. While different models and architectures have been developed for smart grids, only few papers used holonic architectures. For this, we propose in this paper a holonic architecture for smart grids. This type of architectures is relevant to smart grids as it allows the various actors in the grids to work even in the cases of technical problems. Holons in the proposed model are composed of five interconnecting agents that ensure flexibility on the various aspects. This model has been tested and has proven to work on 3 different scenarios. The first scenario simulates a grid in its healthy state. The second one simulates a grid where a region can be disconnected from a blackout for example. The third one simulates a grid with production mismanagement. Results show how the grid distributes the available energy depending on the available production, priorities (if any) and the assurance of the distribution across the various requesting holons.

1 INTRODUCTION

In 2015, 196 countries accepted the Paris Agreement for limiting global climate change caused by global warming to less than 2^{o}C, by restricting the use of fossil fuels (UNFCCC, 2021). In this context, the European Union funds projects to develop solutions reducing the production of greenhouse gases. For example, the MAESHA project, in which the contributions of this article are part, aims at decarbonizing the French island of Mayotte.

In fact, energy production infrastructures are major players in climate change. In first projects, electrical production based on natural gas has proven to be not the ideal solution. First, natural gas is a type of fossil fuel, which means that its energy is still polluting. Second, as it is not available in all countries its price can increase dramatically during transportation problems whether they are caused by accidents or by political conflicts.

Consequently, it is important to find other solutions that can be easier to access and to manage. For these reasons, transition policies from fossils like coal have been discussed in (Spencer et al., 2017) by suggesting the increase of the integration of Renewable Energy Sources (RESs) by encouraging governments and people to install RES generators like Photovoltaic (PV) panels. Although RESs are still costly compared to other energy sources, the study in (Brockway et al., 2019) estimates that the Return Of Investment (ROI) will increase with time (more cost effective) and will reach, in the near future, that of the fossil fuels. On the other hand, one of the biggest challenges when talking about RES is that it is difficult to control, as it highly depends on weather parameters like sun radiations, temperature, wind, etc. This challenge means that the more RESs we have in the Electrical Grid (EG) the harder it is to control energy generation.

As another challenge, the number of Electric Vehicles (EVs) is increasing by the day, which means higher demand to charge their batteries and higher risks of serious problems in the grids like partial or total blackouts (Green et al., 2011). However, with a proper control over these EVs (delaying or advancing the charging process and discharging if needed), it is possible to not only avoid blackouts, but to use these batteries as a storage point to provide energy in the peak hour. This method is called Vehicle to Grid (V2G) (Hannan et al., 2022; Liu et al., 2013). Hav-

[a] https://orcid.org/0000-0003-2666-7631
[b] https://orcid.org/0000-0002-6773-221X
[c] https://orcid.org/0000-0002-1169-8040
[d] https://orcid.org/0000-0003-3273-8272

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ing the uncontrollable generation, and the controllable EVs charging and discharging, the only parameter that we can manage in this case is the demand, by a process called Demand Side Management (DSM). DSM aims to delay, flatten or plan the demand and use battery storage when the demand is higher than the available energy (peak hours) (Kanakadhurga and Prabaharan, 2022), and store the extra energy produced during high generation hours. Thus, in order to benefit from DSM, there is a need to upgrade the traditional EG to a Smart Grid (SG) that can allow for smarter energy usage and routing.

SG's concepts have been defined as it is known nowadays by (Amin and Wollenberg, 2005). It is the new version that aims to upgrade EGs on the different aspects : measurements, predictions, data registry and analytics, control, and communication. It covers all grids' problems and requirements starting from consumers and producers to energy distribution and blackouts handling. SGs improve the communication and the distributed control over the various actors (i.e., consumers, producers, storage facilities and EVs) and integrate the new type of actors called prosumers (Espe et al., 2018). Prosumers are consumers that can produce all or part of their energy demand using RES. An example of prosumers is a house having PV panels where the energy produced can satisfy or not the demands of this house depending on the weather (sun radiation), or an EV having relatively large battery storage where it can charge or discharge depending on the available energy on both the grid's side and the EV's side.

In order to use RESs, batteries and EVs to their maximum potential, SGs require energy routing to be bidirectional, to allow the users to act not only as consumers, but also as producers whenever they have sufficient energy production or storage during peak hours (Ramchurn et al., 2012). However, to reach the optimal performance for prosumers, it is important to have measurements and predictions for the near future. Predictions help SG actors to make their demands or offers to other actors ahead of time, allowing the energy to be routed more effectively with less loss and lower transmission costs, or to delay (if needed) some of the demands before peak hours happen. Indeed, multiple deep learning methods have been proposed to predict energy demands in a flexible or reusable way. (Dudek et al., 2021; Huang et al., 2022) proposed deep learning methods that can be used to predict the demand in various regions. While (Huang et al., 2022; Pallonetto et al., 2022) have proposed deep learning models to predict on different time ranges. (Taleb et al., 2022) proposed a flexible deep learning method that ensures the flexibility on both time ranges and region domains.

Different architectures and models for SGs have been proposed. However, one architecture that has not yet been sufficiently tested or defined in the domain of SGs is the holonic architecture. Indeed, the goal of this paper is to answer the suggestion made by (Howell et al., 2017) by proposing a holonic Smart grid architecture. A holonic architecture is an architecture defined by the aggregation of one universal entity called holon. A holon is an entity that can work (by itself) as a whole while at the same time, being part of a larger entity of the same type (Mella, 2009). In a holonic SG, a holon can be seen in such architecture as the aggregation of multiple microgrids, while each of them is also an aggregation of smaller microgrids until we reach the level of houses or electric devices. The proposed model simulates the behavior of holons among the SG. Holons include various agents which can be modified to simulate various scenarios. For example, our model can include various energy prices (flat prices, dynamic prices, carbon-based prices, etc.) and energy management strategies (shifting, peak and load reduction, peak clipping, valley filling, etc.) and any technologies. Scenarios also includes all kinds of disturbances on the grid, about its structure, its behaviors or external factors.

In this paper, a literature review of Holonic Multi-Agent System (HMAS) and holons is given in Section 2. Section 3 describes the proposed model as both a single holon model and as a holarchic model, as well as discusses some of the possible decision and control methods that can be applied to the proposed architecture. In Section 4, the materials and methods used for the simulations are discussed, as well as the three test cases used on the proposed model. Conclusion and future work are discussed in Section 5.

2 EXISTING MODELS AND GAPS

The idea of holons and holarchy (holons organized in a hierarchical architecture) has been first introduced with the book "The Ghost in the Machine" written by Arthur Koestler in 1967 (Koestler, 1967). (Gerber et al., 1999) introduced the concept of HMASs where one agent can be the aggregation of multiple lower domain agents. The concept of HMASs has then been applied to a diversity of domains like automation, manufacturing and transportation systems (Marík et al., 2013).

While different architectures have been defined for SGs, the most interesting architectures are the ones that are based on holarchies as they provide more flexibility to the different actors of the grid (consumers, producers, prosumers, storage facilities and points of distribution) (Negeri et al., 2013), while at the same time, benefiting from both the decentralization of the decision and the top-down hierarchical organization or surveillance. Indeed, (Ghorbani and Unland, 2016) 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. (Ansari et al., 2015) 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 energy management system holon that is responsible for managing the whole system.

Concerning holonic architecture, (Ferreira et al., 2015) has introduced the concept of single holon modeling where one type of holon can manage anything from a physical device, to an apartment, building, to micro-grids. It also proposes the holon to be multi-threaded, where each holon has a thread for the negotiation with peers, a thread for the negotiation with children, and a third thread for the local behaviours. (Abdel-Fattah et al., 2020) has discussed the application of holonic SGs for self-healing applications, as well as the potential, the challenges and the requirements for SGs in a holonic architecture. (Wallis et al., 2020) has proposed a framework, based on holonic architectures, that is composed of three parts: historical data collection, prediction (FRODO, which stands for Forecasting of Resources for Dynamic Optimization) and decision or strategy selection (OLAF, which stands for Optimal Load and Energy Flow).

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

A holon is the only component of a holonic architecture. Thus, the more holons are flexible and performing, the better the model is. In this section we propose a holon that is composed of five interconnecting main agents, namely: measurement agent, data agent, prediction agent, control agent and communication agent. Figure 1 shows the agents of the holon and their interactions.

3.1 A Holon Of Five Agents

The five agents of a holon are defined as follows:

Measurement Agent: is the agent responsible for collecting data from physical devices: smart devices that are IoT connected, sensors, smart meters. It is the intermediary between the data agent (and all other agents) and these devices.

Prediction Agent: is responsible to provide predictions for future demands and/or generations depending on historical data provided by the data agent. It implements the hybrid deep learning algorithm described in (Taleb et al., 2022), 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 other hand, 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 responsible for handling data, storing these data and sending them to the prediction agent. It is also responsible for storing predictions made by prediction agent and to send them to control agent depending on its requests.

Control Agent: is responsible for decision making, it can be as simple as request-response in an Internet of Energy (IoE) context as well as more sophisticated algorithms implementing Evolutionary Game Theory (EGT) or Q-learning. It takes its decision depending on two flows of informations. 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).

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 step.

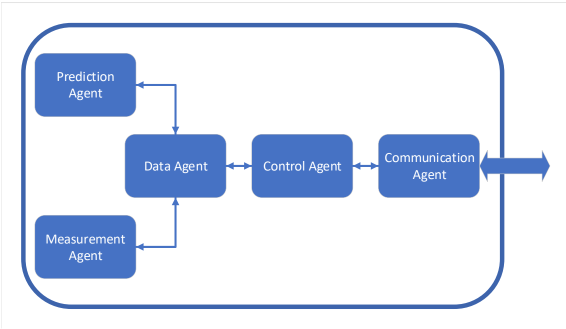

Figure 1: The structure of the proposed holon, composed of five interconnecting agents.

3.2 Holarchic Architecture

A holarchy or holarchic architecture is a holonic architecture composed of holons organised in a hierarchical way. The concept of holarchy is similar to that of a tree based architecture. However, the main difference between the two is that in a holarchy, the parts are autonomous and able to operate independently, while in a tree-based hierarchy, the parts are more dependent on the whole and may not be able to function on their own. The holarchic architecture is used in this paper to provide flexibility in the functional aspect, the spatial aspect and the temporal aspect.

Holons should be able to work for any type of actor in the SG whether it is a physical device, storage facility, EV, or a micro-grid. Measurement agent takes care of the communication with various types of devices or smart meters while communication agent takes care of communicating with other holons that are either lower holons representing smaller micro-grids or the upper holon representing the larger micro-grid. This ensures the flow of data from both sides (devices and/or other holons) to the control agent.

On the other hand, holons are created and distributed on the various levels based on the regional aspect, which means that the super holon on the very first level (the highest level) will represent a whole country or an island in the case of the simulation of this paper. On the second level, each holon represents a region or an actor of equivalent amount of power demand or generation (e.g., a thermal power plant). The third level represents villages or any equivalent actor in terms of the amount of power traded (e.g., RES facility or a storage facility). the architecture can reach down as much as needed depending on the decision of the engineers that will apply this architecture until it reaches the level of simple smart devices like heating devices. Holons continually check at each time step to ensure if any physical devices or subholons are connected to them respectively in order to provide for them or from them the energy that is needed or available. Holons also should also be able to provide predictions on different regional scale whether it is a large region or a small group of buildings or even a small device. Holons in this paper are only connected to their upper holon, to their lower holons, and to their proper devices. In order to have a simpler and more practical architecture, Holons do not communicate directly with other holons on the same level, but instead, they wait for the feedback of their upper holon which will have the broader information.

Moreover, holons should be able to work on different time ranges, depending on which level they are in and with which type of physical actors and holons they are dealing with. Data agent stores the data that could be needed in the next steps for both predictions and decision taking while prediction agent takes care of providing predictions on multiple time ranges depending on the needs of control agent.

Figure 2 shows an example of how a holarchy looks like for the SG while Figure 3 shows a sequence diagram for the five agents of a holon, with social agents of its connected holons.

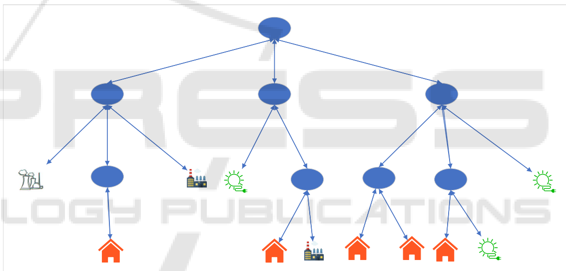

Figure 2: The holarchic architecture. In this image, we can see that the holarchy is composed of three levels whereas it can be extended to as many levels as needed.

3.3 Control Methods

In order to ensure an efficient routing and sharing of energy across the grid, holons should be able to not only take local decisions, but to negotiate by requesting or offering energy. They also should be able to change their decisions (e.g., by delaying demands, or stocking their offer for later use, etc.) depending on the feedback of their upper holons. Indeed, different methods can be applied to the negotiations and decision making for the control of the various holons on the various levels. Also, these methods should follow two specific steps in order to ensure the organization of the communication of the different actors.

Local Decision: Each holon takes its decision based on energy requests and offers of both its con-

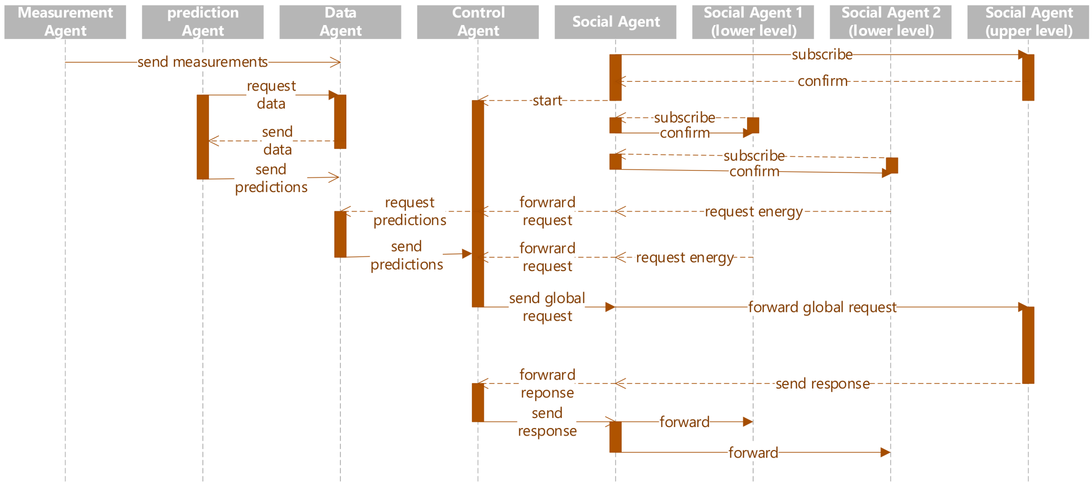

Figure 3: The interaction between the various agents of the holon and the social agents of their connected holons (in this diagram, we considered that the holon is connected to only 2 subholons while this number can be less or more in other cases).

nected actors and its subholons. Requests and offers are decided, ahead of time, based on predictions. These decisions can be taken using various algorithms and methods, like IoE, EGT, optimization, etc.

- The IoE method, proposed in this paper, consists of calculating, at each level, the request/offer ratio. Based on this ratio, a holon decides whether to demand or offer energy to its upper holon. This process happens recursively in a bottom-up approach until it reaches the highest level holon, the holon that is supposed to send its feedback. In peak hours, if the generated energy cannot fulfill all the demands, upper holons feedback will consist of the calculated ratio at the highest level, which it turns will be the percentage to be decreased for each holon and at each level. In this approach, negotiations can be as simple as one iteration of demand and response. Section 4 uses this approach, tested on the proposed architecture, in order to show the distribution of energy in different test scenarios.
- In EGT, demands and requests can be seen as strategies, and each strategy is represented by its own population. Populations evolve depending on the feedback of the upper holon on multi-step negotiations. EGT can be combined with Q-Learning to update the payoff tables for players at each time-step.
- In Optimization methods, requests and offers can be seen as variables that can take positive or negative values. These variables can be updated depending on the feedback of the upper holon at each time-step. In Particle Swarm Optimization (PSO), the feedback received can be considered as the output of fitness function that is responsible to choose the particle with best fitness (in this case, the best offer or demand).

Negotiations and Global Decision: In this step, holons try to achieve a consensus with their upper and lower holons. It is important to specify a maximum number of iterations and to stop whenever optimal values are reached. Simulated annealing is an option to ensure the convergence of the grid.

4 SIMULATION AND RESULTS

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 IoE method proposed in Section 3.3.

4.1 Materials and Methods

The model proposed in this paper has been tested on the data of the island of Mayotte provided by the MAESHA project.

Indeed, weather forecasts, holiday data and historical data of both energy demand and RES production on 60 minutes granularity has been provided for the simulation. The island has two thermal power plants, one Biogas and various RES facilities. The simulation is composed of 3 levels holarchy. The first level consists of the super holon representing the whole island. The second level represents the 17 regions of the island. While it is possible to be defined in other ways, in this simulation, second level holons have the two thermal power plants, the Biogaz plant, and the RES facilities each directly attached to the holon representing their region. On the third level, holons represent the villages of each region. Mayotte has a total of 72 villages which means a total number of 72 holons on the third level. Third level holons start all the energy demands, and their requests propagate to second level holons. Second level holons gather the data from third level holons and verify if their requests can be satisfied in the local network of holons, otherwise, they send their request to upper level holons until they reach a point where their request is fulfilled or until the request reaches the highest level with no sufficient energy. In this case, the super holon will send feedback about lowering the demands, this feedback will then propagate back from higher levels to lower levels until it reaches the lowest levels that are responsible for the demands. Although it is not included in this simulation, it is also possible to have storage facilities that can store energy (in this case they act like consumers) and then to provide this energy (in this case, they act like generators) in later times depending on the need of the SG (depending on the feedback that arrives from higher level holons). The architecture defined in Section 3 has been tested in three scenarios. Having the large number of holons in the island, it is not possible to show the result of the simulation for each holon. For this, The results of these three scenarios are provided for one specific holon (in Figure 4, 5, 6 and 7), showing the energy received by the holon representing **Handréma**, which is a village in the **Bandraboua** region. The reason for choosing this village is that it belongs to a region having PV generation so that in case of a disconnection like in the second case (Section 4.3), it can still demand energy from its region's holon. Any region or a village that can either produce its own energy or demand energy from connected holons should give a similar output as in the second scenario. However, it is worth mentioning that if a holon or a group of holons got disconnected from the grid with zero-productions, they will not be able to satisfy their demands as they have no way for having energy.

4.2 Standard Scenario

The simulation in this scenario is the standard case where all holons on the three levels, described in Section 4.1, are properly connected and thermal production is in its optimal production, which means that all energy demands can be satisfied across the whole grid. Energy requests, that could not be fulfilled locally, propagate from the third level (the lowest level) to upper levels. When the highest level holon receives all requests, it then sends its feedback ranging from 0 (no energy available) to 1 (energy demanded can be fulfilled in full). Figure 4 shows that all the energy, demanded by (**Handréma**), is received.

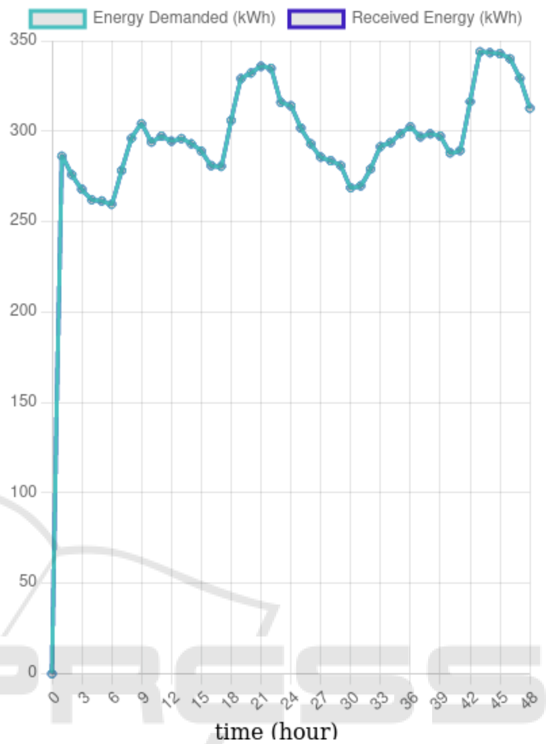

Figure 4: Energy received by a holon representing a village on level 3, in the standard scenario where all the holons across the whole grid are properly connected.

4.3 Disconnected Holon

The second scenario shows what happens to the energy received and consumed in the case if a disconnection happened between a holon in the second level and its upper holon (the holon representing the whole island). In fact, disconnection might happen for multiple reasons, but it is mostly because of technical problems in transmission cables. In this scenario, requests can propagate from villages only to one higher level (i.e., only to their directly upper holon), namely the holon representing the region **Bandraboua**. **Bandraboua** can no longer demand from the holon representing the island because of the disconnection between them. Thus, the only energy that can be sent to its lower holons is the energy produced locally in this region. The upper holon has two choices: the first choice (described in Section 4.3.1) is to give priority to specified holons and give the rest of the energy to the other holons, while the second choice (described in Section 4.3.2) is to distribute the energy proportionally to their demands (which means, as an example, that the holon requesting 10% of the total demand will receive 10% of the available energy).

4.3.1 Holon Prioritization

In this case the disconnected holon representing the region **Bandraboua** gives the priority to the holon representing the village **Handréma** which means that this holon will receive all energy that it needs and the other holons will only receive what is left. Figure 5 shows the received energy for **Handréma** on hourly basis. At the beginning of the simulation at time-step 0, the energy received starts at zero in the first hour as the connection between the holon (**Handréma**) and its upper holon (**Bandraboua**) is not yet established and it is to be established in this time-step. The energy received then increases and decreases depending on the PV energy produced, which is directly correlated to the sun radiations. This explains the zeros received between hours 15 and 25 and after 39 which indicate night-time hours. While this seems like a problem, it can still be a solution to avoid total or partial blackouts. The energy received between time-steps 3 and 13 and 28 and 38 are equal to the energy demand which means that during these time-steps, energy production has exceeded energy demand (for **Handréma**, the prioritized village) and thus, the other villages can share the energy produced that is left. Although this is not included in the current simulation, it is worth mentioning that the energy received during day-time can then be stored in batteries in order to be used depending on predefined priorities throughout the day.

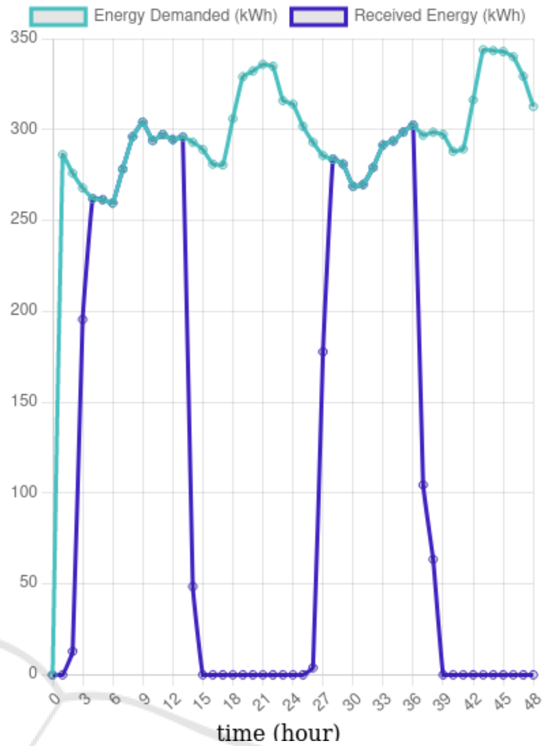

Figure 5: Energy received by a holon representing a prioritized village on level 3, in a scenario where its upper holon is disconnected from the grid and the only energy available is the energy produced locally in the region.

4.3.2 No Priorities Given

In this case, the disconnected holon will not give any priority to any holon and will instead give the energy proportionally to what has been demanded in total. Figure 6 shows the amount of energy received by the holon representing **Handréma**. The results in this figure show that the specified holon never receives a sufficient amount of energy because the total demand is higher than the PV generation.

4.4 Disconnected Plant

In 2023, the thermal power station of **Badamiers** is scheduled to be at the end of its life. Thus, the island will be then using only one power plant which means less energy generation. For this, this test scenario consists in using only the other thermal power plant (located in **Koungou**), the biogas station, and the PV generation. In a similar way to above, whenever the produced energy is not sufficient, thermal energy gets distributed to every village proportionally to the population of the village. Figure 7 shows the energy received for the holon of **Handréma**. In this figure, the energy received from thermal power plants is around 280 kW·h all the time. The result shows that between time-step 2 and 7, and time-step 29 and 32, the received energy meets the energy demand because the amount requested is below the available amount of energy. On the other hand, during the time-steps between 8-13, 16-17 and 33-38, the energy requested was completely fulfilled because of the energy generated additionally to the thermal energy. For all the other time-steps, energy demands were not fully satisfied because of the lack of energy.

5 CONCLUSION AND FUTURE WORK

In this paper, we proposed a holonic smart grid architecture following the concept of single holon modelling, where holons represent geographical zones starting from houses and buildings up to islands or

Figure 6: Energy received by a holon representing a village on level 3, in a scenario where its upper holon is disconnected from the grid and the only energy available is the energy produced locally in the region and no village has any priority.

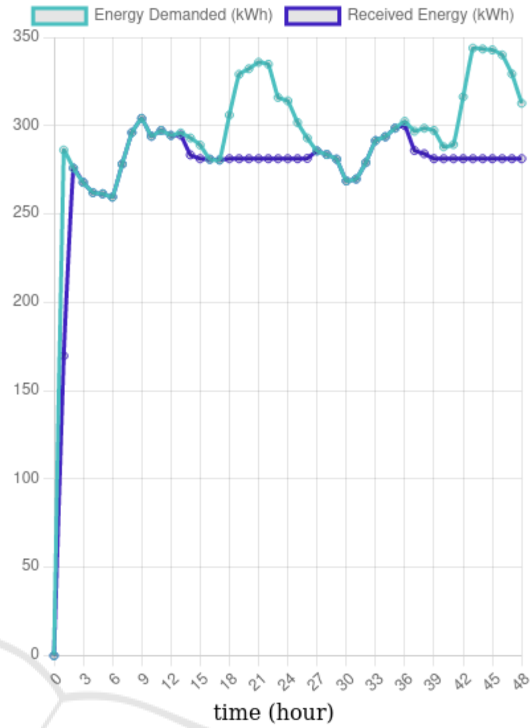

Figure 7: Energy received by a holon representing a village on level 3, in a scenario where only one thermal power plant is operating.

countries as a whole thanks to its flexibility on the regional, spatial and functional aspects. We have discussed the components (agents) of this holon, the interactions between the agents in the same holon, and between the various connected holons as well as some of the methods that can be applied to this architecture. We then applied this architecture to the French island of Mayotte, forming 3 levels holarchy. The first level consists of the highest holon which represents the island as a whole. 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 as supposed to be. The second scenario is a disconnection scenario where a holon is disconnected from the main grid and it has to deal with the energy that it has without going into a blackout. This scenario has been tested on two cases. The first case is a priority case where we give the priority to a specific holon where the second case is a no-priority case where all holons have the same level of priority and have to share the available energy. The third scenario is a test where a thermal power plant is disconnected from the grid. The simulations have proven this architecture to be flexible and effective in both the standard scenario and the scenario where a micro-grid can get disconnected from the main grid. Finally, this paper has focused mainly on the proposition of this new architecture, its feasibility and its flexibility in all aspects. In future works, more sophisticated methods and algorithms will be implemented to this architecture, while introducing the concepts of delays, storage, priorities in more details, the formation of virtual power plants and the negotiations with other holons in multiple iterations before taking decisions.

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