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An Energy management system structure for Neighborhood Networks

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Abstract

The accelerated integration of Renewable Energy Resources (RES) and Dispersed Generations (DGs) has contributed to big shifts in the power grid. The incorporation of home-scale electricity generators (HSEGs) into the Neighborhood Networks is considered and has contributed to the development of more stable and efficient smart grids. The implementation of this system includes an integrated control system along with a power electronic converter. In this paper, a power electronic-based HEMS scheme is presented for the neighborhood network including adjacent HSEGs to achieve an energy positive/neutral neighborhood. A multi home energy hub neighborhood network (MHEHNN) is classified in terms of system structure, functionalities, and energy management system. Different scenarios are investigated to evaluate the significance of proposed control strategy for the case study (a system with two HEHs and two conventional buildings (CBs)) using MATLAB/SIMULINK simulations. A large-scale MHEHNN is often simulated in order to test system performance on a broader scale. The findings obtained reveal that the HEHs offer more resources to the MHEHNNN under the suggested scheme (about 98 percent more than conventional scheme). As a result, by the sale of surplus power, they gain more. By avoiding import payments from the grid, the energy cost of CBs is minimised. Around 98 percent of the entire day is also decreased by the

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grid load.

Keywords: Hierarchical energy management system, Home-scale energy generation, Home energy hub, Renewable energy, Neighborhood network.

Nomenclature

Acronyms

CB	Conventional building
CCB	Central control board
CEMS	Central energy management system
CHP	Combined heat and power
DF	Dispatch factor
DG	Distributed generations
EMS	Energy management system
ES	Energy storage
EV	Electric vehicle
FLC	Fuzzy Logic Controller
HEH	Home energy hub
HEMS	Hierarchical energy management system
HMG	Home microgrid
HSEG	Home-scale energy generation
MCP	Market-clearing price
MG	Microgrid
MHEHNN	Multiple home energy hubs in the neighborhood network
MPPT	Maximum power point tracking
nZEB	Nearly zero energy building
PV	Photovoltaic
RES	Renewable energy resource
SC	Super capacitor
SOC	State of Charge
V2G	Vehicle-to-Grid

Indices	
i	number of iterations , $i \in \{1, 2, \cdots, \textit{number of HEHs}\}$
h	hour, $h \in [1, 2, \cdots, 24]$
Constant Values	
$CP_i(h)$	Hourly power consumption corresponding to *i*th HEH
$Ctrl\_es1$	Switches ES converter between voltage control and constant power control
$Ctrl\_es2$	Switches ES converter between charging and discharging modes
$Ctrl\_ev1$	Switches EV converter between constant power control and off mode
$Ctrl\_pv1$	Switches PV converter between voltage control and one of MPPT/power-reference controls
$Ctrl\_pv2$	Switches PV converter between MPPT and power-reference controls
$\frac{dIL1^*_{inv}}{dt}$	Reference of the first order derivative of inverter current
EP_i	Mean value of exchanged power corresponding to *i*th HEH
$GP_i(h)$	Hourly power generation corresponding to *i*th HEH
$IL1_{inv}{}^*$	Current reference of inductor of inverter filter
Pdc_es^*	Power reference of charging/discharging ES
Pdc_ev^*	Power reference of charging EV
Ppv^*	Power reference of PV generation
$VC_{inv}{}^*$	Voltage reference of capacitor of inverter filter

1. Introduction

Many environmental issues have been posed by growing energy demand and continued depletion of fossil fuels, and the use of RESs has emerged as a helpful solution to this end [1]. However, high penetration of RESs poses severe challenges to systems operators because of irregular nature of wind speed and solar irradiation [2]. Converting different types of RESs, increases the reliability in supplying electrical and thermal loads. For example, the delivery of electrical loads through a gas distribution network through combined heat and power (CHP) units. Furthermore, energy storage (ES) units play a critical role in increasing the control ability, financial advantages and efficiency of the device. Batteries are the most interesting ES technology, usually used for a continuous supply non-responsive loads, reduce electricity cost during peak consumption period, and store excess energy from RESs. Therefore, a combination of high penetration RESs, electricity and natural gas networks, and ESs as a multi-carrier system would be considered as an effective solution in a power system design to improve the system stability, reliability, and flexibility [3]. The residential buildings in power systems are critical components in determining peak demand periods [4]. Therefore, this paper focuses on managing and controlling power using HSEG. In fact, The residential buildings have been considered as active components in the network, acting as both power consumers and generator.

On the other hand, via the electricity distribution grid, every home is interconnected with its other neighbouring homes. Thus, as a lumped unit, a cluster of neighbouring homes can be controlled to achieve an energy positive/neutral neighbourhood network [5]. Such an architecture requires energy management in each homes and in a group of homes. Considering the different energy management strategies, hierarchical scheme is a reliable option in neighborhood network applications which include; primary, secondary, and tertiary levels. At the primary level, power is shared among the different resources. The secondary and tertiary control respectively manage the energy at individual home and at a group of homes. Power-Electronic converters play a key role in exchanging power and regulating system parameters which their controller is often implemented at the primary level. Therefore, the implementation of energy management systems in practice requires an comprehensive framework including decision maker and an unified control system. So that they can interact with each other in a hierarchical architecture.

In recent years, many studies have been developed by researchers to enhance the decision maker and controller. For instance,a collaborative demand response of nearly zero energy buildings (nZEB) has proposed in [6] for cluster-level performance improvements. Control has implemented in two steps: cluster and individual levels. First, the building cluster has considered as one lumped building which the collaborative control identifies the optimal performance at cluster level in response to the dynamic pricing. Then, based on the identified optimal performance, the proposed control coordinates individual buildings' operations using non-linear programming, thereby realizing the collaborations. Similarly, a nZEB control method proposed in [7] that enables full collaborations among nZEBs. But with the difference that the demand prediction uncertainty has taken into account. In [8], a genetic algorithm based dynamic pricing method is proposed to deal with concerns of privacy, communication complexity and high computation load due to increase the number of building. This can reduce power imbalance while does not require information exchanges among individual buildings However, these studies have not provided a comprehensive framework for controlling power electronic converters. The functionality of a power electronics based energy management system (EMS) has demonstrated in [9]. The EMS guarantees that the critical loads are supplied continuously. However, it is just based on a single battery as an energy storage. Another application of power electronic converters in energy management is studied in [10]. The EMS includes RES and hybrid ES but it has implemented on an islanded microgrid. A control and power management system for hybrid systems with both DC and AC buses and loads, in both grid-connected and islanded modes has presented in [11]. In order to achieve the power balance between the hybrid microgrid system and the grid, power electronic converters share power flexibly and efficiently. The EMS, however, is focused only on the state of charge (SOC). But, in the logic of decision-making, considering electricity tariffs leads to wiser decisions in order to achieve a more cost-effective energy exchange. In [12], an intelligent algorithm including electricity tariff has proposed. Thus, EMS is able to charge the battery at the lowest price that leads to the overall system operational cost reduction. In [13], a multi-port converter is presented for low-voltage small-capacity applications. This uses a Fuzzy Logic Controller (FLC) to obtain the desired charging/discharging state of energy battery in grid-connected mode. The algorithm is able to minimize the operational cost because electricity price has used as an input of FLC. Although FLC is an effective and uncomplicated solution for solving multi-objective problems, it will be difficult to determine the rules as the number of inputs increases in a neighborhood framework.

It can also be found that energy conservation encompasses a broad variety of issues that have been discussed only in part in any of the above reports. The goal of this paper is to develop a hierarchical energy management framework (HEMS) for a neighbourhood network, including neighbouring HSEGs. To this end, an analysis of the principles of HSEGs, the functionalities of HEHs and the control mechanisms of power electronics converters has been carried out. This will be useful in developing a structure for creating a hierarchical EMS architecture for community networks. The main contributions of this paper are listed as follow:

- A centralized control system for switching N-number of power converters in an MHEHNN has been implemented.
- Economic issues on the scale of homes in the spontaneous existence of electric vehicles have been considered.
- Interaction of local market power converters based on a SOC-Tariff scheme has been done.

The rest of the paper has been sectioned as follows:

An overview of a neighborhood network, its components and a review of the different types of HSEGs are presented in Section 2. Energy management issues in the proposed neighborhood network, the application of power electronic converters, including types of topologies and control strategies, are presented in Section 3. Section 4, was concluded with a proposed power electronic based HEMS and a MATLAB/ SIMULINK simulation of its architecture.

2. Neighborhood Network Overview

A neighbourhood network is a community of homes clustered geographically close together. They can be considered as a lumped unit to manage their generation/consumption power to meet the local energy requirements. It also can reduce the energy costs and lead to lowers congestion in the power grid as well as mitigation of extra network usage charges [14, 15]. Energy management can be divided into two general load management and generation management approaches. Despite the advantages of the load management methods, they are inefficient in practice due to the leading role of consumers in control the load consumption. They might change consumption period based on their welfare and comfort. Thus, energy generation/storage management in a home can be a promising solution. A group of adjacent homes can be equipped with generation and storage equipment such as RESs, ES, and CHP, forming a neighborhood network to manage the power flow at a wider scale. Each home can supply its internal loads as well as share the excess power with other neighborhood network homes. Hence, the first step is recognizing different concepts of HSEGs.

2.1. ***Home Scale Energy Generators***

HSEGs can be classified as; Home Micro Grid (HMG), Producer-Consumer units (Prosumer), and Home Energy Hub (HEH). Although the performance principles of these concepts are similar to each other, they could be distinguished depending on the number and type of input energy carriers and implementation scale.

2.1.1. ***Home Microgrid***

A set of loads and distributed energy resources that can act as a controllable unit in each grid-connected or islanded operational mode are called a microgrid (MG) [16]. Economic benefits, utilization of clean energies, improvement in energy security, the possibility of delivering electricity to remote areas, flexibility improvement, and better grid reliability are the reasons for developing the MGs [17]. A set of energy generation resources and storage units aggregated in a home is called HMG [18]. The possibility of compensating for the shortage of energy can be supplied locally by employing a set of energy generation resources, storage units, and EVs in HMGs [17]. Each HMG can also sell its excess energy to the grid to supplement peak power consumption. Generally, a building with energy generation capability can be defined as an HMG. In developing countries, load shedding has increased to reduce peak power consumption. As a result, using a group of controlled HMG can be considered as a suitable initiative to tackle this problem. So far, numerous researches have been published regarding types of HMG. Many of them deal only with the financial benefit of a single HMG and the problems of power converters have not been discussed in the forming of an alliance between several HMGs.

2.1.2. ***Prosumer***

A CB is usually considered as a consumer. Having at least one kind of energy generation resource makes it a prosumer [19]. Generally, the prosumer is defined in three general types including electrical [20], thermal [21], and electrical–thermal [22]. Hence, a prosumer can employ several energy carriers and energy conversion methods [22, 23]. Prosumers are considered as important elements in the smart grids, which can share excess energy with the network or other consumers [24]. So far, kinds of research have been done in the field of prosumer-based EMS. Generally, prosumers are used in power systems to improve flexibility, reduce costs and pollution. The technical issues related to the control of power electronic converters have not been addressed in the literature.

2.1.3. ***Home Energy Hub***

HEH is a unit in which conversion, storage, and energy planning are carried out [25]. This way, the possibility of supplying different loads through different energy carriers can be performed in a HEH. As a result, the electrical loads' dependence on the electrical network will be reduced [26]. A HEH may contain some energy resources (renewable or non-renewable), electricity and natural gas distribution network, and solar thermal. It may also supply a variety type of household electrical, heating, and cooling loads. The input energy carriers can be defined based on tariff, pollution, accessibility, and other indices to supply the loads optimally. Due to this fact, the degree of freedom in choosing a more affordable energy carrier is increased [26]. A building [27, 28], a factory or hospital [29, 30], islanded systems such as trains, ships [26] which include energy generation resources, energy converters, transmission systems, storage systems, and computation units can be considered as a type of HEH called micro-energy hub [31]. Figure 1 shows a home-scale micro-energy hub known as HEH. As it is shown in this figure, heating equipment, home appliances, photovoltaic (PV), CHP, electric vehicle (EV), and the battery would be incorporated into an HEH structure. So far, some issues such as performance optimization, optimal use of RESs, optimal management of ESs, technical and financial performance improvement, flexibility and sustainability increase, load estimation, decentralized energy integration in a neighborhood, and energy positive neighborhoods identification have been addressed in different studies in the field of HEH [32].

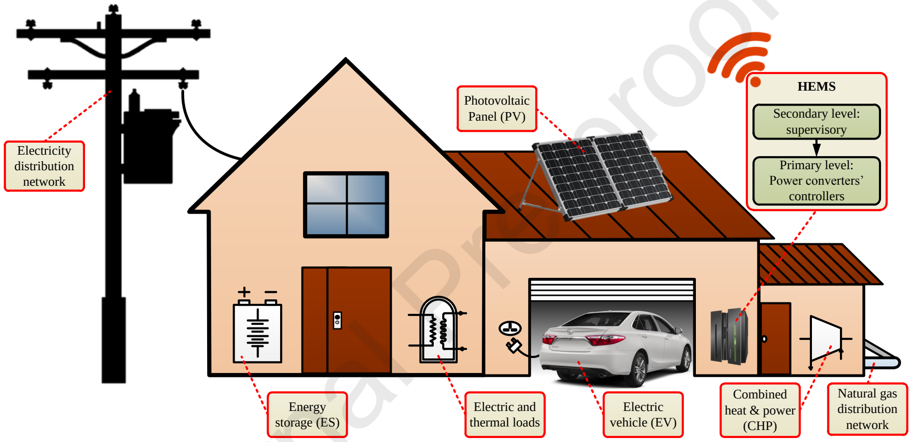


Figure 1: General configuration of an HEH

The distinct points of the HEH as opposed to other definitions is that it can be referred to as a more detailed concept than HMG and prosumer. Since HMG and prosumer can be specified even with one energy carrier, even if they may have energy storage or energy conversion equipment. In other terms, each HEH may be considered HMG or prosumer, but not vice versa. In addition, the definition of EH can be applied to a nation. Therefore, the HEH concept will be used in this work. It is necessary to mention that to prevent the excessive extension of the discussion, the electrical loads have been considered here, and thermal loads will be included in future studies.

2.2. Functionalities of HEH

The elements in an HEH can be divided into DC and AC sides. On the DC side, several resources, DC loads, and storages are connected to a common DC bus through the DC-DC converters. On the AC side, the AC loads, grid, and CHP are connected. Flowing power between two DC and AC parts will be possible by employing a bidirectional DC-AC converter. Normally, each power electronic converter has its own control system, which leads to expected power flow according to the measured quantities such as voltage and current. In an HEH, where several elements are interacting with each other, a central controller is needed to do proper power sharing. Therefore, a central energy management system (CEMS) is usually used as a supervisory control system to make decisions at the secondary level and send them to the primary level to control the power electronic converters.

As the potential of the elements in the HEH is limited, preparing to achieve technical and economic targets on a broader scale would become feasible by the development of a community network. For this reason, the configuration of the MHEHNN, including many neighbouring HEHs and CBs, is clarified in Section 2.3.

2.3. Structure of MHEHNN

A standard neighbourhood network structure is seen in Figure 2. The neighbourhood network will span a spectrum of multiple homes to several hundred homes. Some of them can be considered as HEH (local generators) and some as CB (local loads). The CBs can supply their power requirements either by the grid or local generators. The HEHs can sell their excess power to the grid or provide the local loads as well as supplying their internal loads. In conventional energy management methods, all consumers receive the same signal from the electricity company. This leads to the same time shift of using high consumption appliances for the homes existing in an MHEHNN that causes unwanted consumption peak at another time [33]. Coordination mechanisms can be employed in the MHEHNNs to solve this problem [34], which will be discussed in Section 3.

The MHEHNN provides the necessary foundation of exchanging power and information for coordination algorithms to achieve an energy positive/neutral neigh-

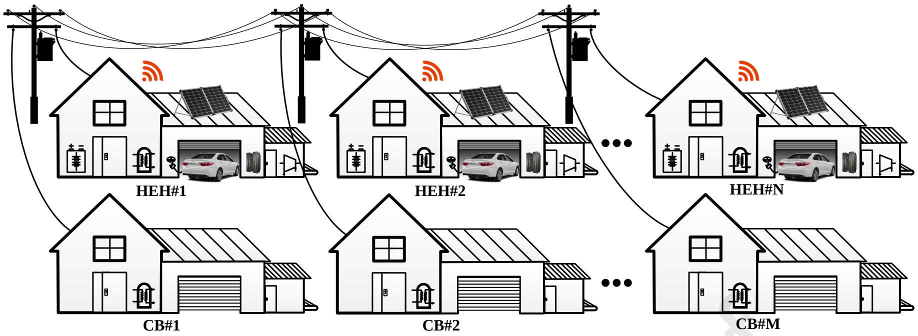


Figure 2: The case study neighborhood network

borhood. This can be helpful at on-peak hours of the grid. Some of the existing approaches obtaining this characteristic are reducing the energy consumption, developing the use of multi-carrier systems, exploiting types of RES, and using energy-storing/ converting devices. Here, this has been done through energy management system in two HEH and MHEHNN scales [35].

3. Energy management in MHEHNN

From a control and connectivity architecture viewpoint, the coordination algorithms involve two centralised and decentralised setups. In the centralized configuration, the data such as the amount of power generation of HEHs and consumption of HEHs and CBs are sent to the CEMS, separately. The CEMS then optimally plans their generation or utilisation systems. The optimal programme knowledge was eventually sent back to the HEHs and CBs. Data is exchanged or shared directly between homes in the decentralised setup. Therefore, a distributed process is needed to schedule the power generation and consumption of HEHs and CBs. Both methods are successful in reducing peak load and reducing energy costs. However, the use of decentralized approaches has been more prominent in this regard.

On the other hand, the centralized configuration is suitable in finding optimal strategies, but not in a large scale application because the optimization calculations will get complex [36]. In contrast, decentralized configuration needs more bandwidth and more time to reach convergence because of the need for establishing serial connections and the high number of iterations [37].

The hierarchical scheme provided a compromise between centralized and decentralized configurations. The main objectives of each level are determining the reference value of exchanged power between elements based on the received data. But, these levels vary in cases such as responding time, input data and required infrastructures. Although MHEHNN is not necessarily widespread, because of the high number of controlled resources, the advantages of implementing a hierarchical scheme can be of benefit. The detailed description of each level is stated in Section 3.1 [38, 39].

3.1. ***Architecture of HEMS***

Figure 3 shows the considered HEMS architecture for MHEHNN, in which the tertiary level processes the data in the scale of a neighborhood and then, sends the information to the secondary level in each HEH. Finally, the secondary level determines the scenarios and changes the primary level actions.

3.1.1. ***Primary level***

The key level, also known as the local control or internal control, is in charge of decision making based on the local measurements. Therefore, in addition to being influenced by higher levels, it can respond rapidly to local variations. Diagnosing grid-connected or islanded operation modes, converter control, power-sharing, and power balance are the main tasks of this level [40, 41]. The control methods related to this level can be based on with or without communication. Centralized control, distributed control, master-slave control, and voltage angle droop control are communication-based techniques. These approaches involve high bandwidth communication links between the converters. In addition, the cost and complexity of these strategies are greater than those without contact. Excellent communication links reduce reliability and system development possibility. However, the local measurement-based converters, including traditional droop method (P-F/Q-V), evolved droop methods, P-V/Q-F droop control, and virtual frame transformation, are managed without communication methods. These methods also have desirable

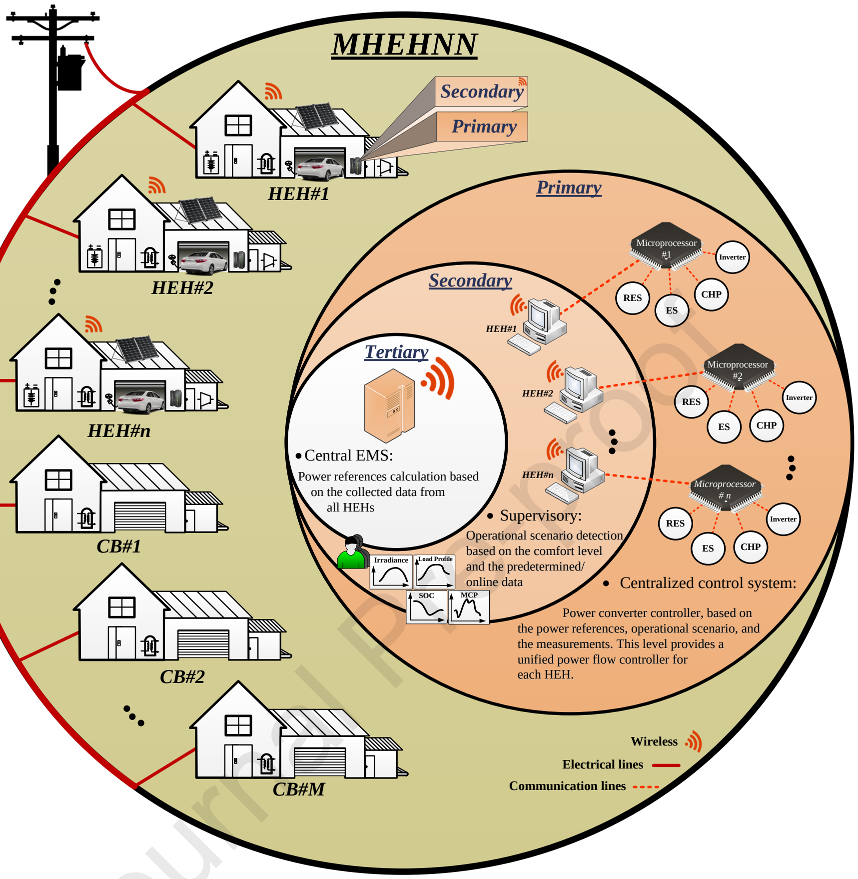


Figure 3: HEMS architecture in an MHEHNN

characteristics such as flexibility, develop-ability, and easy implementation [42]. However, the main disadvantages of droop based methods are inaccurate power-sharing, slow transient response, and circulating current among the inverters.

3.1.2. Secondary level

Secondary level regulation is responsible for economic and efficient HEH activity, often referred to as EMS [43]. This is the highest degree of hierarchical architecture in island mode and must provide an immediate quick response to unexpected shifts in load and RESs. The key objective of the EMS is to define unit involvement and efficient power sharing of available resources for generating electricity. The dedication of the unit involves optimization issues that organise a collection of energy generating tools to accomplish a shared purpose, such as cost savings or sales growth.

Existing voltage amplitude and frequency deviations created at the first level will also be removed at the second level of control. So far, some approaches have been introduced, such as real-time optimization and decentralised hierarchical control to achieve the goals of the second level [44]. The secondary level has a slower response time compared with the primary level [45].

3.1.3. ***Tertiary level***

Many articles have not dealt with higher levels of optimal performance of HMG's [46]. In grid-connected mode, the possibility of economic sharing of HEHs' excess power would be given by the community grid. In this mode, the tertiary level is able to coordinate several HEHs based on OPF methods [47]. In order to minimize electricity generation costs and distribution line losses, the nominal voltage and active/reactive power injected by HEHs are calculated at this stage.

Due to large-scale optimization, solving the OPF problem is difficult. Device and the number of drawbacks that are nonlinear. Up to now, numerous algorithms, including Newton-Raphson [48], interior point methods [49], quadratic programming [50], non-linear programming [51], and particle swarm optimization [52] have been developed to solve the OPF problems. Majority of the highlighted methods only guarantee local optimization while semi-definite and second-order programming based methods are effectively able to find the global optimum solution of OPF problem in the grid [53].

3.2. ***The role of power electronic in HEMS***

The development of HSEG causes high penetration of RESs in the distribution network. However, it is fundamentally unpredictable and spontaneous, and in the household application sizes, their output voltage is usually low. The RESs are connected to the grid using electronic power converters to overcome operational constraints, as seen in Figure 4 [54].

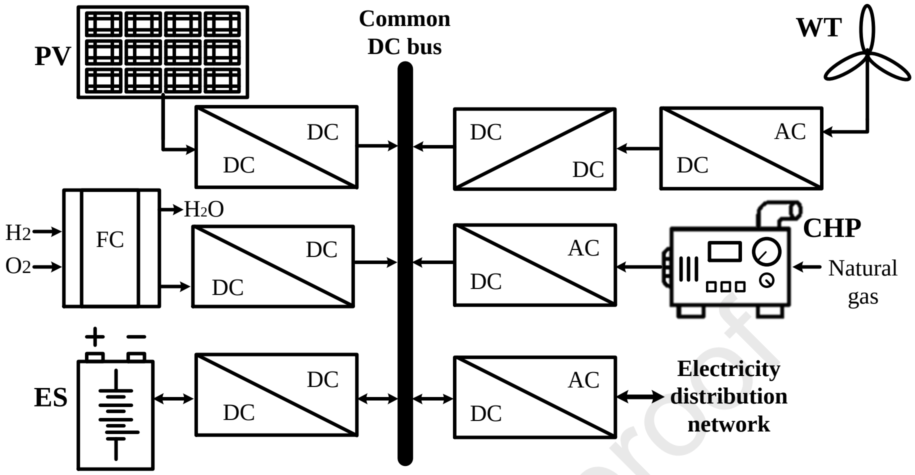


Figure 4: General scheme of a typical HEH in power electronic aspect

Power electronic converters make the RESs systems controllable to achieve the desired features in the EMS applications [55]. To date, power electronic converters have been used in a range of energy management applications with the purpose of peak-saving and critical load supply during power outage [9, 56], Maximum Power Point Tracking (MPPT) [57–60], Battery Charger and SOC Balancing [61, 62], Power Sharing [63, 64], and Power Factor Correction [65–67]. In Sections 3.2.1, topology and control aspects of implementing a power electronic-based EMS are explained.

3.2.1. ***Topology***

Two general topologies can be considered for power electronic converters: single-port (conventional) and multi-port. In the conventional topology, each RES has a separate converter. The outputs of these converters are connected to a common AC or DC bus. In some cases, a communication bus is also added to this topology to establish the connection between different converters. A typical single-port topology scheme of HEH is depicted in Figure 4. As the number of power electronic converters increases in this topology, the cost of the system will be increased.

As the multiple input services are combined into a single converter, multi-port converters are used as a cohesive structure. As it is evident in Figure 5, this topology provides several input and output ports to connect the resources, loads, and ESs. Due to the simplicity and cost savings in the choice of elements used in this topology, its application can be in EVs, uninterruptible power supply, spacecraft, and energy management system [68, 69]. Limitations in the number of input sources and control complexity are the main disadvantages of the multi-port converters [70].

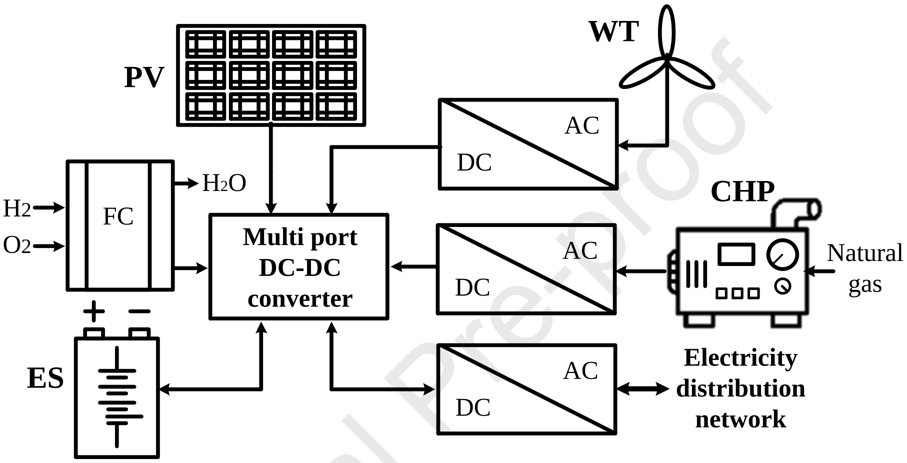
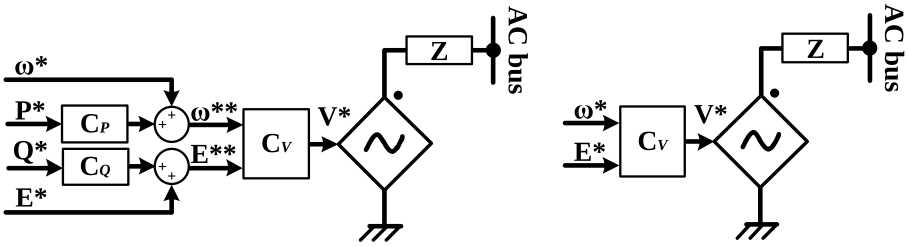


Figure 5: Multi-port topology of integrating different RESs

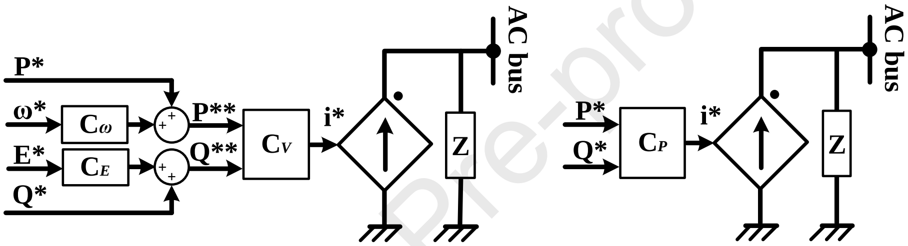
3.2.2. *Control scheme*

HEH can be separated electrically into two AC and DC, as shown in Section 2.2. The AC side output is associated with the operation of the DC-AC converters (inverter) and the DC side performance is associated with the operation of a group of DC-DC converters. The following are briefly explained: control schemes and operating modes of power electronic converters.

DC-AC converters. As shown in Figure 6, inverters can operate in two general operational modes as a dependent current source or dependent voltage source such that they can supply the desired current and amplitude/frequency of AC voltage, respectively. From the tertiary level (CEMS) point of view, each HEH is considered as an inverter that operates as a grid-connected dependent current source. In this case, CEMS can control the active and reactive power flow between the HEHs



(a) Voltage source



(b) Current source

Figure 6: Inverter operational modes [71]

and the grid. HEH can operate in the islanded mode operation as long as it does not need to exchange power (neither receive nor inject). In this case, the inverter acts as an independent voltage source that is able to provide the required voltage amplitude and frequency.

Grid-connected inverter control issues are addressed in some researches. For instance, a comparative study on Lyapunov-function based control scheme is presented in [72]. However, most researches considered a DC source in the input of the inverter which is able to supply any amount of power with constant voltage. Hence, there is no limitation in providing power, while the voltage stability and the quality of power supply on the DC side is a very critical, as the challenging problem is in RES based applications. Therefore, the role of each DC-DC converter should be specified in terms of the amount of power and voltage required for stabilization in the DC bus. Their characteristics should be considered in the inverter control scheme.

DC-AC converters. As a series of multiple parallel DC-DC converters, the DC side of HEH can be viewed. To share the power and control the output voltage, there are two general classes of methods: active and passive. From the schematic point of view, the active control methods are divided into four groups: centralized, master-slave, average load sharing and circular chain control [73]. In the master-slave method, a converter is configured to regulate the amplitude and frequency of voltage as well as to determine the current reference of other converters (slaves). The requirement for a supervisory control was considered as a disadvantage of this method. In the average load sharing method, a connection line is used to transfer the information of the average current. The current reference value of each converter was performed through a resistance connected to its current sensor. Circulating current can also be eliminated by this control scheme. The reliability of this method is more than the master-slave method, and its configuration is modular and expandable. In the chain control method, the current reference of each source is taken from the previous source. Master-slave method is dependent on a master unit to control the current limitation. In chain control method, there is no need for the master unit. So far, the aforementioned methods have been used in numerous researches. Power-sharing and voltage controlling have done well in these researches, but needing the connection lines among the different converters is a challenge [74].

In the centralized method, a central control board (CCB) is needed to determine the current reference of each converter (Figure 7). To determine the current reference, the central control board divides the measured load current by the number of parallel DC-DC converters. Depending on the total measured load current, in addition to the need for a central control board, the implementation of this method may be difficult on a large scale. In this paper, the centralized method will be used, but the reference current of each converter will determine in a different way.

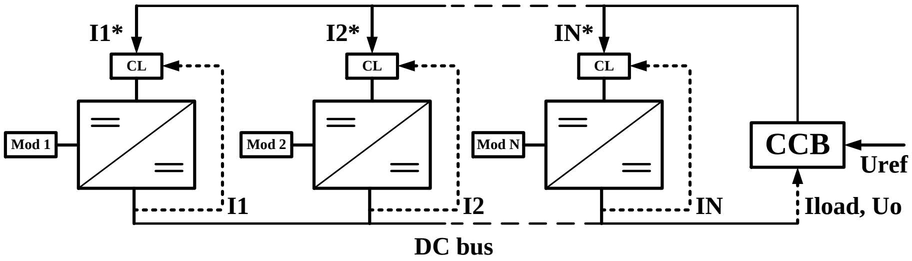


Figure 7: Centralized control method of DC-DC converters [74]

3.3. *Summary*

Some of the most relevant studies in the energy management field are compared in terms of implementation scale and concept, types of equipment, supervision architecture, tariff consideration, and control scheme in Table (1). The lack of a systematic system for the simultaneous economic management of electricity and thermal energy carriers, as seen in this table, as well as the consideration of a variety of separate outlets linked to the dc side of the inverter, such as RESs, ES and EV, is deeply felt in the literature. In general, the research investigates financial issues at a neighborhood scale; each power plant is modeled as an inverter connected to the grid with a DC voltage source as the inverter input. In contrast, most studies on power converter control ignore economic issues in decision making. The gas tariff has been used rarely in the EMS design for MGs integration of RESs and CHP. In addition, few studies have discussed the economic problems of hierarchical design at both secondary and tertiary control stages. A basic general initiative to remove the barriers and introduce EMS is discussed in Section 4.

4. Power electronic based HEMS for an MHEHNN

The execution of a HEMS relies on the control of the power electronic converters. The control mechanism is influenced by such economic and technological criteria, such as the tariffs of the energy carriers, the SOC of the batteries and the quantities measured, such as voltages and currents. In the next part, the implementation of a power-based electronic HEMS platform on a traditional MHEHNN architecture is discussed.

Table 1: Published papers for energy management

Ref	Under the concept of:	Scale of implementation	Resources /Storages	Hierarchical control level			Economic considerations at the level of:	Tariff considerations		Control scheme:	
				Primary	Secondary	Tertiary		Electricity	Natural gas	Inverters	DC-DC converters
[75]	MG	Home	PV, WT, ES	✓	✓	x	Secondary	✓	x	x	✓
[76]	MG	Home	PV, ES	✓	✓	x	Secondary	✓	x	x	x
[21]	MG	Building	PV, WT	✓	✓	✓	Secondary and tertiary	✓	x	✓	x
[22]	MG	Residential building	PV, ES, WT, CHP	✓	✓	x	x	x	x	✓	x
[27]	PC	A part of distribution network	PV, ES, EV, CHP, WT	✓	✓	✓	Secondary and tertiary	✓	✓	x	x
[9]	MG	Low power	ES	✓	x	x	x	x	x	x	x
[77]	EH	Neighborhood Network	Any kind of RESs	x	✓	✓	x	x	x	x	x
[78]	MG	Not mentioned	PV, ES	✓	✓	✓	x	x	x	✓	✓
[79]	MG	Building	PV, ES, EV	✓	✓	x	Secondary	✓	x	x	✓
[80]	MG	MGs	PV, ES, WT	✓	✓	✓	Secondary	✓	x	✓	x
[81]	MG	Neighborhood Network	Some integrated RESs	x	x	✓	x	x	x	x	✓
[82]	MG	Neighborhood Network	ES, Super capacitor (SC)	✓	✓	✓	Tertiary	✓	x	x	✓
[83]	MG	Not mentioned	DC voltage source	x	✓	x	x	x	x	✓	x
[84]	MG	Residential building	PV, ES, EV, WT	✓	✓	x	x	✓	x	x	✓
[85]	MG	Not mentioned	Some integrated RESs	✓	✓	✓	Tertiary	x	x	x	✓
[86]	EH	Not mentioned	PV, ES, CHP	✓	✓	✓	Secondary	✓	✓	x	✓
[87]	MG	Single-phase low power	DC voltage source	✓	✓	x	x	x	x	✓	x
[88]	DC MG	Not mentioned	DC energy sources, ES	✓	✓	x	x	x	x	x	✓
[89]	MG	Not mentioned	PV, ES, WT, FC, CHP	✓	✓	x	x	x	x	✓	✓
[90]	MG	Not mentioned	PV, ES	✓	✓	✓	x	x	x	x	x
[91]	MG	Two adjacent MGs	DC voltage source	✓	✓	x	x	x	x	✓	x
[92]	MG	Several parallel MGs	DC voltage source	✓	✓	x	Tertiary	✓	x	✓	x
[93]	MG	Several parallel inverters	DC voltage source	✓	✓	✓	x	x	x	✓	x
[94]	MG	Several parallel MGs	DC voltage source	✓	✓	✓	Tertiary	x	x	✓	x
[95]	MG	Not mentioned	PV, ES, WT	✓	✓	✓	Secondary	x	x	✓	x
[11]	MG	Not mentioned	PV, ES	✓	✓	x	x	x	x	✓	x
[96]	MG	Several parallel MGs	RESs, ES, CHP	✓	✓	✓	Tertiary	✓	x	x	x
[97]	EH	Building	PV, ES, EV	x	x	x	x	✓	✓	x	x
[98]	PC	Home	PV, ES, EV	x	x	x	x	✓	x	x	x
[99]	MG	Not mentioned	PV, ES, WT, SC	✓	✓	x	Secondary	✓	x	x	x
[100]	AC/DC MG	Not mentioned	Several AC and DC power generators	x	x	x	x	x	x	✓	✓
[101]	MG	Several neighboring MGs	PV, ES, WT, CHP	x	x	x	x	✓	x	x	x
[102]	DC MG	Not mentioned	PV, ES, WT, EV	x	x	x	x	x	x	x	✓
[103]	EH	Low-voltage small-capacity areas	PV, ES, WT, FC	x	x	x	x	✓	x	✓	✓
[104]	EH	Neighboring an EH and several PV PCs	PV, CHP	x	x	x	x	✓	✓	x	x
[105]	MG	Low-voltage low-power	PV, ES, SC	x	x	x	x	x	x	x	✓
[106]	MG	Building	PV	✓	✓	x	x	x	x	x	x
[107]	MG	Not mentioned	PV, CHP, FC	x	x	x	x	x	x	x	✓
[108]	MG	Not mentioned	PV, CHP, ES	✓	✓	x	x	x	x	x	✓

4.1. The MHEHNN structure under the study

An MHEHNN including two HEHs and CBs have been considered to evaluate the proposed HEMS performance. The energy management in this structure is performed in two general scales: the HEH and the neighborhood network. At the scale of HEHs, decisions on the amount of energy consumed or sold generated/converted and the energy stored are taken on the basis of parameters such as electricity and natural gas tariffs, SOC and secondary level irradiance. On the other hand, each HEH can affect the other HEHs' decisions through the tertiary level at the neighborhood scale. The HEHs are equipped with PV, ES, EV, and CHP devices which have their converter as shown in Figure 8.

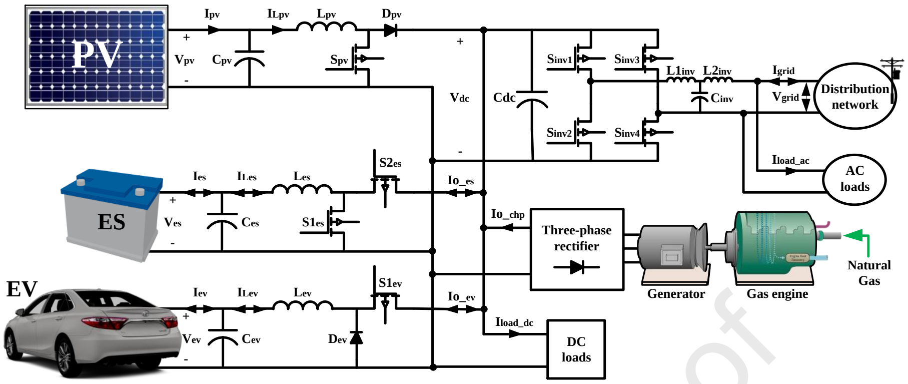


Figure 8: DC-DC and DC-AC converters used in under the study HEHs

Different schemes of the control systems have been discussed in Section 3.2.2. However, these schemes need the power reference of power electronic devices determined by the different levels of HEMS. Hence, the input/output signals of each level, and their tasks, would be addressed in the following.

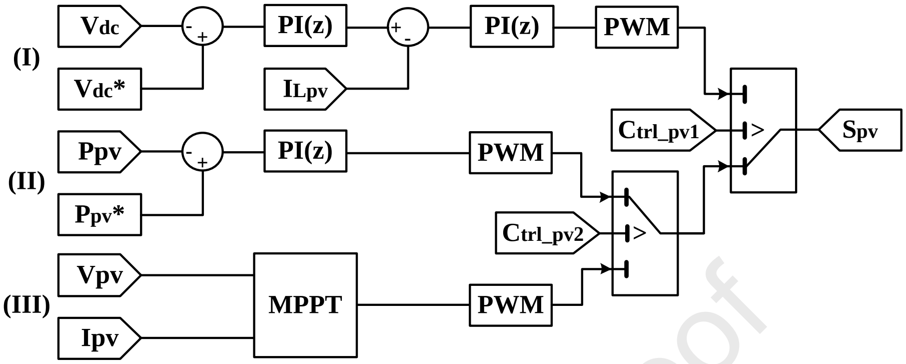
The inputs of the tertiary level include data such as the amount of shortage/excess power of each HEH, the amount of shortage power of each CB, electricity and natural gas tariffs, and also the HEH feed-in tariffs. Secondary level inputs include the load profile, irradiance, energy and natural gas tariffs, the SOC of ES and EV batteries, as well as the tertiary level power reference. The inputs of the primary level controller was the power reference established by the secondary level and the measured voltage/current. The process of defining the power references is that the primary level switches the converters to keep the power balance continuously. Then, the secondary level determines the scenario and the shortage/excess energy of each HEH based on the input data. At the same time, the data will be sent to the tertiary level. The tertiary level determines the power references of the inverters and sends them back to the secondary level. As a consequence, the switching pattern of the converters can be modified by applying the scenario and changing the power comparison values defined by the secondary and tertiary stages. In this way, the control mechanism affected by the power system data would be set up to switch the power electronic converters. However, the primary level should be able to damp any undesirable power disturbances independently. Thus, the DC bus voltage variations should be considered in the control system which is importance to supply the DC loads reliable. So far, this issue was only considered by a few researchers [11]. The detailed explanations of different controller schemes are depicted in Figure 9. As illustrated in this figure, the DC-DC boost converter connected to the PV can be controlled by three operating modes: (1) voltage control, (2) power-reference control, and (3) MPPT. The first mode only happens if the HEH is islanded, and the ES is unable to adjust the DC link voltage. The second and third modes are designed to produce the desired power according to the secondary level and the maximum available PV power, respectively. The DC-DC buck converter connected to the EV is controlled by constant power to charge the EV battery under the rated current. The bidirectional DC-DC converter connected to the ES can also be operated under two modes of constant voltage or constant power. The bidirectional inverter control is based on the control schematic which is presented in [72] which is discussed in Section 3.2.2.

4.2. ***Scenarios***

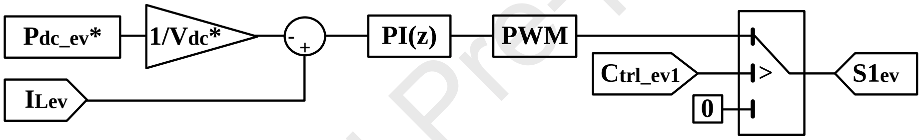
Scenarios show how power is exchanged among the power sources and ESs at different time intervals. The scenarios are determined based on the internal loads, electricity and natural gas tariffs, SOC of energy storage, with the aim of simultaneously achieving the financial and technical benefits. The following scenarios are considered:

I. When generated power of PV is higher than the local load then the HEMS can choose one of the storing or selling the excess power scenarios. Storing may itself be done in two forms of saving in the ES or charging EV (if existent). In this case:

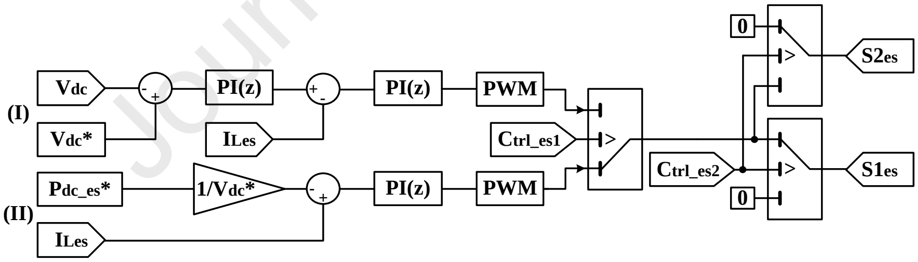
    - A higher tariff/ higher SOC condition is suitable to sell.
    - A lower tariff/ lower SOC condition is ideal for storage.
    - A lower tariff/ higher SOC and a higher tariff/more moderate SOC conditions are more suitable for storage and sell, respectively.



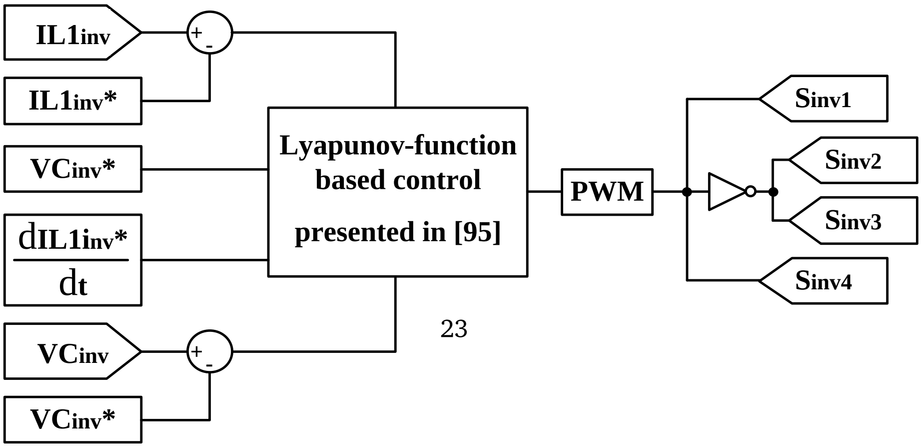
(a) boost converter connected to PV



(b) buck converter connected to EV



(c) Bidirectional DC-DC converter connected to ES



(d) bidirectional DC-AC converter connected to the grid

But these conditions require further investigation.

II. In the case that the PV generated power is less than load requirements, the HEMS can choose either discharging the ES or purchasing the shortage of power from the grid scenarios. In this case:

  - A higher tariff/ higher SOC condition is suitable to release the ES.
  - A lower tariff/ lower SOC condition is suitable to buy.
  - A lower tariff/ higher SOC and a higher tariff/more moderate SOC conditions are more suitable to buy and discharge the ES, respectively. But these conditions require further investigation.

In the above situations, CHP can also be used if natural gas is economical in the production of a certain amount of electricity. In the lower tariff-higher SOC and higher tariff-moderate SOC conditions, it is not easy to make choices on a wide variety of potential conditions. In fact, the desirable situation in these states are relative, and it may change by changes in tariff and SOC value as well as the satisfaction degree and comfort level of HEH owners. Hence, a flexible scenario selector is needed to solve the above-mentioned problem. The method should be able to select two scenarios at a given SOC when the tariff varies and vice versa. For this work, the scenario selector method proposed in [109] is used. In this method, decision making is based on three parameters: market clearing price (MCP), SOC of ES (SOC_{ES}), and SOC of EV (SOC_{EV}). As shown in Figure 10, the intersection of variations of these three parameters creates a cube. The operational point of HEHs will change in this 3D space. This space can be divided into some district subspaces by determining the minimum and maximum values of SOC_{ES} and SOC_{EV} by the HEHs' owners. It should be noted that two sets of minimum and maximum value have considered for SOC: economic and technical. The economic values determined by owners to change their approach getting more profits and the technical benefits. Also, the minimum and maximum technical values of SOC are considered 20% and 90%, respectively. Each subspace in Figure 10 specifies applying a specific scenario. The geometric shapes of these sub-spaces show the flexibility feature of the proposed method. For a given SOC, if the tariff changes, the scenario will change, too.

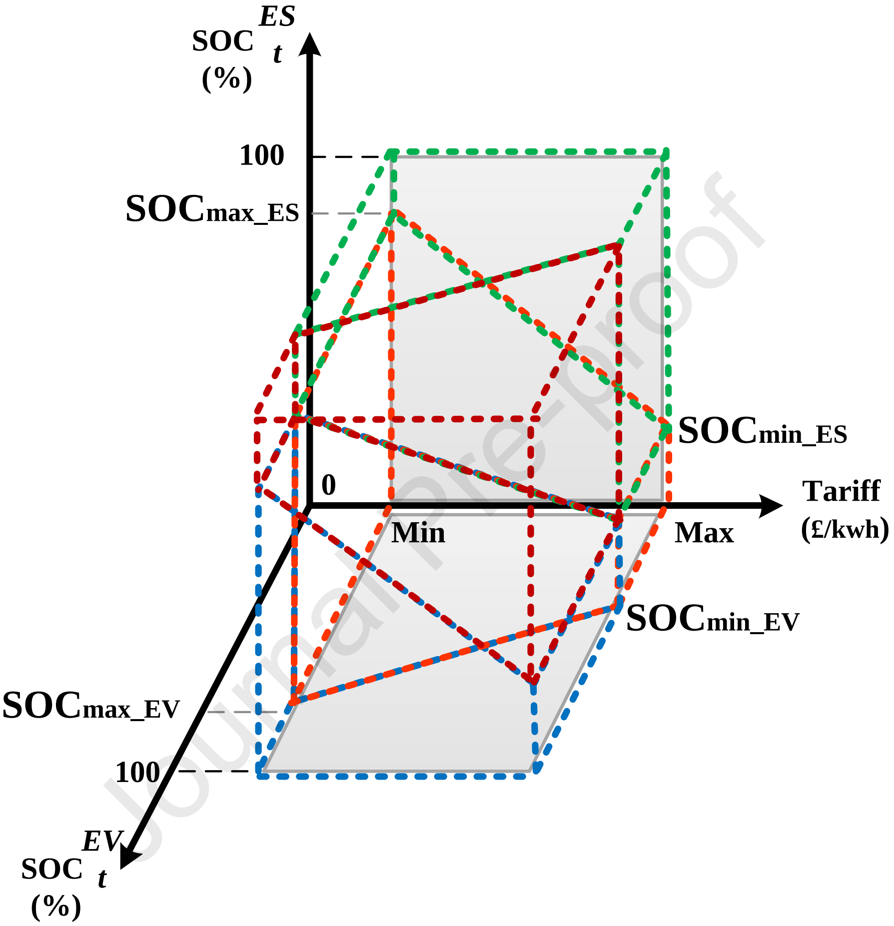


Figure 10: The possible 3D area of HEH condition

It should be observed that the circumstances under which ES or EV does not Accessible or linked, the future space becomes a 2D space. In addition, CHP can also be used to sell or store electrical energy. The condition for this is that the cost of electrical energy produced by the consumption of natural gas must be less than the cost of importing power from the grid [109]. Figure 11 shows all potential sub-spaces of the scenario selector process. A detailed explanation of the sub-spaces shown in Figure 11 is also given below. The descriptions are presented under two general conditions: the PV power is more than the load power (i.e., $P_{pv} > P_{load}$) and the PV power is less than the load power (i.e., $P_{pv} < P_{load}$).

I. When $P_{pv} > P_{load}$, getting inside the sub-spaces (a)-(f) marks to:

- a) The charging of the EV is a priority. then selling the amount of power to the grid and eventually the ES.
- b) The sale of excess energy to the grid is a priority. Then charge the EV and finally charge the ES.
- c) The charging of the EV is desired. Then bill the ES and eventually sell the surplus power to the grid.
- d) the charging of the ES is a priority. Then sell the surplus electricity to the grid and eventually bill the EV.
- (e): Selling the excess power to the grid is in priority. Then charging the ES.
- (f): Charging the ES is in preference. Then, selling the excess power to the grid.

II. When $P_{pv} < P_{load}$, getting inside the sub-spaces (a)-(f) shows:

- (a): First, discharging the ES and then, purchasing power from the grid to meet the internal shortage of energy and charging the EV.
- (b): First, discharging the ES and then, purchasing power from the grid to meet the inner shortage power.
- (c): Purchase power from the grid to match the inner shortage of energy and charging the EV.
- (d): Purchase power from the grid to meet the internal shortage power and then, discharging the ES.
- (e): First, discharging the ES and then, purchasing power from the grid to match the inner shortage power.

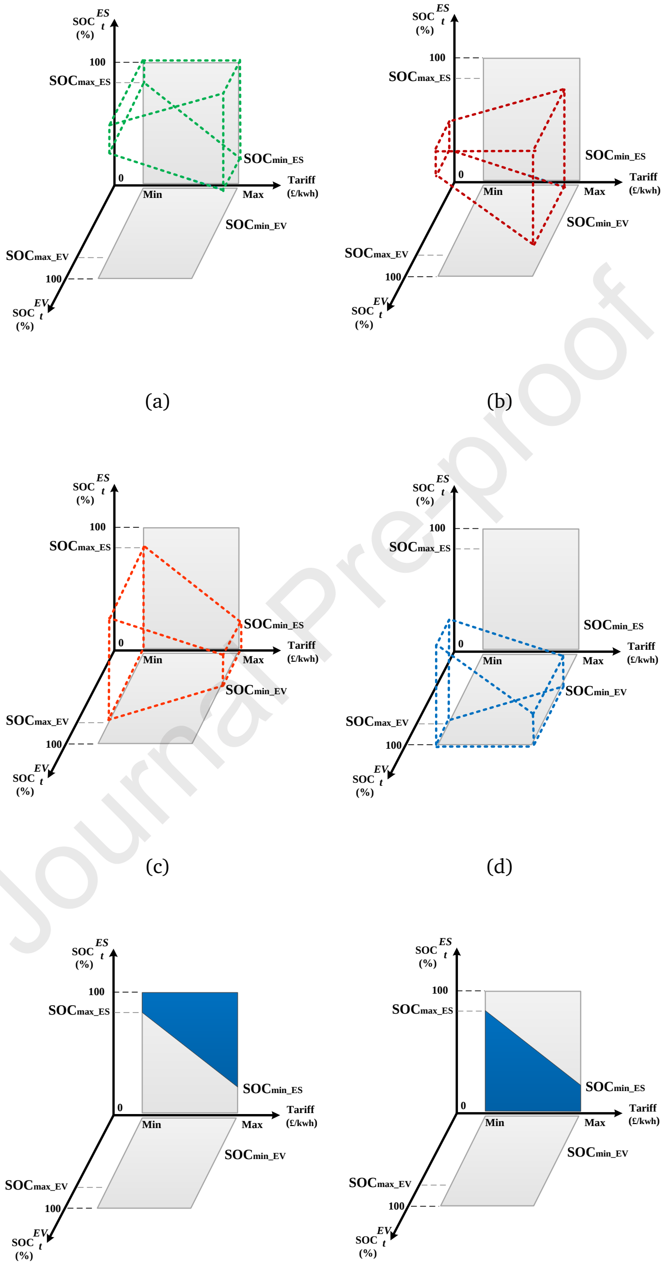
- (f): Purchase power from the grid to meet the internal shortage and charging the ES.

Figure 12 shows the general block diagram regarding the methodology applied in the case study. As it is obvious, the primary level and the secondary level of hierarchical architecture located in each HEHs are depicted. In general, the secondary level prioritizes the possible processes in HEHs based on the input data and the difference between generation and demand. In the presence of excess power, these processes include selling electricity to the grid and ES/EV charging. Purchasing electricity from Grid, charging/discharging ES, and charging EV are included in possible processes when there is shortage power, too. The defined scenarios are applied to the circuit via `Ctrl`_XXX commands of the power references have a total of more than 200 lines in the MATLAB function block. Therefore, they have not presented here. Reference signals have also starred. Then, this data is sent to the initial level which its details have already been stated.

4.3. ***Simulation***

In addition to the SOCs, analysis of the electricity tariff in the proposed HEMS may adjust the amount of financial benefit. Hence, two methods namely, (1) the proposed SOC-Tariff-based scheme and (2) conventional SOC-based scheme presented in [11] are compared in the following. The investigations are carried out through the computer simulation in the MATLAB/SIMULINK environment. As earlier stated, the configuration of MHEHNN under the study includes two HEHs and two CBs. The technical specifications of HEHs are shown in Table 2. The main objective of simulation is to assess the proposed scenario detector scheme performance in comparison with the conventional method in achieving technical and financial avails. For this reason, the control system capability in tracking the references and proper dynamic response at the time of changing the scenario as well as energy cost reduction have also been evaluated.

The simulations are carried out in 24 seconds representing 24 hours of a day. The electricity tariff (in £/kWh) considered in this time interval is shown in Figure 13. The simulation results are presented in Section 4.3.1.



(a) (b)

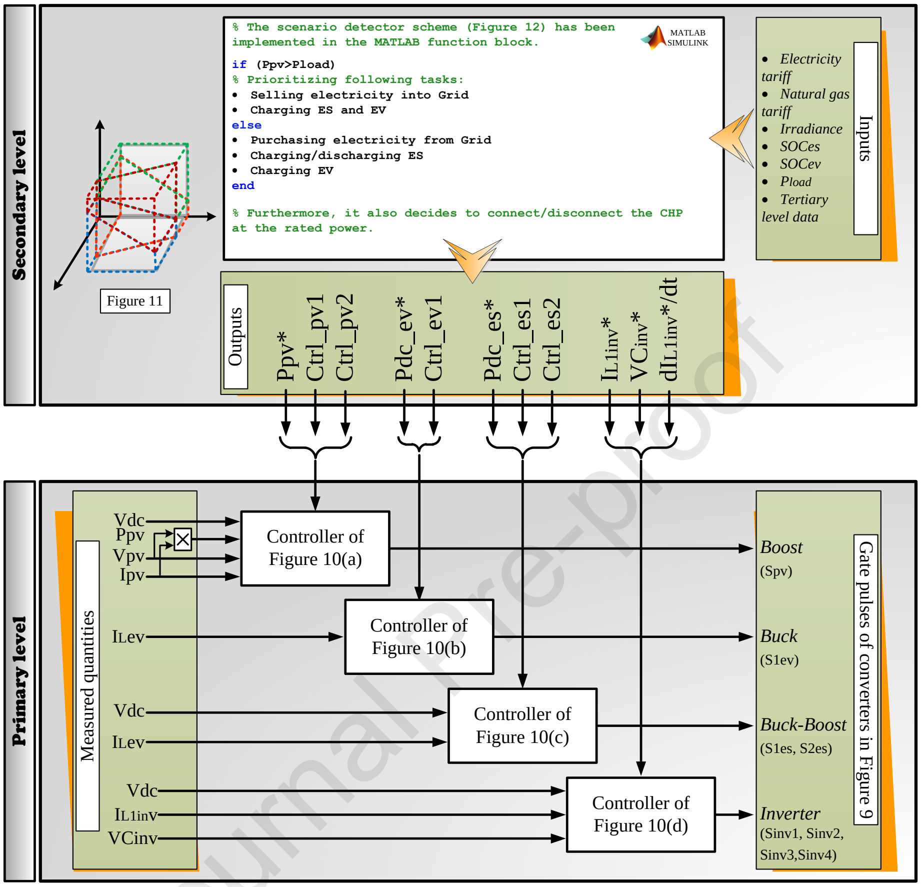
(c) (d)

(e) (f)

Figure 11: Possible sub-spaces of the proposed scenario detector scheme

Table 2: Technical specifications of the configuration under the study

Parameters	HEH#1	HEH#2
DC-link voltage	410 V	
Maximum power of PV	5450 W (for irradiance=1000 W/m^2)	
PV voltage at MPP	288 V	
PV current at MPP	19 A	
Voltage of ES	260 V	
ES charging rate	5 A	3.5 A
Maximum ES discharging rate	15 A	10 A
ES capacity	50 Ah	35 Ah
Primary value of ES' SOC	80 %	55 %
Voltage of EV	260 V	
EV charging rate	2.5 A	2 A
EV capacity	25 Ah	20 Ah
Time interval that EV is connected	[00:00-10:00,16:00-18:00,22:00-24:00]	[00:00-07:00,17:00-24:00]
Primary value of EV' SOC	80 %	20 %
Grid voltage	230 V	
Grid frequency	50 Hz	
CHP nominal power	4 kW	
SOC_{min_ES}, SOC_{min_EV}	40 %	
SOC_{max_ES}, SOC_{max_EV}	70 %	
Batteries usage limitation	[20-90] %	
Inductors value	L_{pv} =200 μH, $L_{es} = L_{ev}$ =2.7 mH $L1_{inv}$ =1.4 mH, $L2_{inv}$ =0.7 mH	
Capacitors capacity	C_{pv} =1.7 mf, $C_{es} = C_{ev}$ =0.6 mf C_{dc} =9.6 μf, C_{inv} =50 μf	



```
% The scenario detector scheme (Figure 12) has been
implemented in the MATLAB function block.
if (Ppv>Pload)
% Prioritizing following tasks:
•  Selling electricity into Grid
•  Charging ES and EV
else
•  Purchasing electricity from Grid
•  Charging/discharging ES
•  Charging EV
end
% Furthermore, it also decides to connect/disconnect the CHP
at the rated power.
```

Figure 12: Methodology

4.3.1. Simulation results

In order to avoid the expansion of the topics of the article, it is believed that The grid has allowed MHEHNN to transfer some volume of power beforehand. Data on the tertiary level is therefore believed to be available. The quantity of excess capacity is therefore known as a requirement for financial rewards and no marketing technique has been used. The primary level is hired to achieve appropriate technical characteristics such as fast dynamic response and accurate reference tracking. This level controls parallel DC-DC converters and inverter based on the data obtained from the measurement and the secondary level. In particular, the primary level serves as the central control panel that controls parallel DC-DC converters

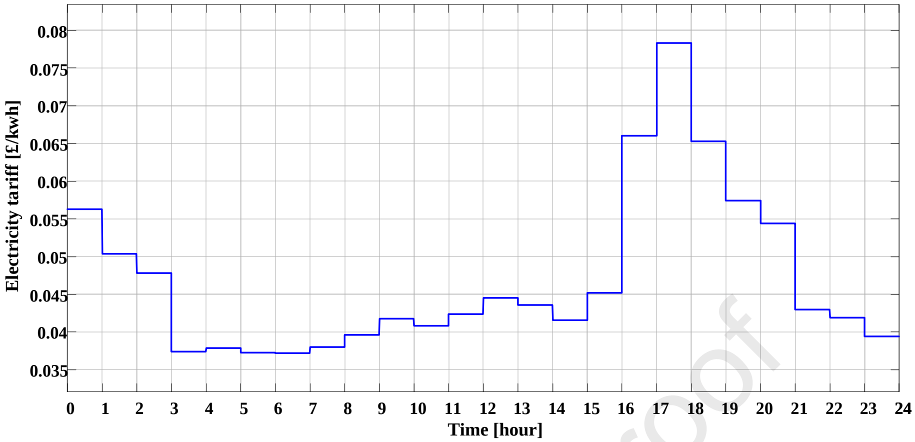


Figure 13: Electricity tariff

and the inverter in unified and based current source methods, respectively (see Section 3.2.2). The generated PV power and its corresponding reference curve are shown in Figure 14. It is clear that the PV controller (as seen in Figure 9(a)) reacts rapidly and precisely to the reference variations.

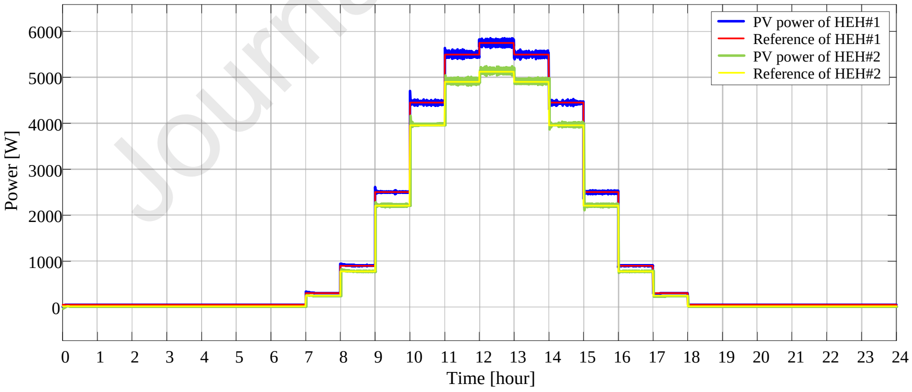


Figure 14: Generated and reference of PV power

Figure 15 shows the exchanged power of ES and EV in HEH 1 and HEH 2 under the proposed scheme. The positive and negative values of exchanged power indicate the discharging and charging modes, respectively. As shown in this figure, the control system (Figure 9(b) and Figure 9(c)) design is appropriately done for both power flow directions as the steady-state condition has achieved less than 0.00025 seconds at the points of changing the scenarios. The power of EVs is always negative, because they are only being charged and there is no Vehicle-to-Grid (V2G) technology here. As it is evident, in the middle of the day, when the PV generation is maximum, the ESs are charged at a higher rate.

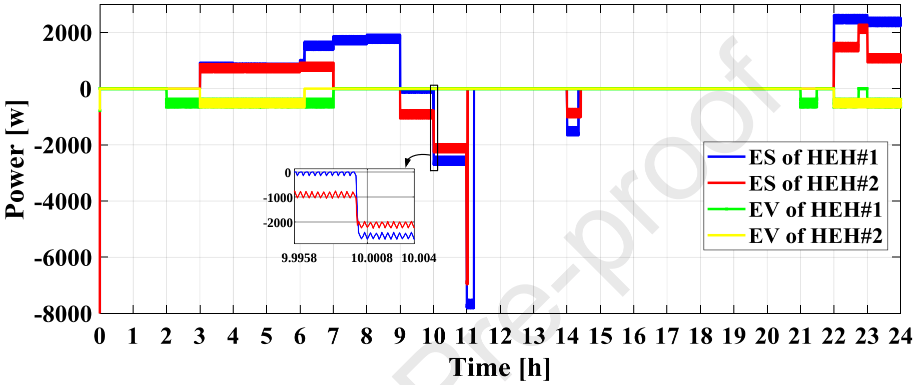
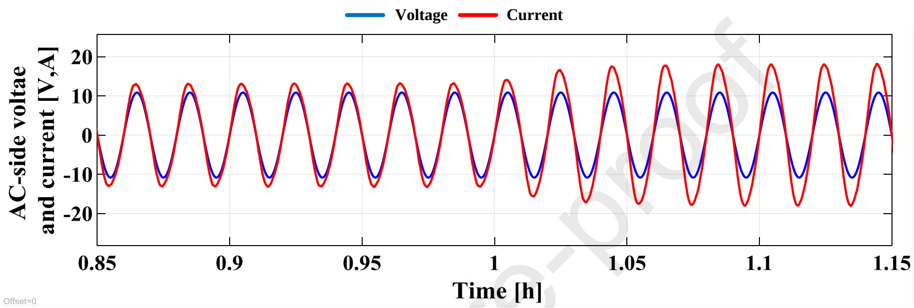


Figure 15: Power curves of a) ES and b) EV in HEH1 (proposed scheme)

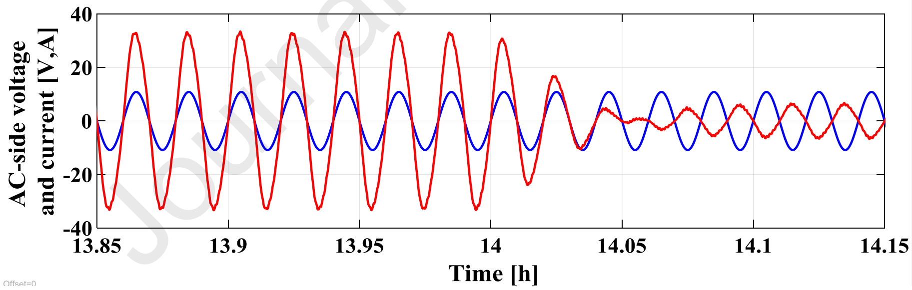
The voltage and current response at the AC side of inverters is another technical characteristic that should be studied, especially at the times of changing the scenarios. This has been investigated in Figure 16 which shows the decreasing and evolving in the direction of the grid current. For a more accurate comparison of voltage and current curves, the voltage has scaled-down 30 times in Figure 16. Being accurate in this figure, it takes about three cycles to achieve the steady-state operation which is an exciting feature of the inverters under the system control scheme shown in Figure 9(d).

DC bus voltage stabilisation criteria are of high significance when supplying a stable power supply for DC loads. Here, the grid-connected inverters are responsible for offsetting the DC bus voltage. As seen in Figure 17, DC bus voltage has an appropriate ripple of around 0.6 per cent of nominal voltage and a maximum voltage of 1.5 per cent. Transients that have occurred in the voltage profile can be found to be absolutely irrelevant in real-time experiments of 1-hour time measures.

The proposed scheme makes good use of CHP at its nominal capacity when the



(a) HEH#1



(b) HEH#2

Figure 16: Grid side voltage and current curves in: (a) HEH#1 and (b) HEH#2 (Voltage curve is scaled-down 30 times)

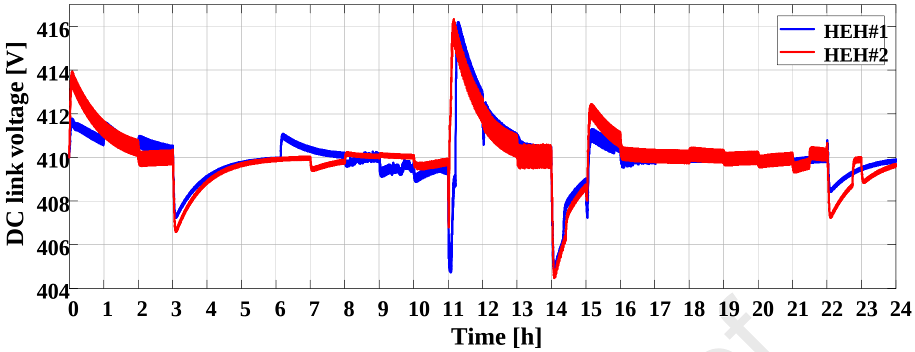


Figure 17: DC bus voltage of HEHs (proposed scheme)

natural gas is more economical than purchasing the same amount of electricity. The condition that natural gas being economical than the electricity is also determined regarding the natural gas electricity equivalent tariff G_{ET}=(3600.T_{gas})/(μ.Qg) [109]. Where 3600 is the coefficient of converting power to energy, T_{gas} is the natural gas tariff; Q_g is the energy of one cubic meter of natural gas (37000 KJ/m^3), and μ is the efficiency of converting heat to electricity in the CHP (95%). Whenever GET is less than electricity tariff, CHP will be taken into operation. Here, the natural gas tariff has been considered as constant and equal to 0.425 £/m^3. The value obtained for GET is 0.0435 £/KJ. Therefore, the CHP operation time intervals include [00:00-03:00], [11:00-14:00], and [15:00-22:00]. Depending on the amount of energy generation/consumption, the CHP may be involved in supplying the HEH load, CBs load, and selling to the grid. The internal load profile of HEHs and CBs are illustrated in Figure 18.

The exchanged power profiles of HEHs and grid under the proposed scheme are shown in Figure 19. The positive and negative values of power in the HEHs indicate the sell (HEHs →MHEHNN →grid) and purchase (grid →MHEHNN →HEHs) of power, respectively. In some hours, the exchanged power rate between the HEHs and the MHEHNN reaches zero, which means that HEHs supply their internal loads independently. The purchased power from the grid has also increased to meet the CBs demand in zero power rate intervals. The performance of the HEMS is evaluated for every 24 hours. Over a 24-hour period, the mean value of exchanged

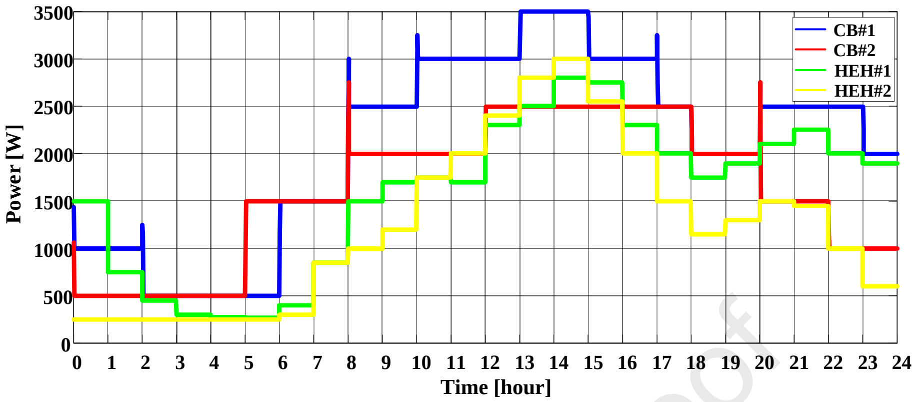


Figure 18: The load profile of HEHs and CBs

power corresponding to each HEH can be obtained by Eq. 1.

$$\mathrm{EP_i} = \frac{\sum_{h=1}^{24}(\mathrm{GP_i}(h) - \mathrm{CP_i}(h))}{24} \tag{1}$$

Where $\mathrm{GP_i}$ and $\mathrm{CP_i}$ are the hourly PV generated/ES utilized power and consumed power in *i*th HEH, respectively. Similarly, the mean value of exchanged power of the MHEHNN is obtained as the sum of the hourly difference between the power sold to the grid and purchased from the grid divided by 24.

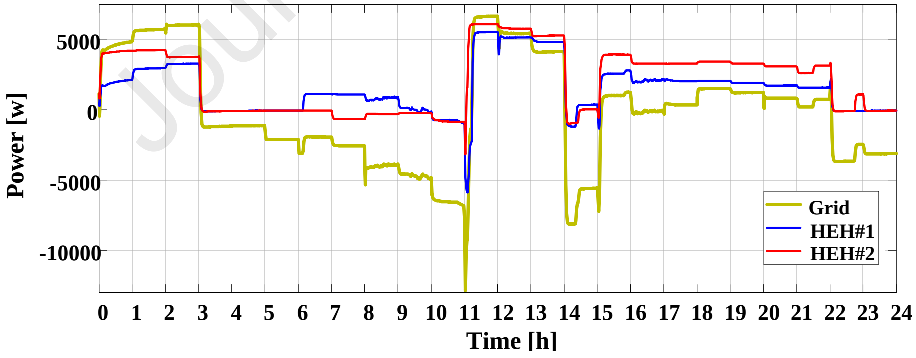


Figure 19: Exchanged power curves (proposed scheme)

The exchanged power profiles of HEHs and grid under the conventional scheme are shown in Figure 20. The average values of these power curves is compared with the benefits of the proposed scheme in Table (3). According to the numerical results, the HEHs participation in the local market has greatly increased under the

Table 3: The mean value of exchanged power

Methods	HEHs to MHEHNN		MHEHNN to Grid
	HEH#1	HEH#2	
Proposed scheme	1553 W	2069 W	-87.69 W
Conventional scheme	-477.7 W	-690.1 W	-4877 W

proposed scheme. It means the HEHs may supply the local loads instead of charging the ESs at some hours while focus of conventional schematic was only on supplying internal loads and maximum charge of ESs. Thus, the share of local generators in supplying local loads has increased which reduces the dependency of the MHEHNN on the grid. As a result, the mean value of power purchased by MHEHNN from the grid (MEHEHNN to Grid) is reduced by about 98%. From the HEHs point of view, they have earned more income by selling the surplus power. Under ther proposed scheme, HEH 1 and HEH 2 have sold about 37.2 kWh and 49.6 kWh power (mean values×24h) while they had purchased about 11.4 kWh and 16.5 kWh under the conventional scheme, respectively. From the CBs point of view, electricity cost will also reduce by avoiding additional grid fees and purchasing lower electricity price from local market.

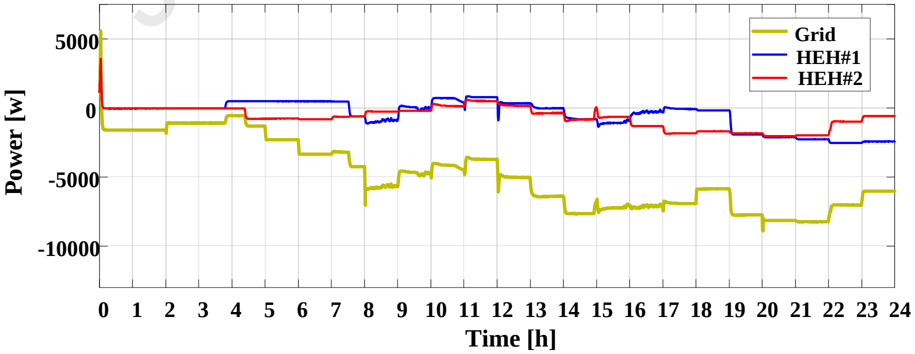
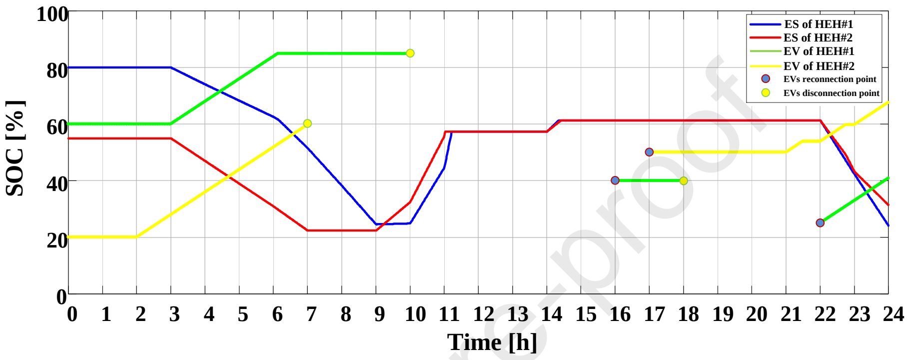


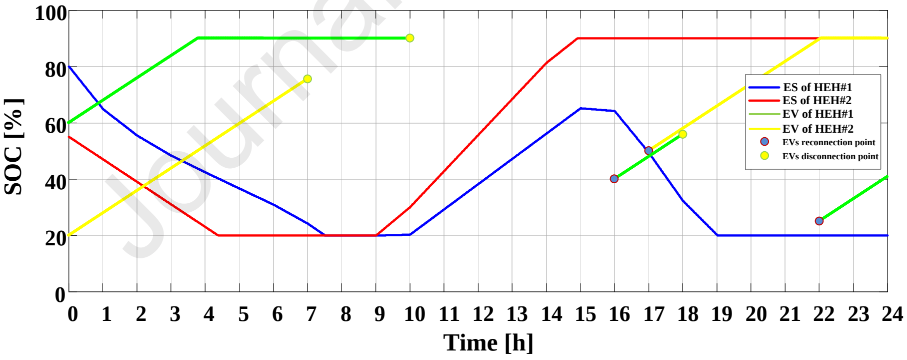
Figure 20: Exchanged power curves (conventional scheme)

Figure 21 shows the changes in SOC of ESs and EVs under both proposed and conventional schemes. There are several re-connection points with separate SOCs from the last SOCs before the EVs are disconnected. This allows the investigation into plug and play systems to be more accurate. While the HEHs have obtained more financial gains under the proposed system, it is well known that the SOCs under this scheme are much smaller than the traditional scheme. It was to be expected because the conventional scheme focuses on the technical benefits. However, an association between the financial advantage and the final SOCs can be accomplished by changing the boundaries in Figure 11. In comparison, during the early hours of the next day, the SOC cut may be paid because energy tariffs are typically lowered during those hours.

According to the results, the success of the secondary level in increasing profits of MHEHNN and reducing the grid dependency has proved. Furthermore, the appropriate dynamic response of the controller applied at the primary level has assured the supremacy of the proposed system over the functional aspects of the traditional scheme. Now that the benefits of the proposed approach have been established, a large-scale case study involving 10 HEHs and 20 CBs has been applied. In this regard, 10 different irradiation patterns for HEHs, 30 different load curves for all homes (HEHs and CBs), different SOCs for EVs after each connection and different initial SOCs for ESs have been determined. Other system specifications such as battery capacity, PV panel parameters, CHP capacity, etc. are in accordance with Table (2). The results are summarized in Table (4) and Table (5). Negative numbers in the columns demand and EV indicate consumption. Also, in the ES column, the negative numbers indicate charge mode and the positive number signify discharge mode. In the last column, the negative and positive numbers represents the purchased power from the network and sold power to the network, respectively. According to the results, MHEHNN sells an average of about 15 kW to the network under the proposed scheme. While in conventional scheme, it purchases an average of about 7.8 kW from the grid.



(a) proposed schemes



(b) conventional schemes

Figure 21: SOC of ESs and EVs under the a) proposed and b) conventional schemes

Table 4: The mean value of exchanged power in the large-scale case study (proposed scheme)

HEH number	Generation	From ES	CHP	Demand	Charging EV	Power sold to MHEHNN
1	1552.5 w	325 w	1045.5 w	-865 w	-110 w	1948 w
2	1332 w	21.5 w	2008.5 w	-210.5 w	-122.5 w	3029 w
3	1276 w	217 w	2080 w	-833 w	-129 w	2611 w
4	1517 w	145.5 w	1833 w	-598 w	-112.5 w	2785 w
5	1640 w	109 w	1724 w	-1085 w	-83 w	2305 w
6	1136.5 w	76 w	2215.5 w	-764.5 w	-106.5 w	2557 w
7	1332 w	298 w	2027 w	-904 w	-110 w	2643 w
8	1262 w	114 w	2085 w	-469 w	-109 w	2883 w
9	1628.5 w	188 w	1722.5 w	-533.5 w	-156.5 w	2849 w
10	1166.5 w	191 w	2194 w	-948 w	-112.5 w	2491 w
MHEHNN to Grid=15460 w HEHs to CBs=10641 w						

Table 5: The mean value of exchanged power in the large-scale case study (conventional scheme)

HEH number	Generation	From ES	Demand	Charging EV	Power sold to MHEHNN
1	1552.5 w	-86.5 w	-865 w	-140 w	461 w
2	1332 w	-215.5 w	-210.5 w	-245 w	661 w
3	1276 w	-245 w	-833 w	-166.5 w	31.5 w
4	1517 w	-185 w	-598 w	-193 w	541 w
5	1640 w	-197.5 w	-1085 w	-128.5 w	229 w
6	1136.5 w	-244 w	-764.5 w	-188 w	-60 w
7	1332 w	-197.5 w	-904 w	-150 w	80.5 w
8	1262 w	-200.5 w	-469 w	-210 w	382.5 w
9	1628.5 w	-196.5 w	-533.5 w	-187.5 w	711 w
10	1166.5 w	-220 w	-948 w	-234.5 w	-236 w
MHEHNN to Grid=-7839.5 w HEHs to CBs=2801.5 w					

5. Conclusion

This paper presents various types of HSEGs, energy management approaches and the role of power electronics in the implementation of energy management in the neighbourhood network. A general system for energy management in the neighbourhood network has therefore been developed. The efficiency of the built system consisting of four households (two HEHs and two CBs) and a large-scale MHEHNN (ten HEHs and 20 CBs) was investigated. HEMS is proposed to assess the amount of power shared between these buildings. The HEMS consists of three stages, where only primary level (power converter control) and secondary level (scenario detector) output is evaluated. Scenario identification is based on the SOC-Tariff system, which has the ability to conflict with financial and technological advantages. A SOC-based conventional scheme is hired to show the proposed schematic strengths. The results show that HEHs participation in the has greatly increased to sell their surplus power under the proposed scheme. At a given power generation, it means the HEHs may supply the local loads instead of charging their ESs at some hours. In contrast, focus of conventional schematic was only on supplying internal loads and maximum charge of ESs. Hence, the final SOC of ESs and EVs in proposed scheme is lower than conventional scheme. This means that the total financial and technical benefits of an MHEHNN are almost constant and are limited by each other. So increasing in one will decrease the other. The proposed method interacts between financial and technical profit by applying the SOC-Tariff scheme by adjusting the upper and lower SOC limits in the proposed scenario detection method. As the results show, the mean value of power purchased by MHEHNN from the grid is reduced by about 98% under the proposed schematic in four homes system. Therefore, HEHs, CBs, and grid achieves benefits by selling surplus power, exempting from the grid usage fees, and peak-shaving, respectively. In the large-scale MHEHNN, the HEHs meet the total demand of CBs under the proposed scheme. While, under the proposed schematic, only about 25% of CB demand is met by HEH and the rest is met by the grid. The installed equipment in the distribution network such as transformers, circuit breakers, lines, and etc. should be able to process additional power injected by HEHs. Furthermore, the loads and irradiance have assumed to be definite for the day-ahead. But in practical applications, these are associated with uncertainty. These may limit the maximum benefit of a neighborhood network. Therefore, it is necessary to study the optimal capacity of HEHS in the neighborhood network and considering the uncertainty issues. For future studies, the thermal loads will be included and multi-objective optimization-based energy management will be used to maximize the technical and financial benefits of all participants in MHEHNN.

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HEH number	Generation	From ES	CHP	Demand	Charging EV	Power sold to MHEHNN
1	1552.5 w	325 w	1045.5 w	-865 w	-110 w	1948 w
2	1332 w	21.5 w	2008.5 w	-210.5 w	-122.5 w	3029 w
3	1276 w	217 w	2080 w	-833 w	-129 w	2611 w
4	1517 w	145.5 w	1833 w	-598 w	-112.5 w	2785 w
5	1640 w	109 w	1724 w	-1085 w	-83 w	2305 w
6	1136.5 w	76 w	2215.5 w	-764.5 w	-106.5 w	2557 w
7	1332 w	298 w	2027 w	-904 w	-110 w	2643 w
8	1262 w	114 w	2085 w	-469 w	-109 w	2883 w
9	1628.5 w	188 w	1722.5 w	-533.5 w	-156.5 w	2849 w
10	1166.5 w	191 w	2194 w	-948 w	-112.5	2491 w
MHEHNN to Grid= 15460 w HEHs to CBs=10641 w						

HEH number	Generation	From ES	Demand	Charging EV	Power sold to MHEHNN
1	1552.5 w	-86.5 w	-865 w	-140 w	461 w
2	1332 w	-215.5 w	-210.5 w	-245 w	661 w
3	1276 w	-245 w	-833 w	-166.5 w	31.5 w
4	1517 w	-185 w	-598 w	-193 w	541 w
5	1640 w	-197.5 w	-1085 w	-128.5 w	229 w
6	1136.5 w	-244 w	-764.5 w	-188 w	-60 w
7	1332 w	-197.5 w	-904 w	-150 w	80.5 w
8	1262 w	-200.5 w	-469 w	-210 w	382.5 w
9	1628.5 w	196.5 w	-533.5 w	-187.5 w	711 w
10	1166.5 w	-220 w	-948 w	-234.5 w	-236 w
MHEHNN to Grid= -7839.5 w HEHs to CBs=2801.5 w					

Table 1: Papers conclusion

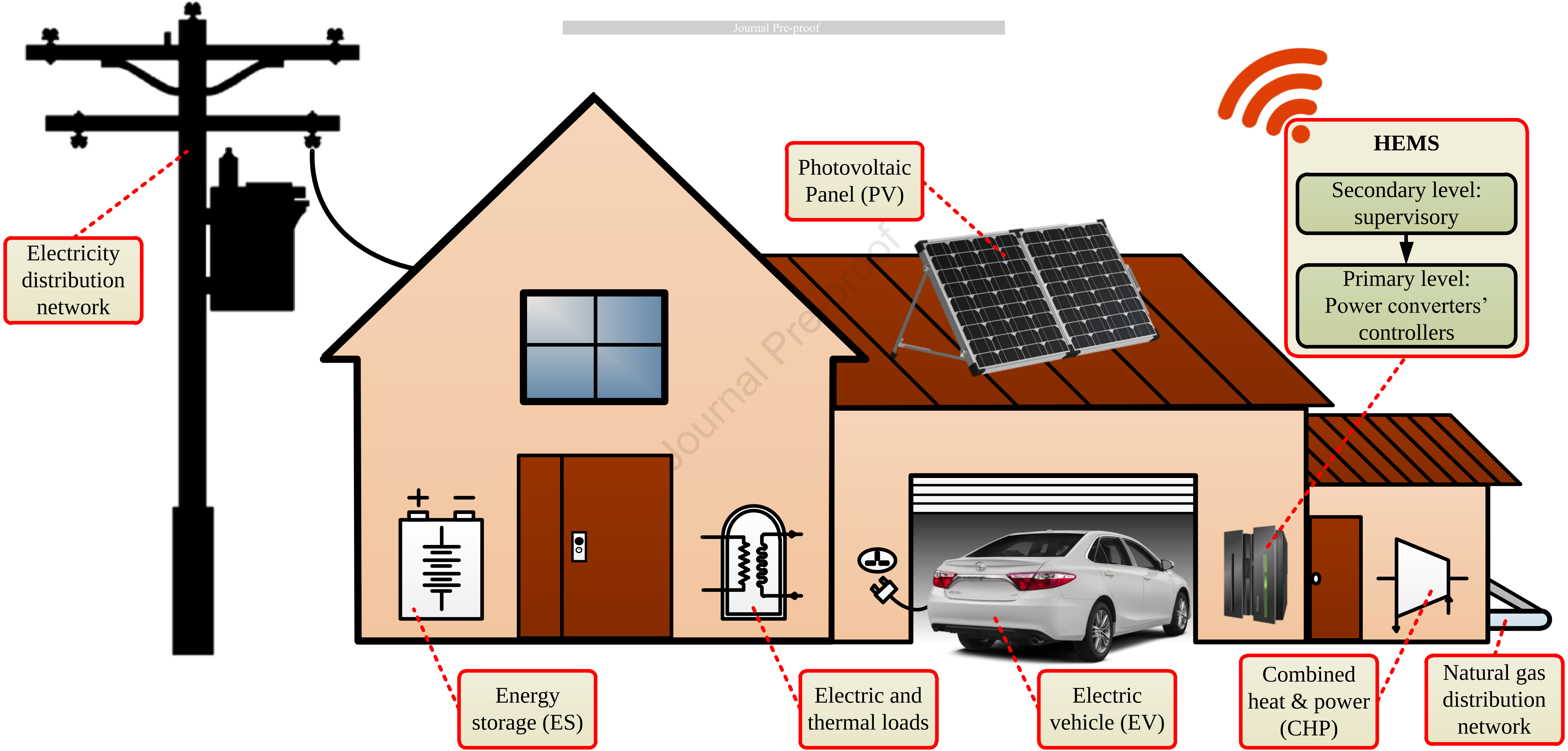
Ref	Under the concept of:	Scale of implementation	Resources /Storages	Hierarchical control level			Economic considerations at the level of:	Tariff considerations		Control scheme:	
				Primary	Secondary	Tertiary		Electricity	Natural gas	Inverters	DC-DC converters
[24]	MG	Home	PV, WT, ES	✓	✓	✖	Secondary	✓	✖	✖	✓
[25]	MG	Home	PV, ES	✓	✓	✖	Secondary	✓	✖	✖	✖
[29]	MG	Building	PV, WT	✓	✓	✓	Secondary and tertiary	✓	✖	✓	✖
[30]	MG	Residential building	PV, ES, WT, CHP	✓	✓	✖	✖	✖	✖	✓	✖
[37]	PC	A part of distribution network	PV, ES, EV, CHP, WT	✓	✓	✓	Secondary and tertiary	✓	✓	✖	✖
[73]	MG	Low power	ES	✓	✖	✖	✖	✖	✖	✖	✖
[93]	EH	Neighborhood Network	Any kind of RESs	✖	✓	✓	✖	✖	✖	✖	✖
[94]	MG	*Not mentioned*	PV, ES	✓	✓	✓	✖	✖	✖	✓	✓
[95]	MG	Building	PV, ES, EV	✓	✓	✖	Secondary	✓	✖	✖	✓
[96]	MG	MGs	PV, ES, WT	✓	✓	✓	Secondary	✓	✖	✓	✖
[97]	MG	Neighborhood Network	Some integrated RESs	✖	✖	✓	✖	✖	✖	✖	✓
[98]	MG	Neighborhood Network	ES, Super capacitor (SC)	✓	✓	✓	Tertiary	✓	✖	✖	✓
[99]	MG	*Not mentioned*	DC voltage source	✖	✓	✖	✖	✖	✖	✓	✖
[100]	MG	Residential building	PV, ES, EV, WT	✓	✓	✖	✖	✓	✖	✖	✓
[101]	MG	*Not mentioned*	Some integrated RESs	✓	✓	✓	Tertiary	✖	✖	✖	✓
[102]	EH	*Not mentioned*	PV, ES, CHP	✓	✓	✓	Secondary	✓	✓	✖	✓
[103]	MG	Single-phase low power	DC voltage source	✓	✓	✖	✖	✖	✖	✓	✖
[104]	DC MG	*Not mentioned*	DC energy sources, ES	✓	✓	✖	✖	✖	✖	✖	✓
[105]	MG	*Not mentioned*	PV, ES, WT, FC, CHP	✓	✓	✖	✖	✖	✖	✓	✓
[106]	MG	*Not mentioned*	PV, ES	✓	✓	✓	✖	✖	✖	✖	✖
[107]	MG	Two adjacent MGs	DC voltage source	✓	✓	✖	✖	✖	✖	✓	✖
[108]	MG	Several parallel MGs	DC voltage source	✓	✓	✖	Tertiary	✓	✖	✓	✖
[109]	MG	Several parallel inverters	DC voltage source	✓	✓	✓	✖	✖	✖	✓	✖
[110]	MG	Several parallel MGs	DC voltage source	✓	✓	✓	Tertiary	✖	✖	✓	✖
[111]	MG	*Not mentioned*	PV, ES, WT	✓	✓	✓	Secondary	✖	✖	✓	✖
[112]	MG	*Not mentioned*	PV, ES	✓	✓	✖	✖	✖	✖	✓	✖
[113]	MG	Several parallel MGs	RESs, ES, CHP	✓	✓	✓	Tertiary	✓	✖	✖	✖
[114]	EH	Building	PV, ES, EV	✖	✖	✖	✖	✓	✓	✖	✖
[115]	PC	Home	PV, ES, EV	✖	✖	✖	✖	✓	✖	✖	✖
[116]	MG	*Not mentioned*	PV, ES, WT, SC	✓	✓	✖	Secondary	✓	✖	✖	✖
[117]	AC/DC MG	*Not mentioned*	Several AC and DC power generators	✖	✖	✖	✖	✖	✖	✓	✓
[118]	MG	Several neighboring MGs	PV, ES, WT, CHP	✖	✖	✖	✖	✓	✖	✖	✖
[119]	DC MG	*Not mentioned*	PV, ES, WT, EV	✖	✖	✖	✖	✖	✖	✖	✓
[120]	EH	Low-voltage small-capacity areas	PV, ES, WT, FC	✖	✖	✖	✖	✓	✖	✓	✓
[121]	EH	Neighboring an EH and several PV PCs	PV, CHP	✖	✖	✖	✖	✓	✓	✖	✖
[122]	MG	Low-voltage low-power	PV, ES, SC	✖	✖	✖	✖	✖	✖	✖	✓
[123]	MG	Building	PV	✓	✓	✖	✖	✖	✖	✖	✖
[124]	MG	*Not mentioned*	PV, CHP, FC	✖	✖	✖	✖	✖	✖	✖	✓
[125]	MG	*Not mentioned*	PV, CHP, ES	✓	✓	✖	✖	✖	✖	✖	✓

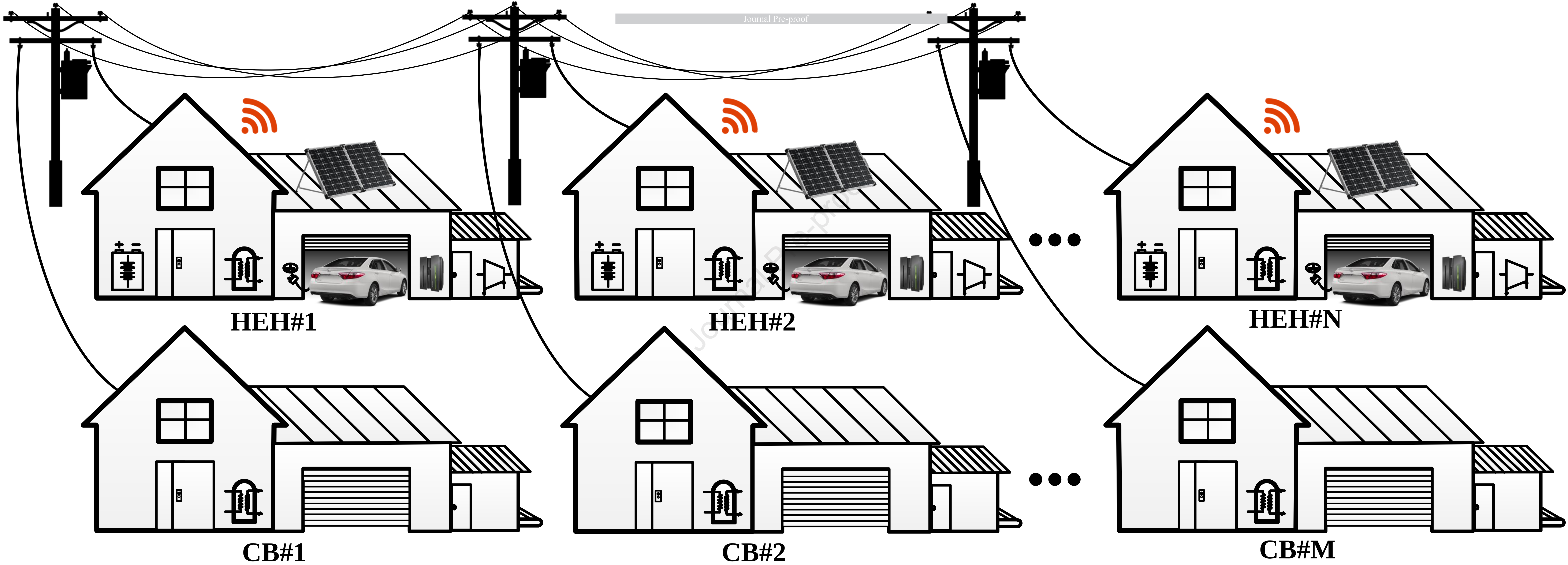
Table 1: Technical specifications of the configuration under the study

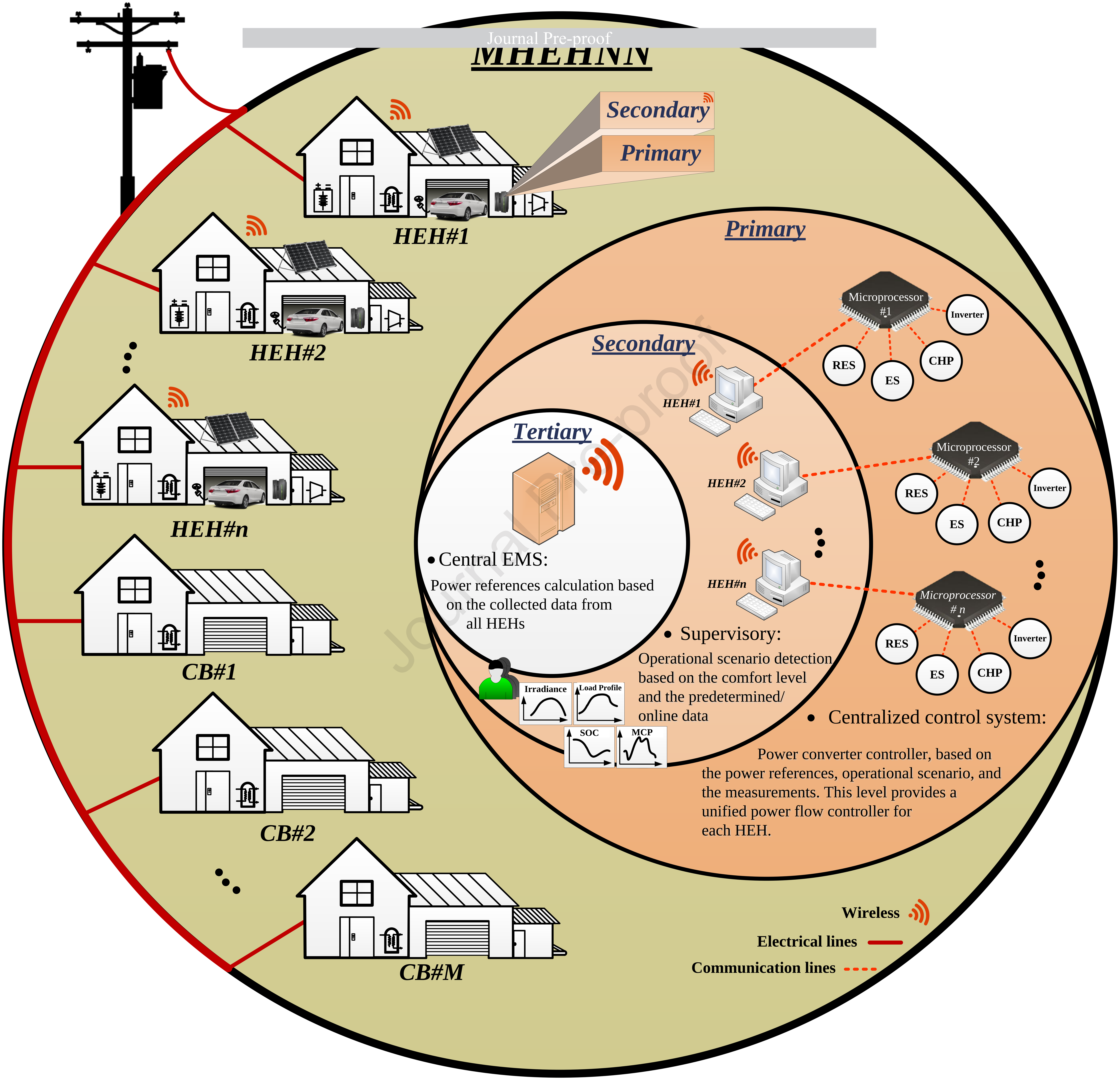
Parameters	**HEH 1**	**HEH 2**
DC-link voltage ($V_{DC\text{-}link}$)	410 V	
Maximum power oMaximumf PV ($P_{PV\text{-}MPPT}$)	5450 W (for irradiance=1000 W/m^2)	
PV voltage at MPP ($V_{PV\text{-}MPPT}$)	288 V	
PV current at MPP ($I_{PV\text{-}MPPT}$)	19 A	
Voltage of ES (V_{ES})	260 V	
ES charging rate	5 A	3.5 A
Maximum ES discharging rate	15 A	10 A
ES Capacity (C_{ES})	50 Ah	35 Ah
Primary value of ES' SOC ($SOC0_{ES}$)	80%	55 %
Voltage of EV (V_{EV})	260 V	
EV charging rate	2.5 A	2 A
EV Capacity (C_{EV})	25 Ah	20 Ah
Time interval that EV is connected	[00:00-10:00,16:00-18:00,22:00-24:00]	[00:00-07:00,17:00-24:00]
Primary value of EV' SOC ($SOC0_{EV}$)	80 %	20 %
Grid voltage ($V_{Grid\text{-}RMS}$)	230 V	
Grid frequency (f)	50 Hz	
CHP rated power (C_{CHP})	4 kW	
SOC_{min_ES} , SOC_{min_EV}	40 %	
SOC_{max_ES} , SOC_{max_EV}	70 %	
Batteries usage limitation	[20-90] %	
Inductors value	L_{pv}=200 μH, L_{es}=L_{ev}=2.7 mH $L1_{inv}$=1.4 mH, $L2_{inv}$=0.7 mH	
Capacitors capacity	C_{pv}=1.7 mf, C_{es}=C_{ev}=0.6 mf C_{dc}=9.6 μf, C_{inv}=50 μf	

Table 1: The mean value of exchanged power

Power directions / Methods	HEHs to MHEHNN		MHEHNN to Grid
	HEH#1	HEH#2	
Proposed scheme	1553 W	2069 W	-87.69 W
Conventional scheme	-477.7 W	-690.1 W	-4877 W


Electricity
distribution
network
Photovoltaic
Panel (PV)
HEMS
Secondary level:
supervisory
Primary level:
Power converters'
controllers
Energy
storage (ES)
Electric and
thermal loads
Electric
vehicle (EV)
Combined
heat & power
(CHP)
Natural gas
distribution
network


HEH#1
HEH#2
HEH#N
CB#1
CB#2
CB#M



- Central EMS:

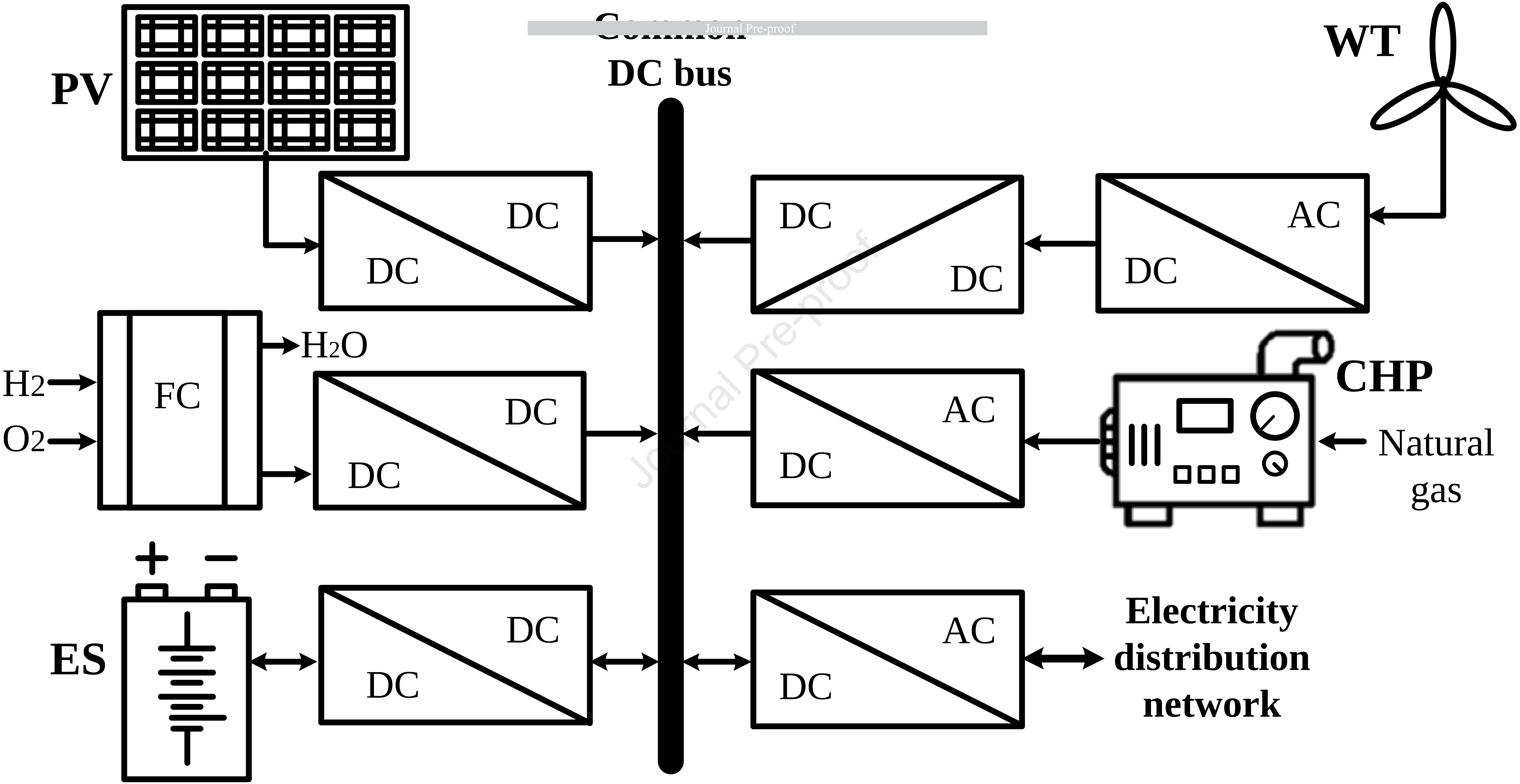
Power references calculation based on the collected data from all HEHs

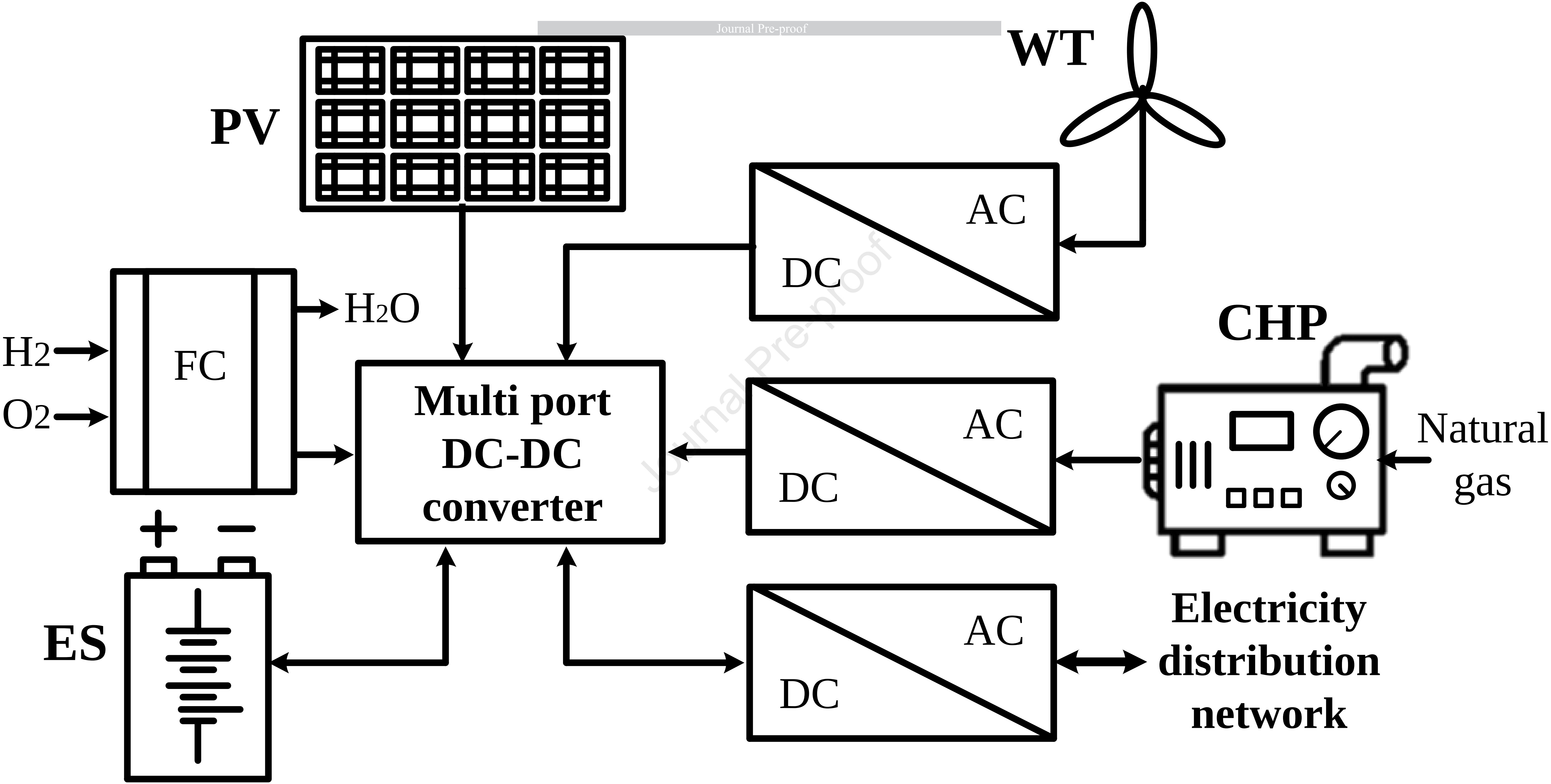
- Supervisory:

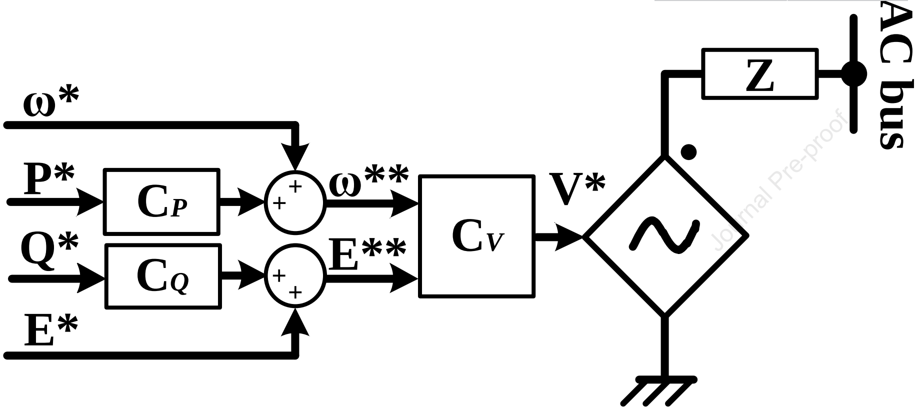
Operational scenario detection based on the comfort level and the predetermined/ online data

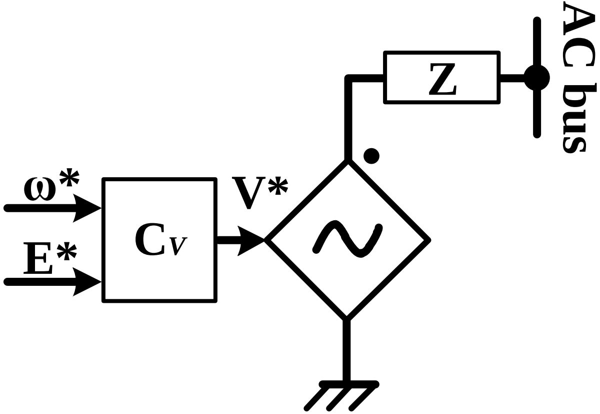
- Centralized control system:

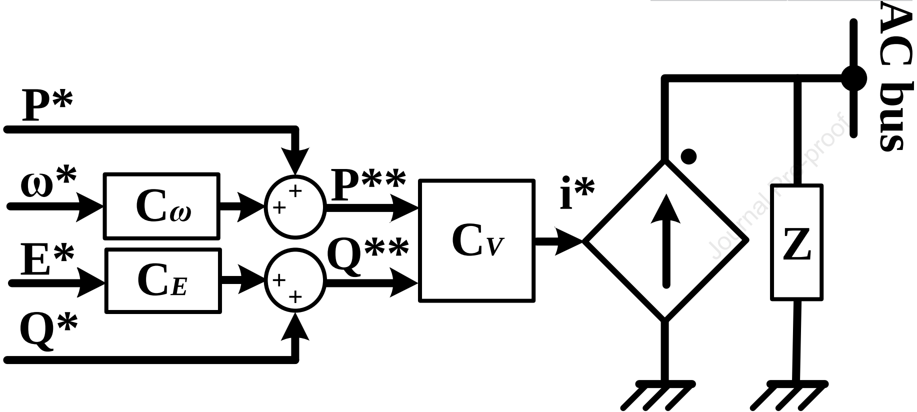
Power converter controller, based on the power references, operational scenario, and the measurements. This level provides a unified power flow controller for each HEH.

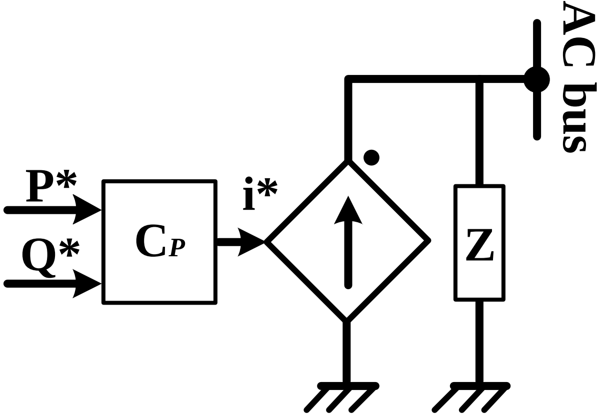

Common
DC bus
PV
DC
DC
WT
DC
DC
AC
DC
FC
H_2
O_2
H_2O
DC
DC
CHP
AC
DC
Natural
gas
ES
+
−
DC
DC
AC
DC
Electricity
distribution
network

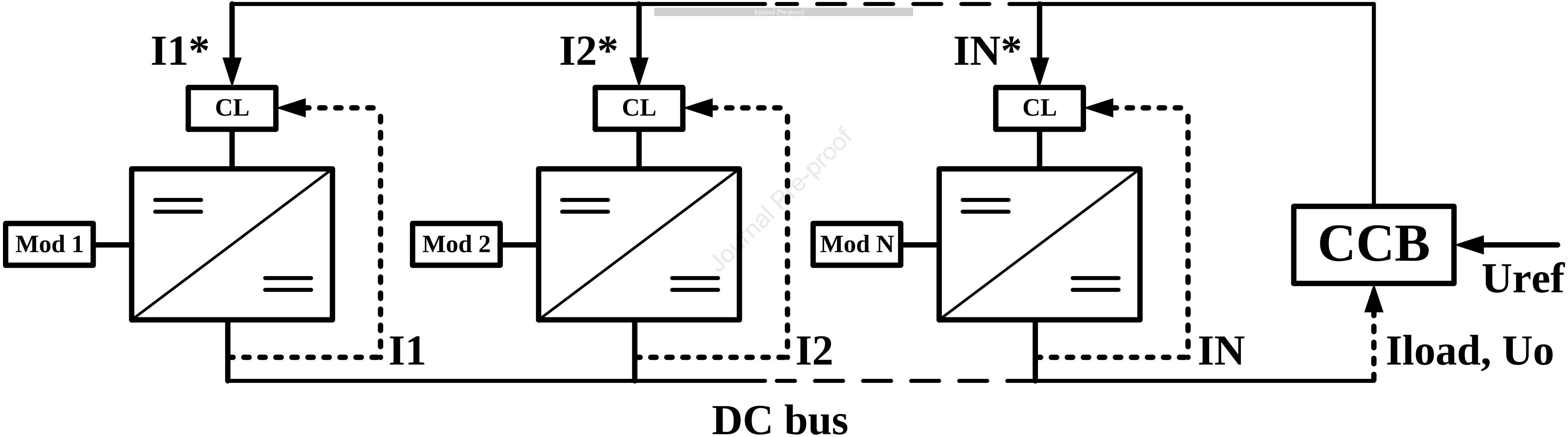

PV
WT
AC
DC
H₂O
H2
O2
FC
CHP
Multi port
DC-DC
converter
AC
DC
Natural
gas
+
−
ES
AC
DC
Electricity
distribution
network

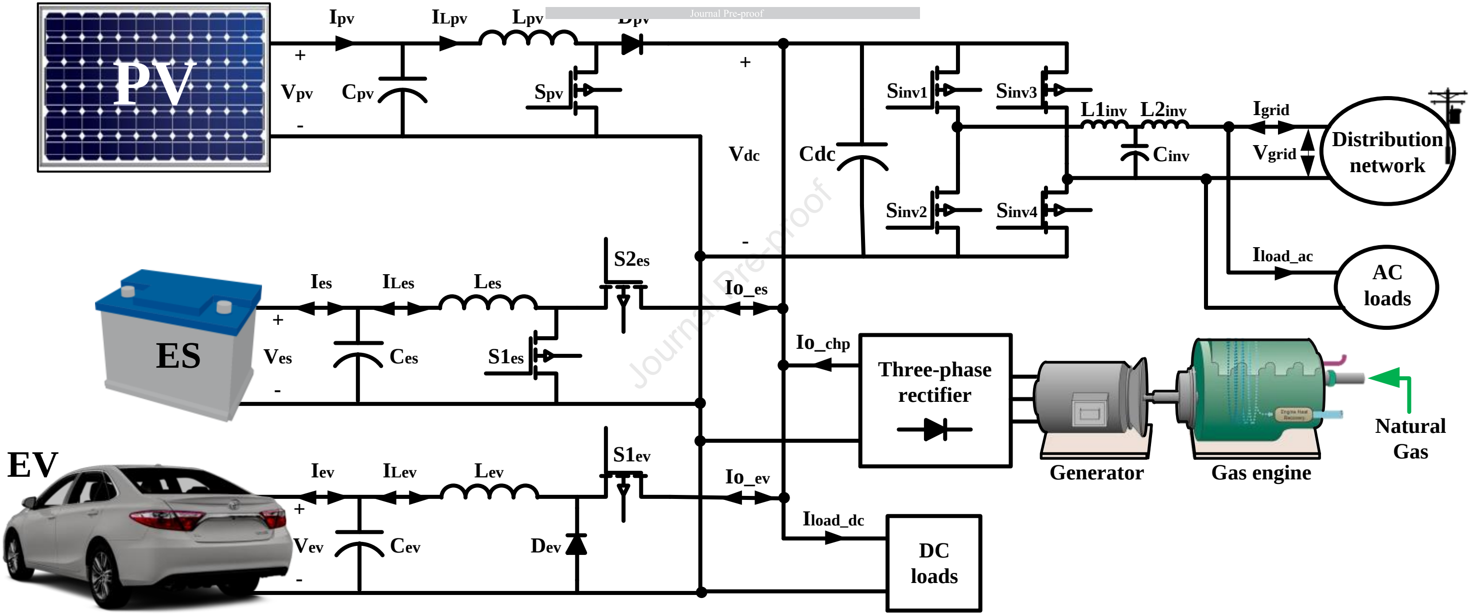

ω*
P*
C_P
+
+
ω**
Q*
C_Q
+
+
E**
E*
C_V
V*
Z
AC bus

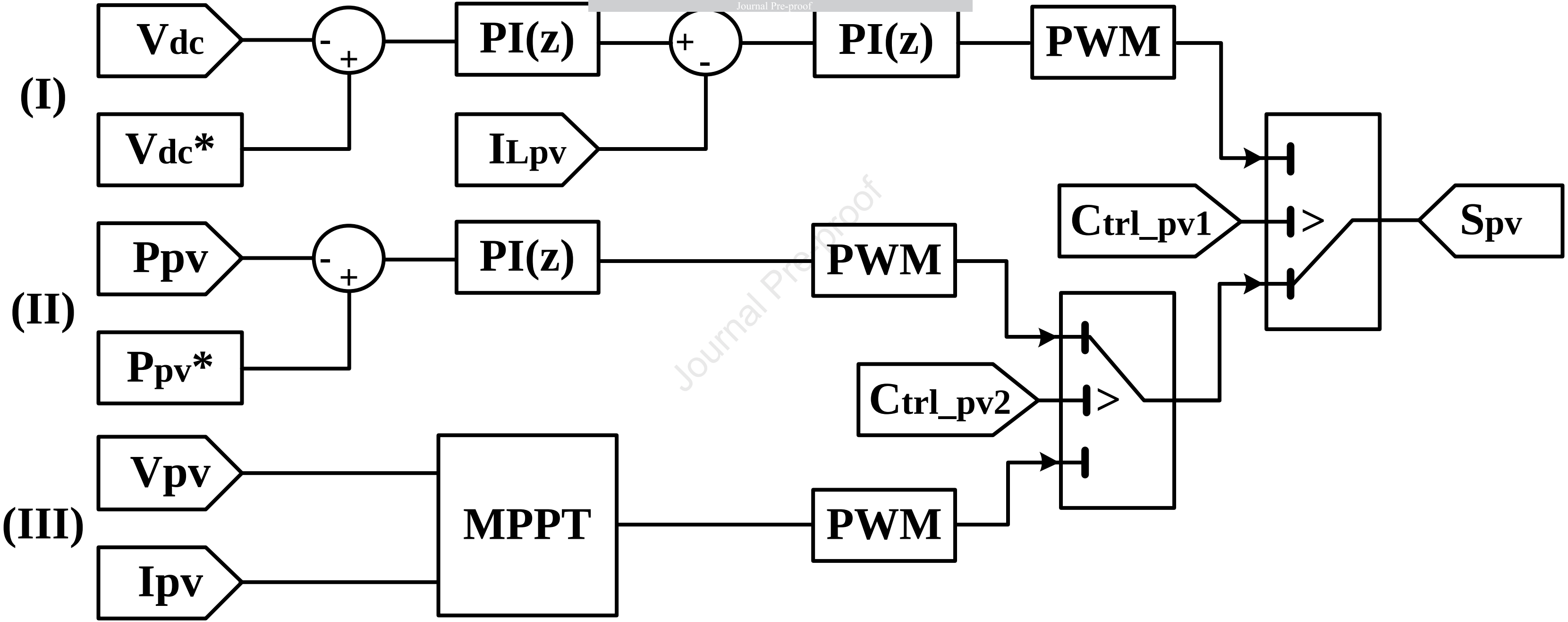

ω*
E*
C_V
V*
Z
AC bus

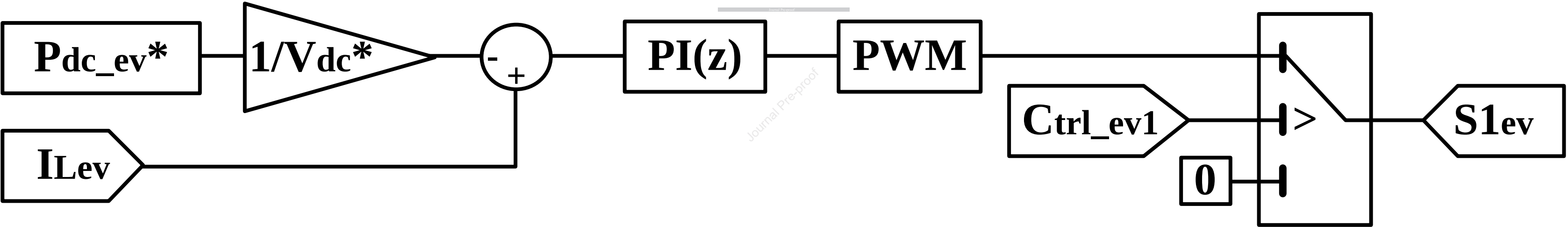

P*
ω*
Cω
E*
CE
Q*
+
+
+
+
P**
Q**
CV
i*
Z
AC bus

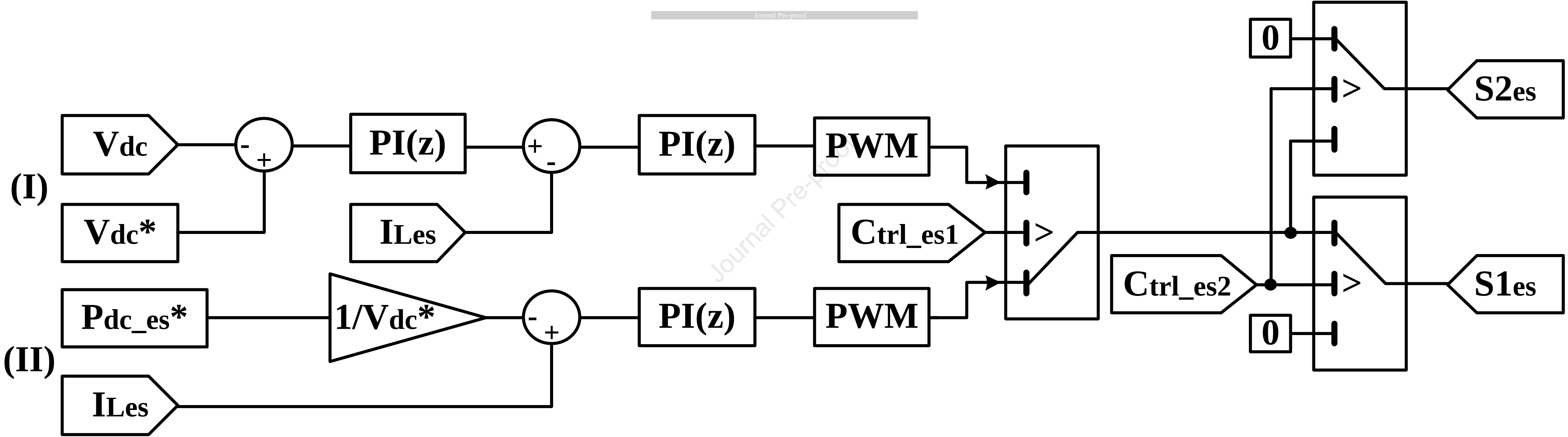

P*
Q*
CP
i*
Z
AC bus

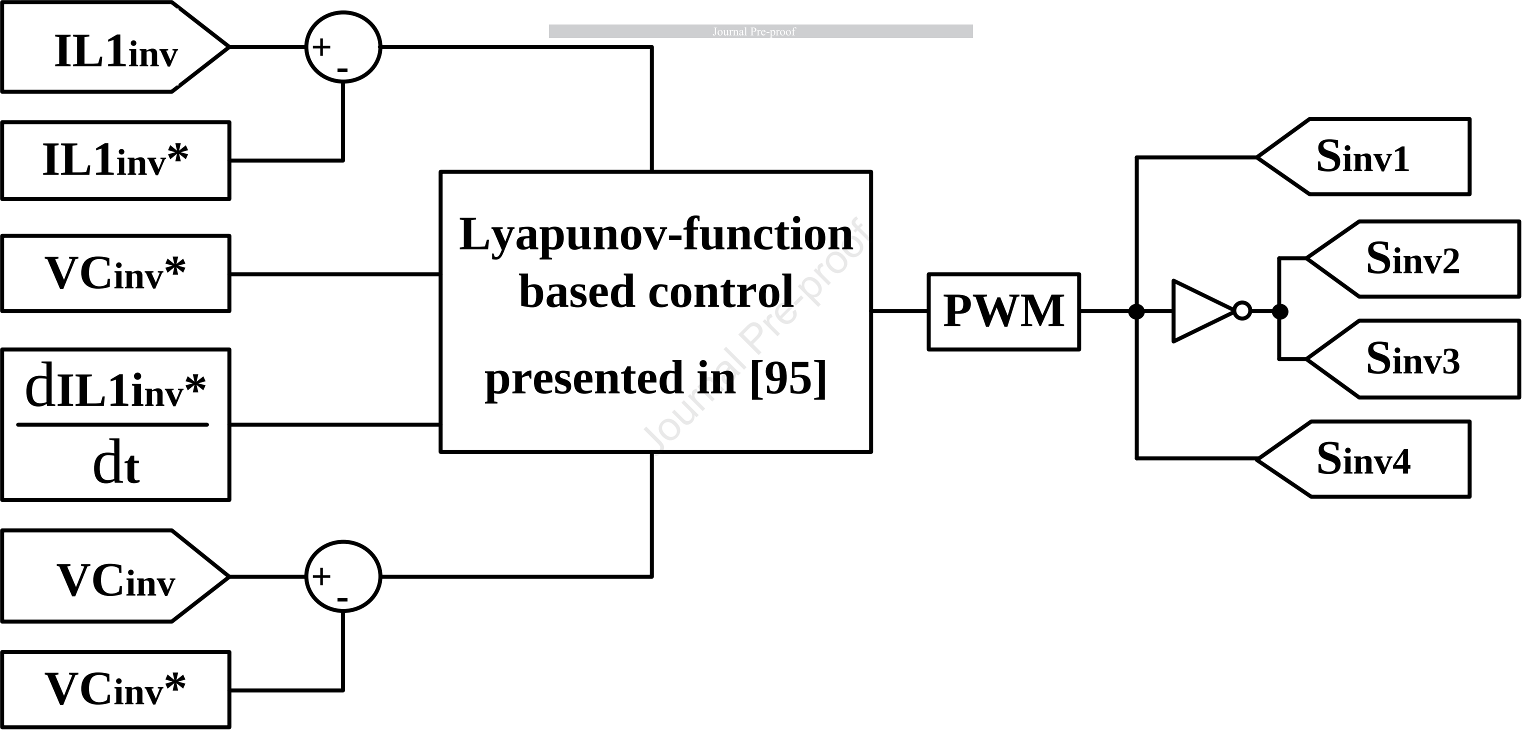

I1*
I2*
IN*
CL
CL
CL
Mod 1
Mod 2
Mod N
CCB
Uref
I1
I2
IN
Iload, Uo
DC bus

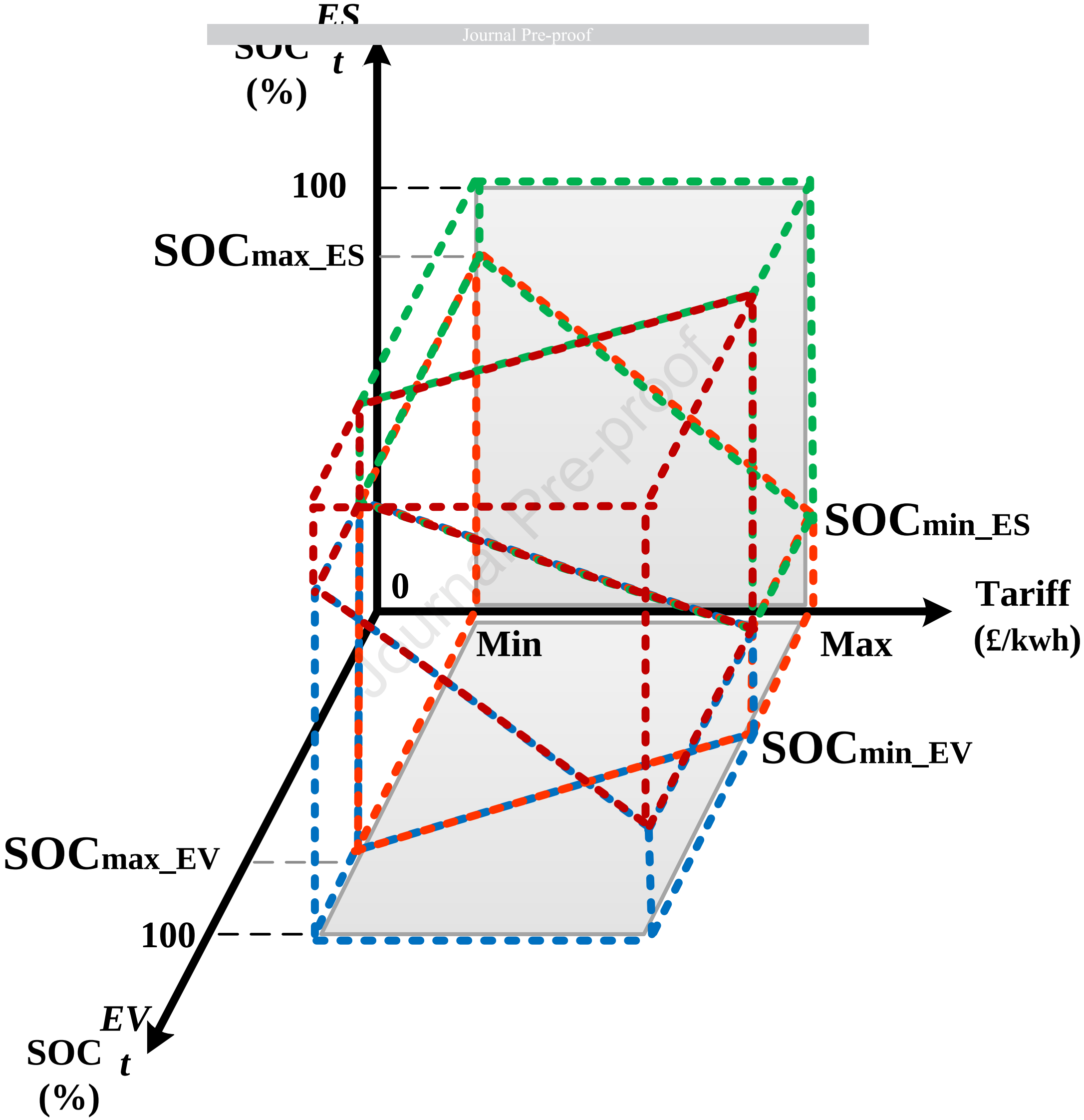

PV
Ipv
ILpv
Lpv
Dpv
+
Vpv
-
Cpv
Spv
+
Vdc
-
Cdc
Sinv1
Sinv3
Sinv2
Sinv4
L1inv
L2inv
Cinv
Igrid
Vgrid
Distribution network
Iload_ac
AC loads
ES
Ies
ILes
Les
S2es
+
Ves
-
Ces
S1es
Io_es
Io_chp
Three-phase rectifier
Generator
Gas engine
Natural Gas
EV
Iev
ILev
Lev
S1ev
+
Vev
-
Cev
Dev
Io_ev
Iload_dc
DC loads

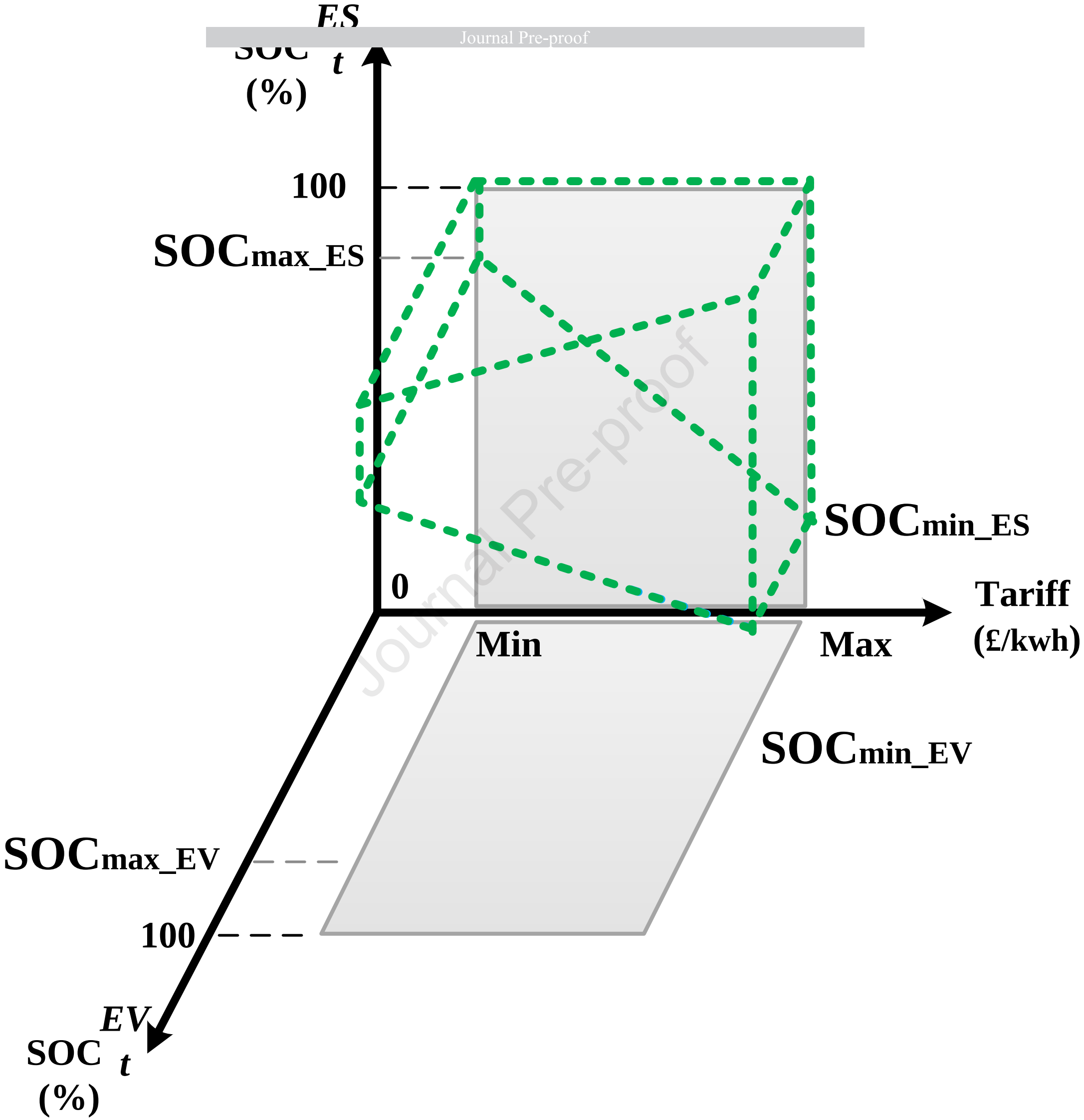

(I)
Vdc
Vdc*
-
+
PI(z)
+
-
ILpv
PI(z)
PWM
(II)
Ppv
Ppv*
-
+
PI(z)
PWM
(III)
Vpv
Ipv
MPPT
PWM
Ctrl_pv1
>
Ctrl_pv2
>
Spv

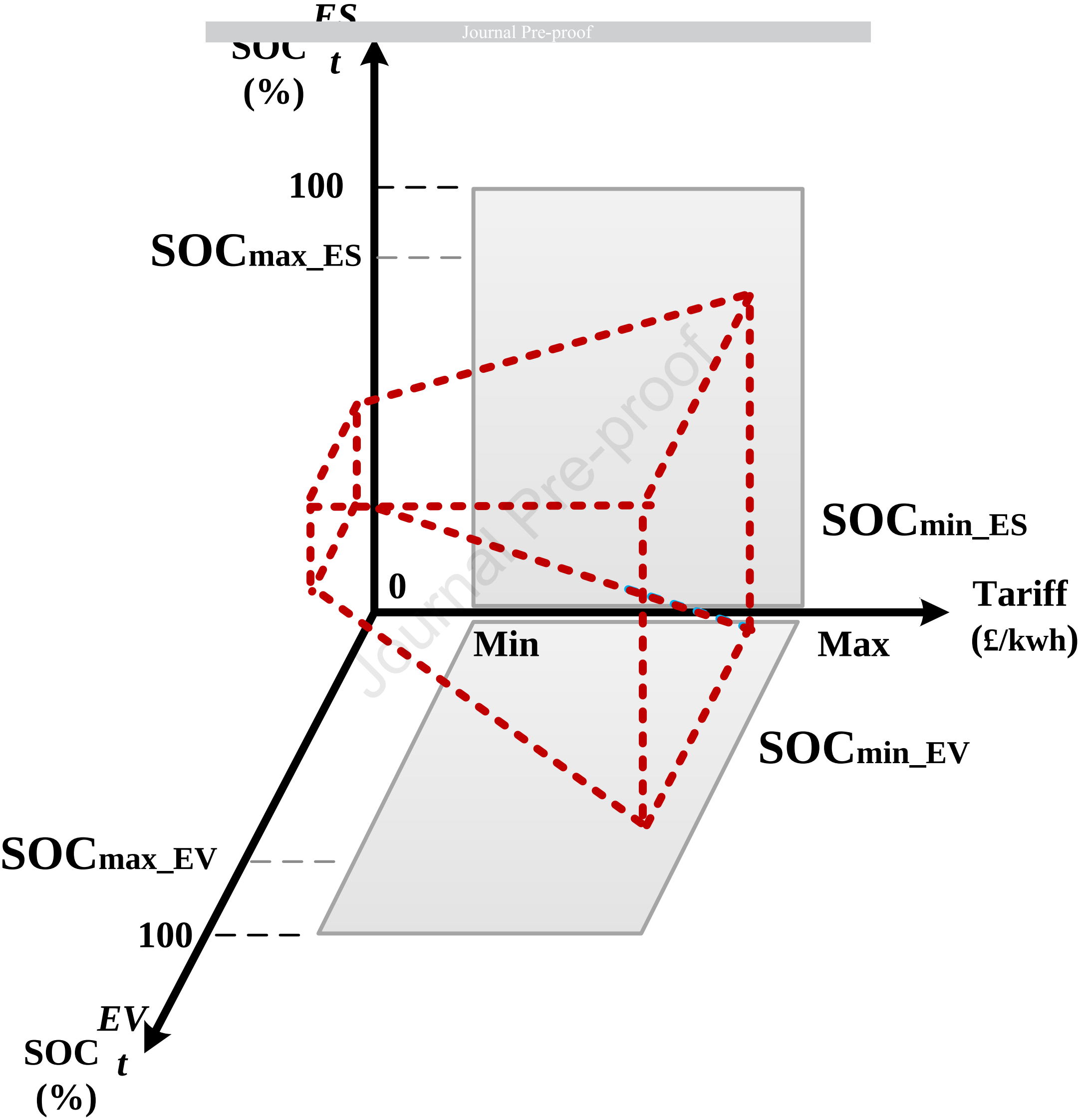

Pdc_ev*
1/Vdc*
-
+
PI(z)
PWM
ILev
Ctrl_ev1
>
0
S1ev

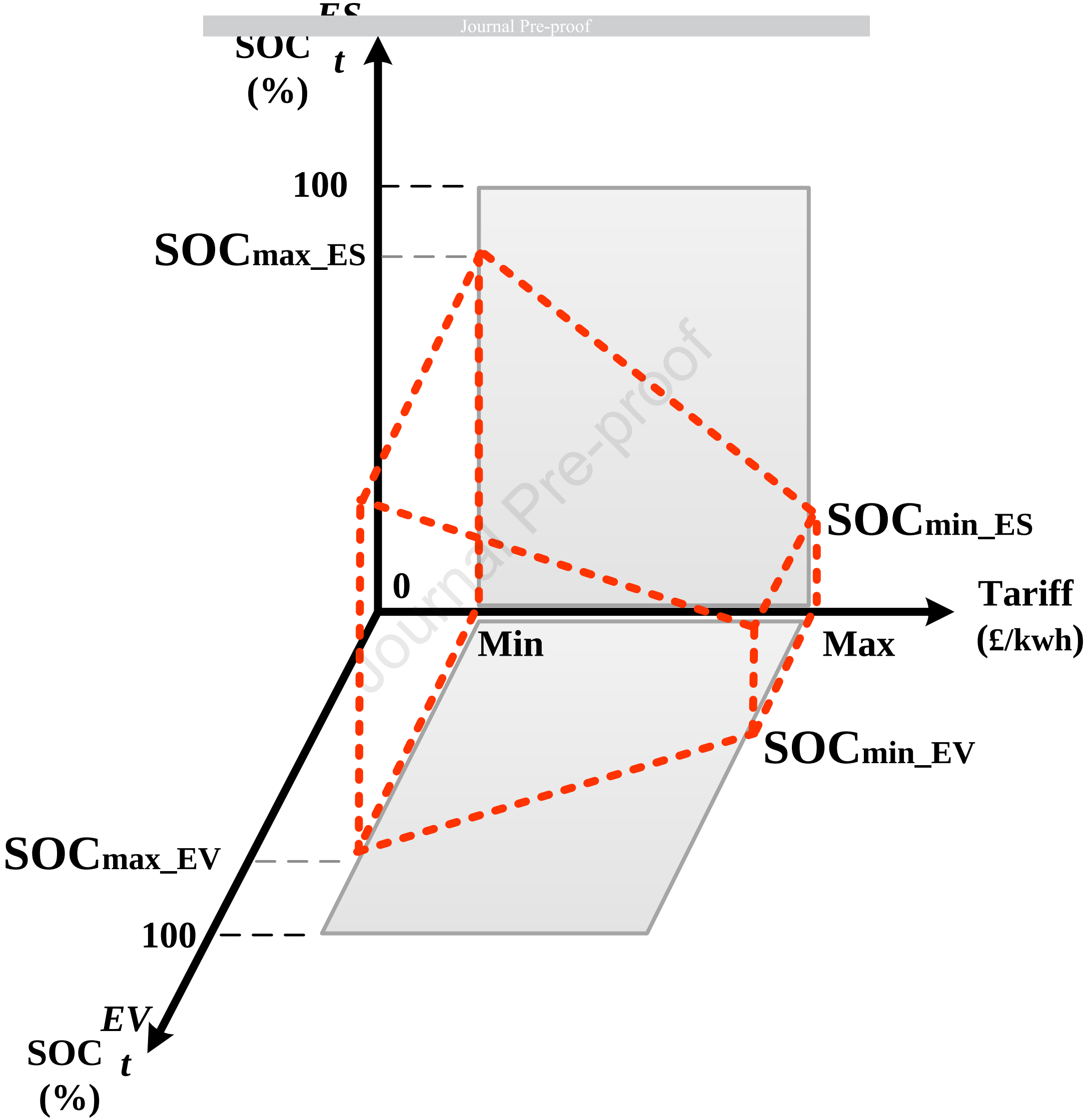

(I)
(II)
Vdc
Vdc*
-
+
PI(z)
+
-
ILes
PI(z)
PWM
Pdc_es*
1/Vdc*
-
+
ILes
PI(z)
PWM
Ctrl_es1
>
Ctrl_es2
0
>
0
>
S2es
S1es


IL1inv
+
-
IL1inv*
VCinv*
dIL1inv*
dt
VCinv
+
-
VCinv*
Lyapunov-function based control presented in [95]
PWM
Sinv1
Sinv2
Sinv3
Sinv4

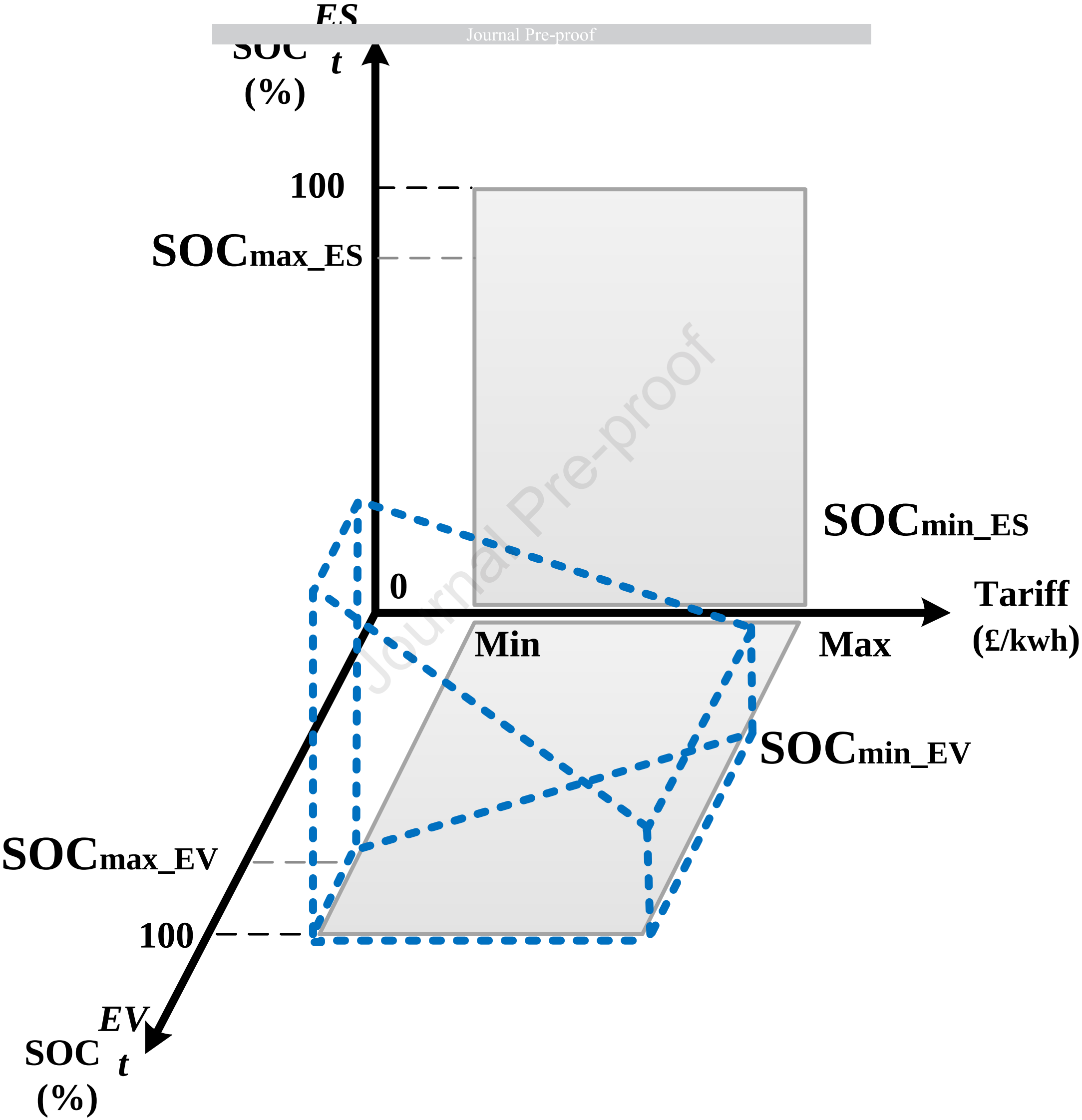

SOC_t^{ES}
(%)
100
SOCmax_ES
SOCmin_ES
0
Tariff
(£/kwh)
Min
Max
SOCmin_EV
SOCmax_EV
100
SOC_t^{EV}
(%)

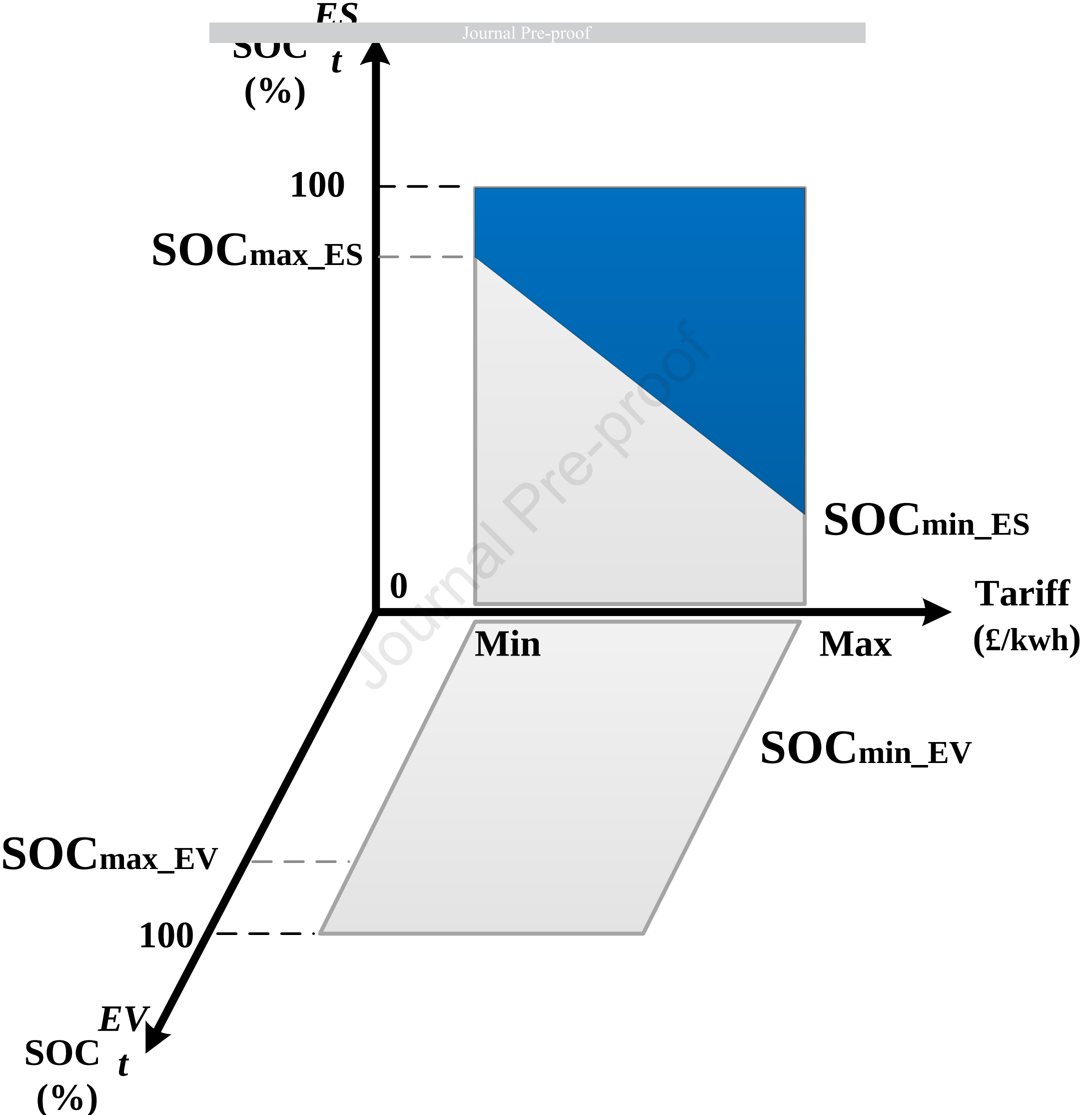

SOC_t^{ES} (%)
100
SOCmax_ES
0
SOCmin_ES
Tariff (£/kwh)
Min
Max
SOCmin_EV
SOCmax_EV
100
SOC_t^{EV} (%)


SOC_t^{ES} (%)
100
SOCmax_ES
SOCmin_ES
0
Tariff (£/kwh)
Min
Max
SOCmin_EV
SOCmax_EV
100
SOC_t^{EV} (%)

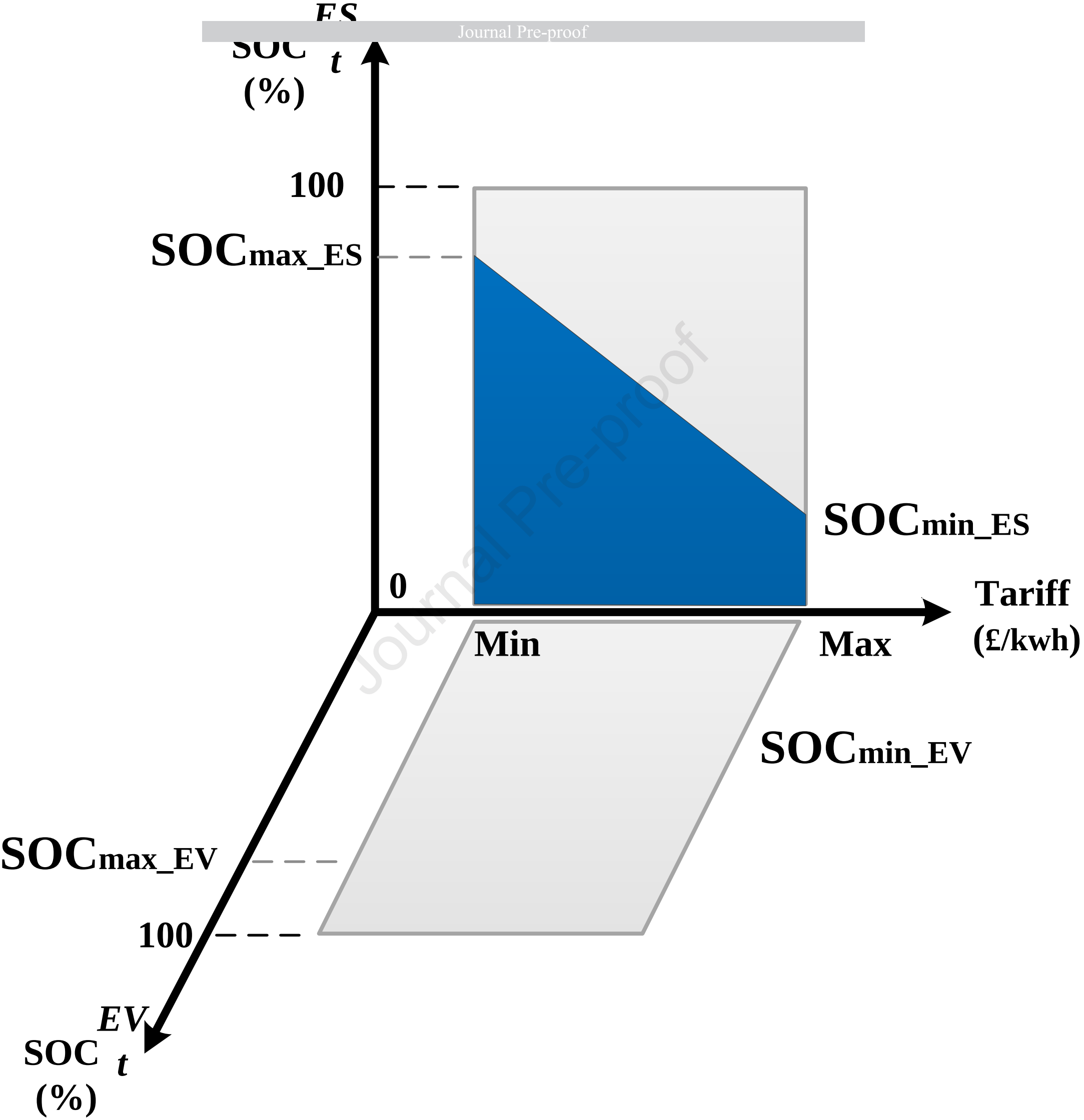


SOC_t^{ES} (%)
100
SOCmax_ES
SOCmin_ES
0
Tariff (£/kwh)
Min
Max
SOCmin_EV
SOCmax_EV
100
SOC_t^{EV} (%)

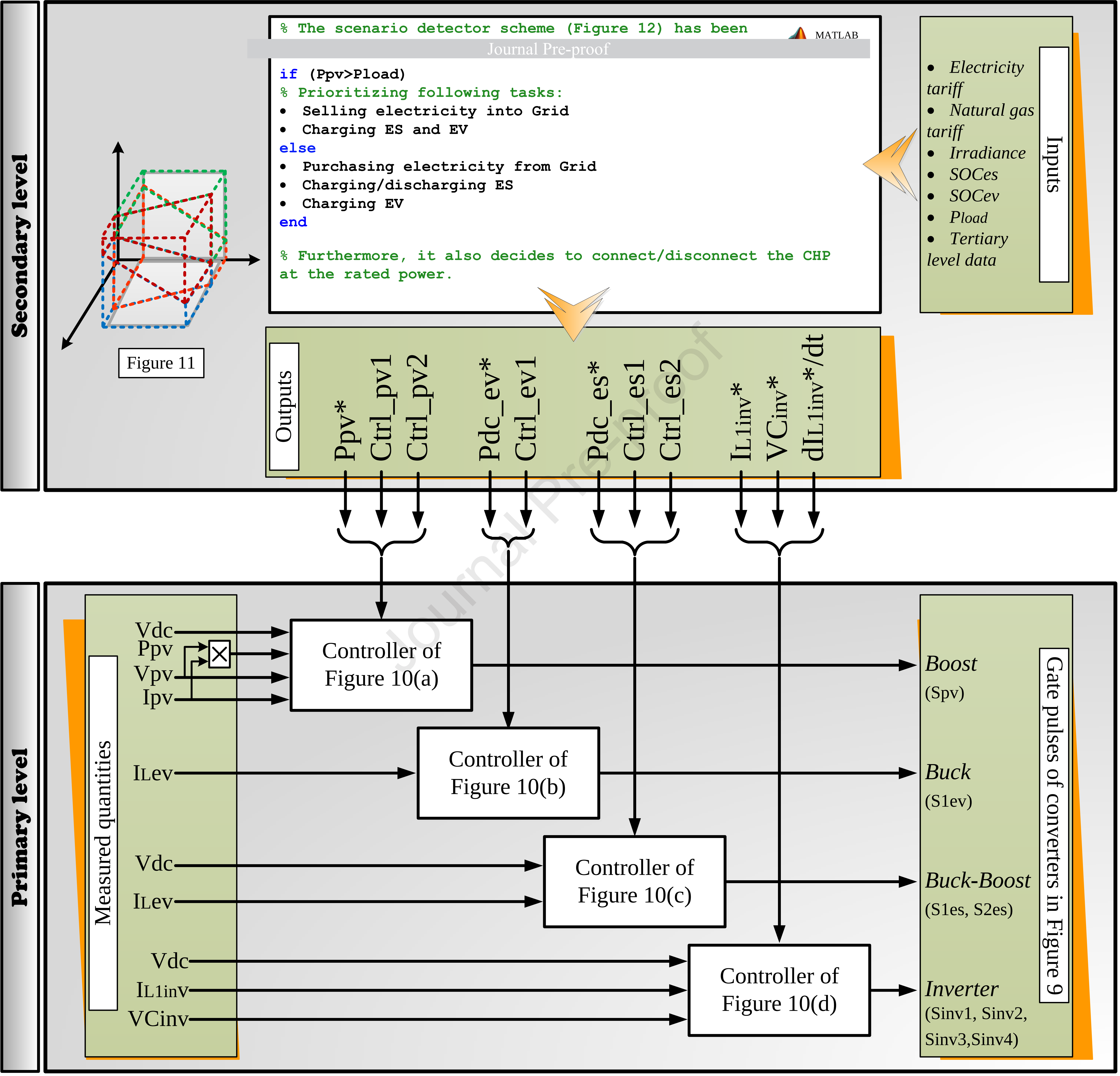

SOC_t^{ES} (%)
100
SOC_{max_ES}
SOC_{min_ES}
0
Tariff (£/kwh)
Min
Max
SOC_{min_EV}
SOC_{max_EV}
100
SOC_t^{EV} (%)



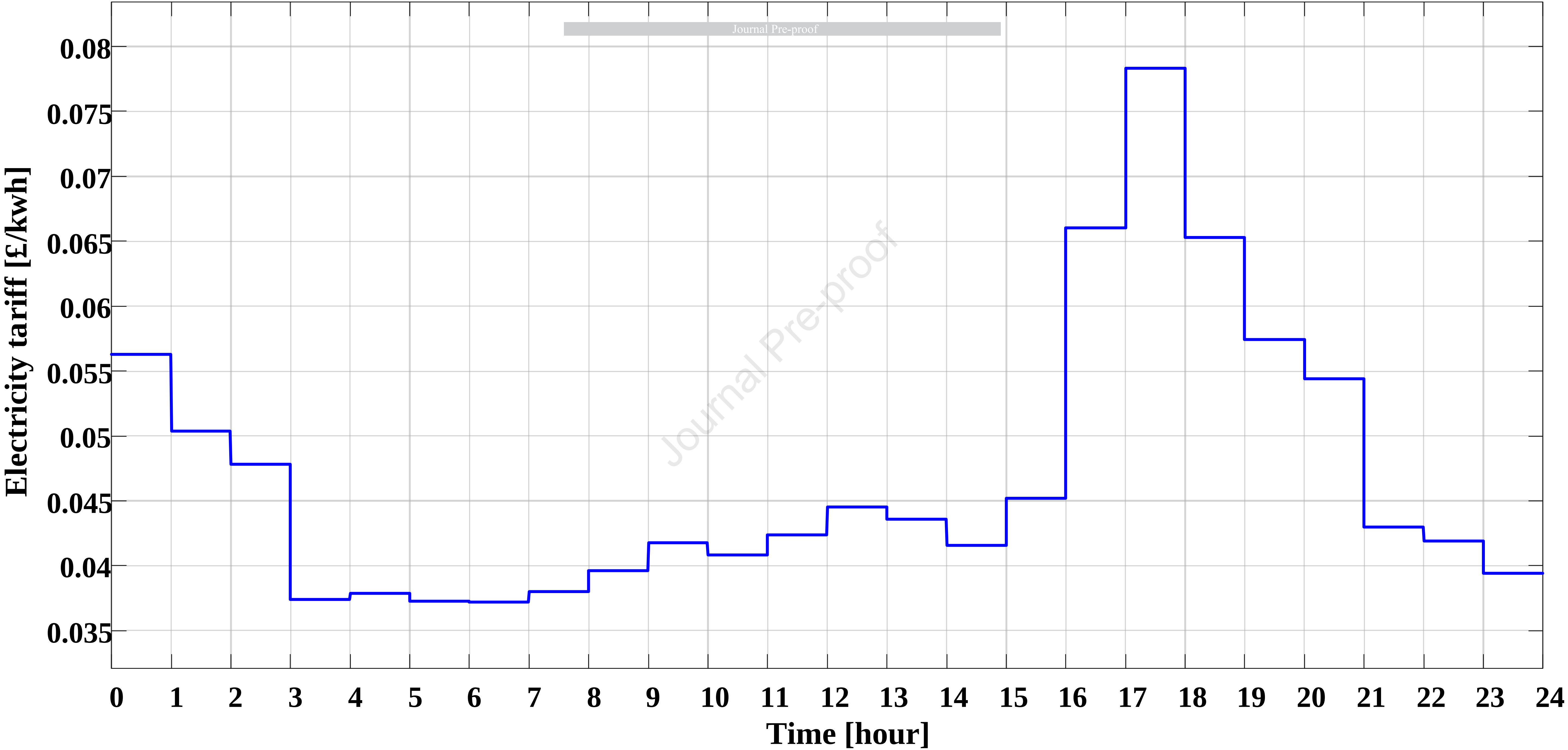
SOC_t^{ES} (%)
100
SOC_{max_ES}
SOC_{min_ES}
0
Tariff (£/kwh)
Min
Max
SOC_{min_EV}
SOC_{max_EV}
100
SOC_t^{EV} (%)



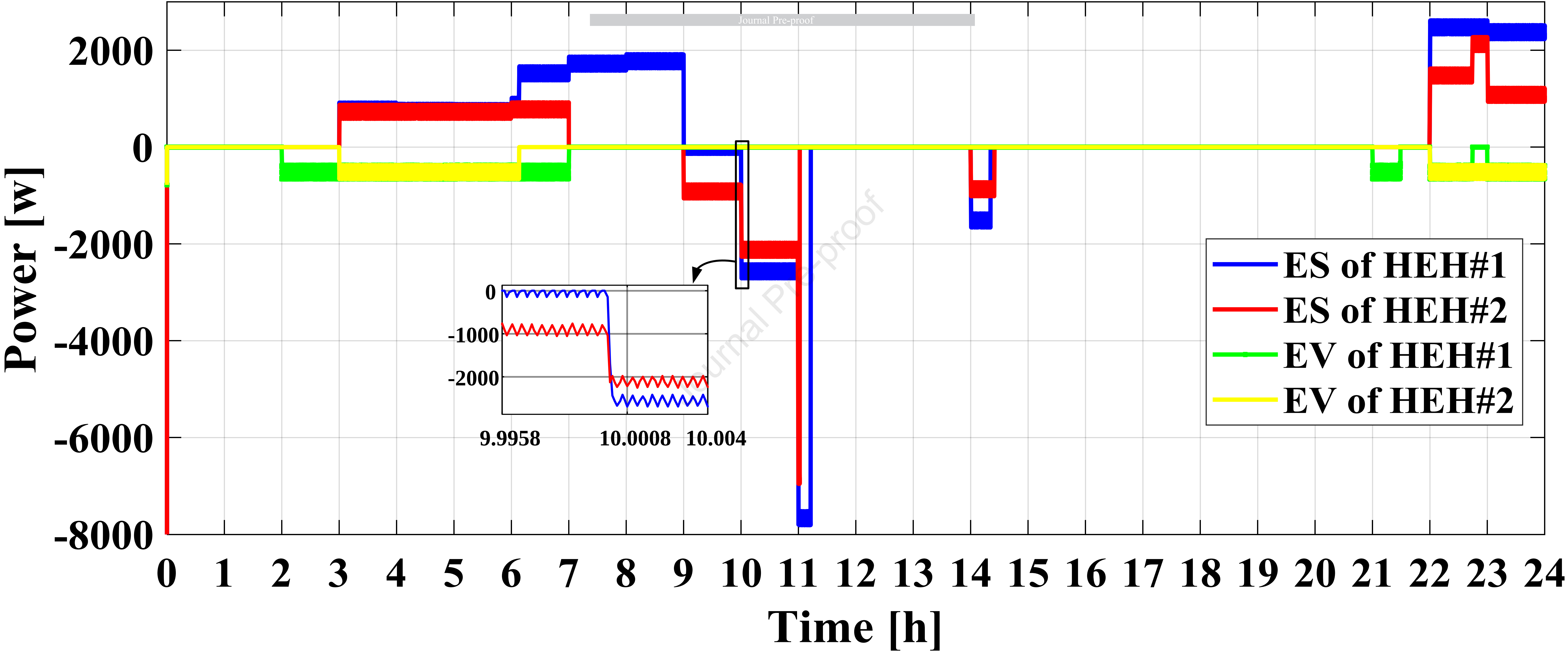
SOC_t^{ES} (%)
100
SOC_{max_ES}
SOC_{min_ES}
0
Tariff (£/kwh)
Min
Max
SOC_{min_EV}
SOC_{max_EV}
100
SOC_t^{EV} (%)

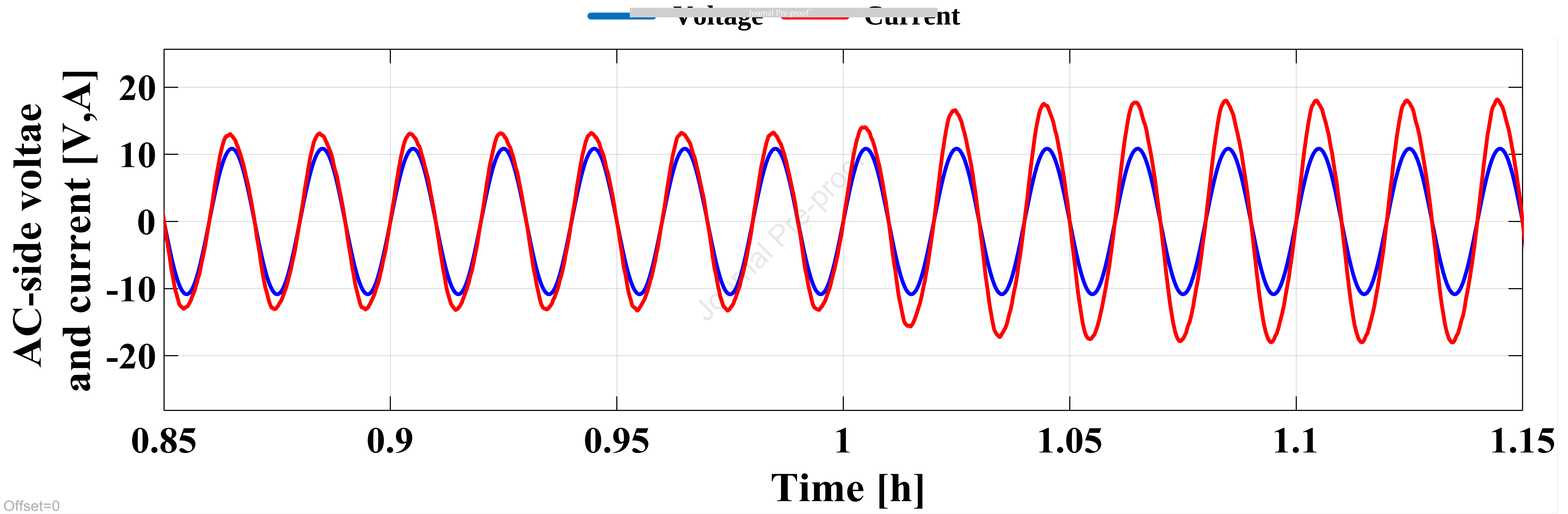


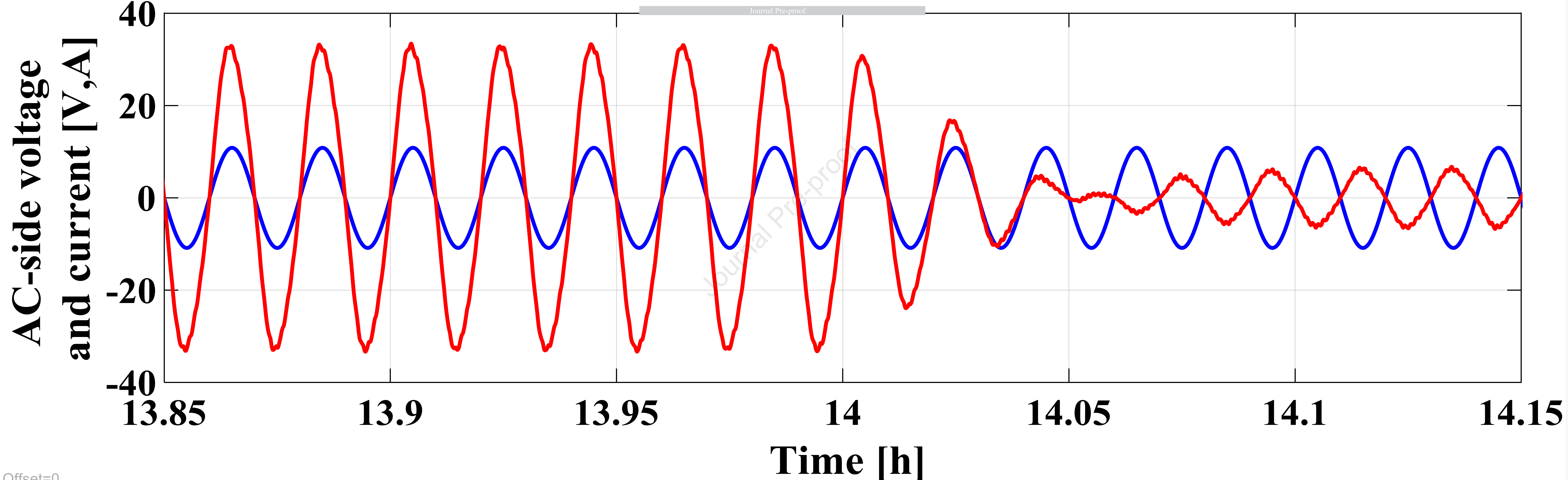
```
% The scenario detector scheme (Figure 12) has been
if (Ppv>Pload)
% Prioritizing following tasks:
•  Selling electricity into Grid
•  Charging ES and EV
else
•  Purchasing electricity from Grid
•  Charging/discharging ES
•  Charging EV
end

% Furthermore, it also decides to connect/disconnect the CHP
at the rated power.
```

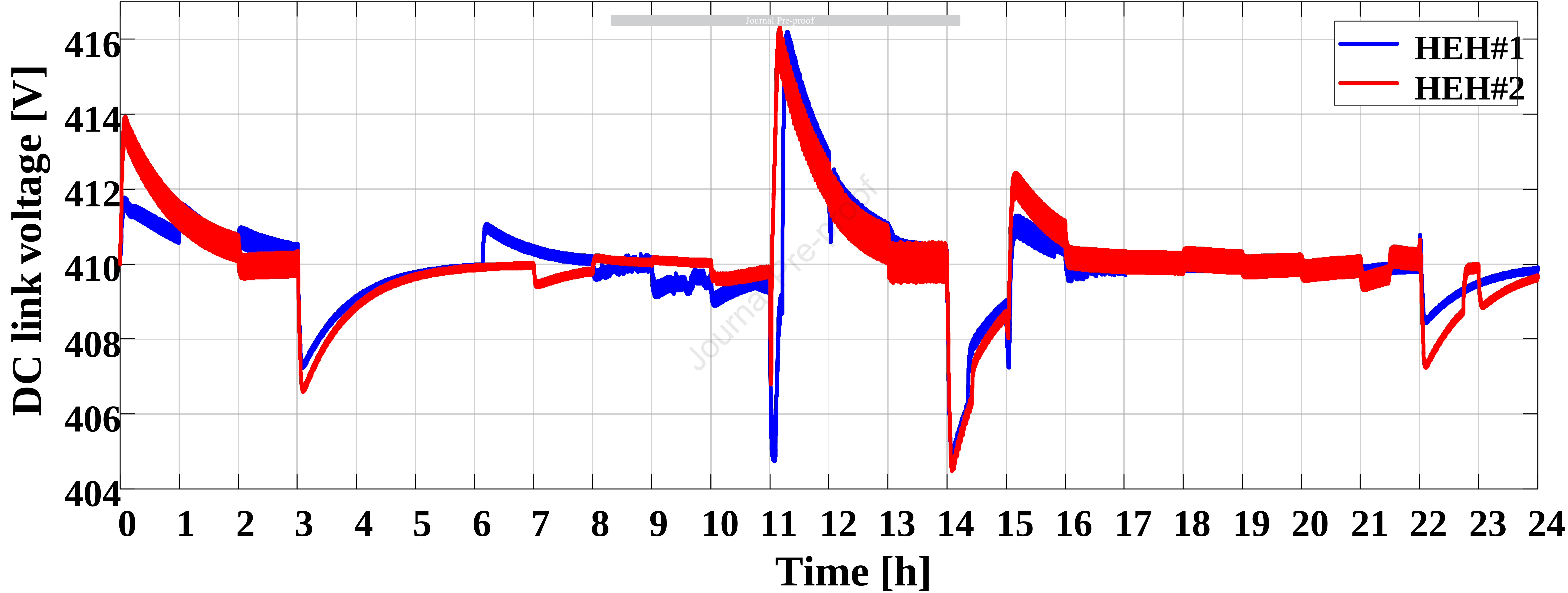

Electricity tariff [£/kwh]
0.08
0.075
0.07
0.065
0.06
0.055
0.05
0.045
0.04
0.035
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Time [hour]

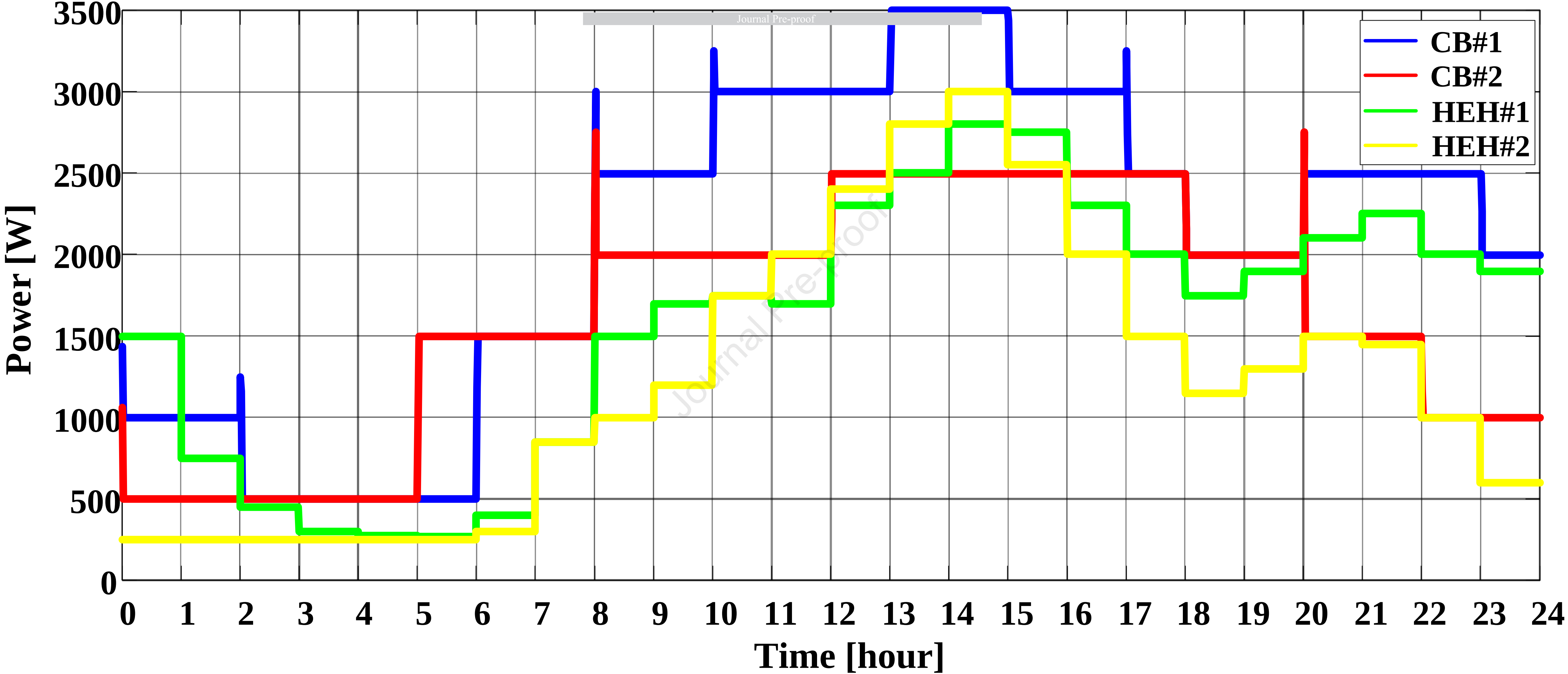

PV power of HEH#1
Reference of HEH#1
PV power of HEH#2
Reference of HEH#2
Power [W]
6000
5000
4000
3000
2000
1000
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Time [hour]

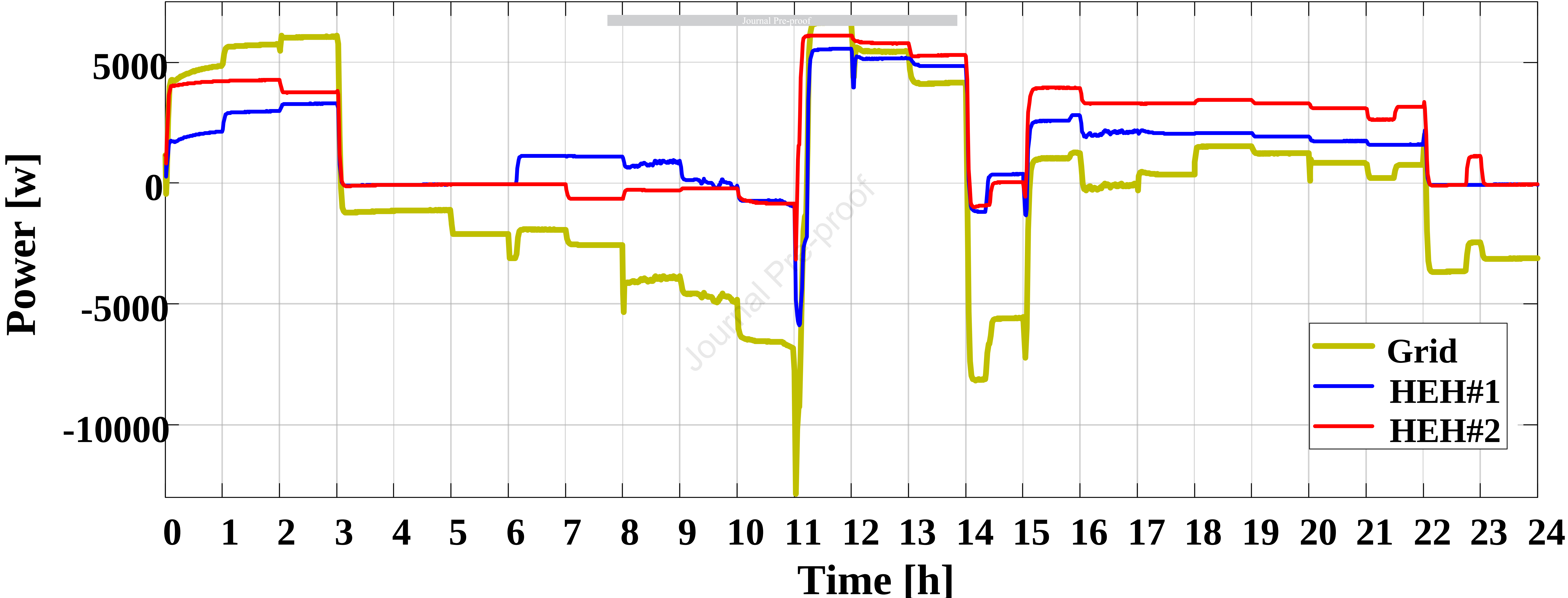

Power [w]
2000
0
-2000
-4000
-6000
-8000
Time [h]
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
ES of HEH#1
ES of HEH#2
EV of HEH#1
EV of HEH#2
0
-1000
-2000
9.9958
10.0008
10.004

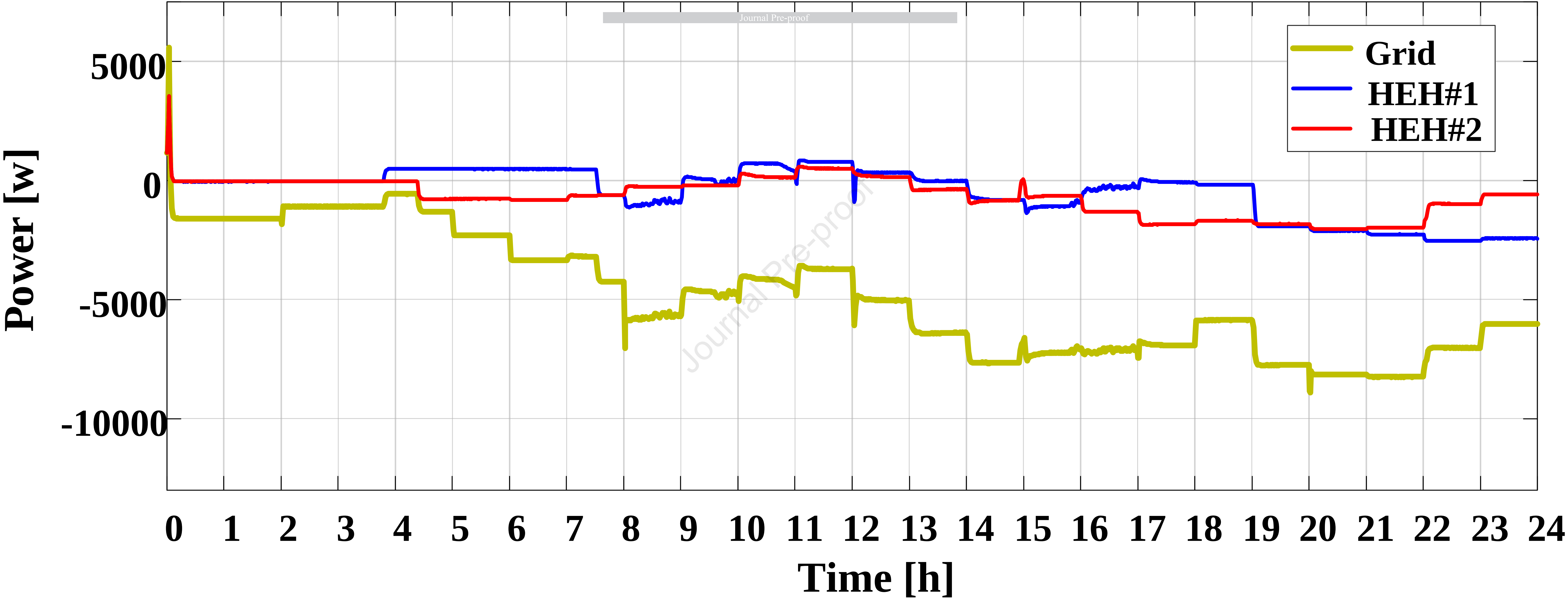

Voltage
Current
AC-side voltae
and current [V,A]
20
10
0
-10
-20
0.85
0.9
0.95
1
1.05
1.1
1.15
Time [h]
Offset=0

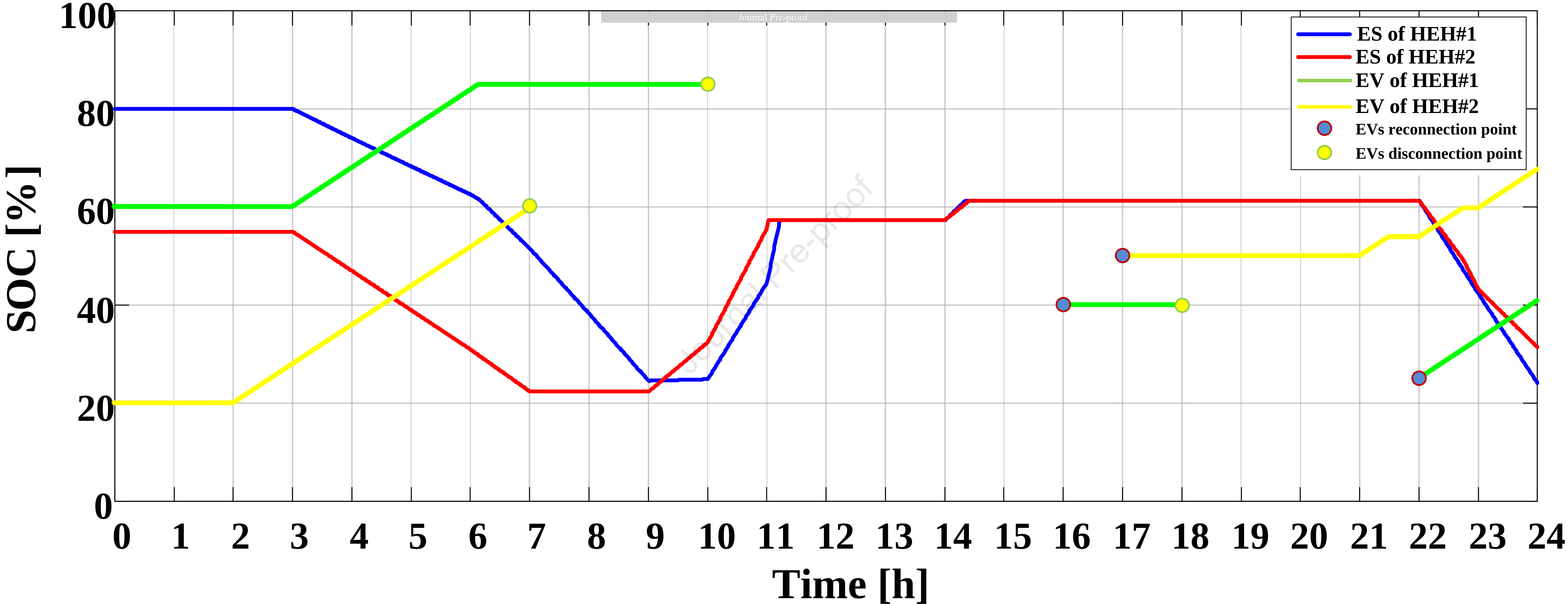

AC-side voltage
and current [V,A]
40
20
0
-20
-40
13.85
13.9
13.95
14
14.05
14.1
14.15
Time [h]
Offset=0

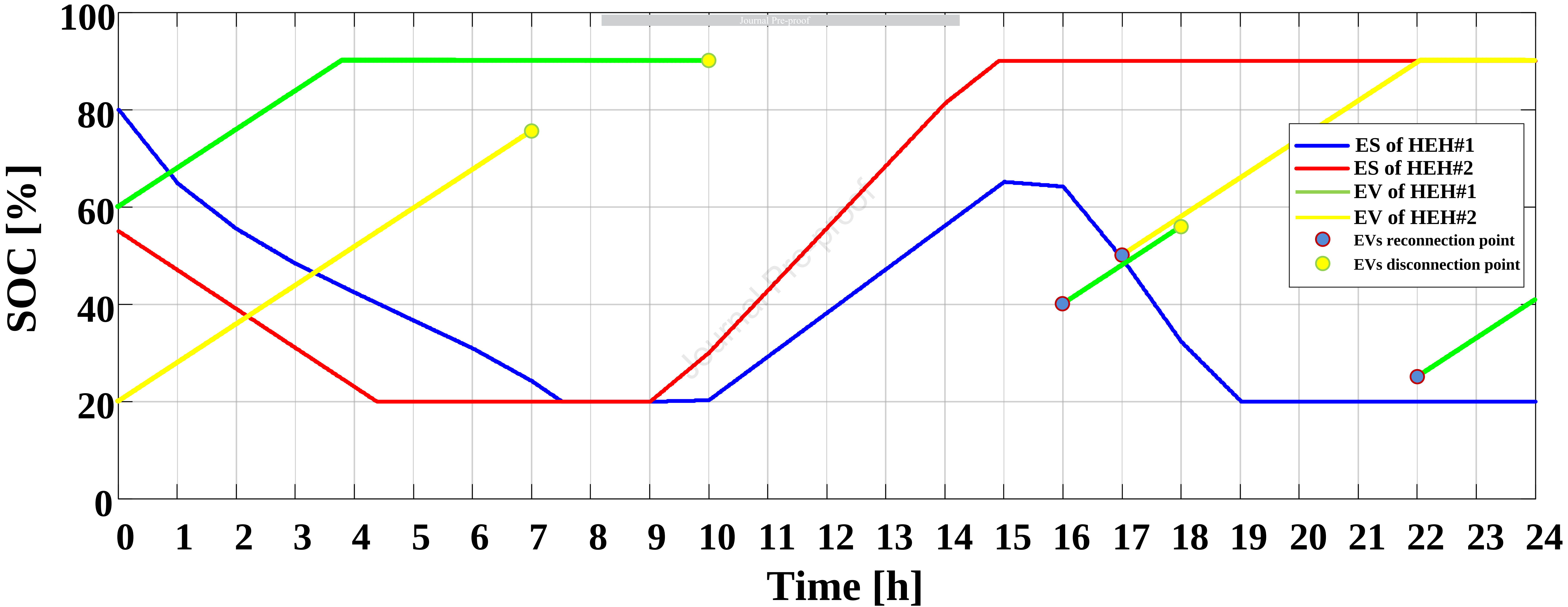

HEH#1
HEH#2
DC link voltage [V]
416
414
412
410
408
406
404
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Time [h]


3500
3000
2500
2000
1500
1000
500
0
Power [W]
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Time [hour]
CB#1
CB#2
HEH#1
HEH#2


Power [w]
5000
0
-5000
-10000
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Time [h]
Grid
HEH#1
HEH#2


Grid
HEH#1
HEH#2
Power [w]
5000
0
-5000
-10000
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Time [h]


SOC [%]
0
20
40
60
80
100
Time [h]
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
ES of HEH#1
ES of HEH#2
EV of HEH#1
EV of HEH#2
EVs reconnection point
EVs disconnection point



100
80
60
40
20
0
SOC [%]
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Time [h]
ES of HEH#1
ES of HEH#2
EV of HEH#1
EV of HEH#2
EVs reconnection point
EVs disconnection point

Highlights

- Different types of Home-Scale Energy Generators have been tried.
- A power electronic-based Hierarchical Energy Management System scheme is given.
- N-number of power converters has been switched based on the SOC-Tariff scheme.
- An energy-positive/neutral neighborhood network has been accomplished.

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