DREAM-GO

D6.1

Deliverable D6.1 – v3.0

DREAM-GO built scenarios and conclusions about the undertaken experimental tests

Deliverable

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1. Introduction

The daily increment of electricity consumption all around the world makes different concerns for all parts of society. Environmentalists are worried about the impact of high greenhouse gas emission, and electricity network operators are concerned for the unsustainable future of the power system with a low level of efficiency. Also, the lack of awareness of consumption in the demand side makes these issues more impressive. There are several solutions to overcome these barriers, such as demand-side management, Demand Response (DR) programs, and Distributed Renewable Energy Resources (DRERs). The first term (demand-side management) enables the network operator to overcome the lack of awareness of customer´s consumption/generation rate. The second term (DR programs) offers flexibility for the power system by scheduling and modifying the rate of consumption/generation, and the last term (DRERs) leads to having clean energy production as well as reducing the network congestion. The main structure of this work is illustrated in Figure 1 concerning the implementation of short and real-time DR programs.

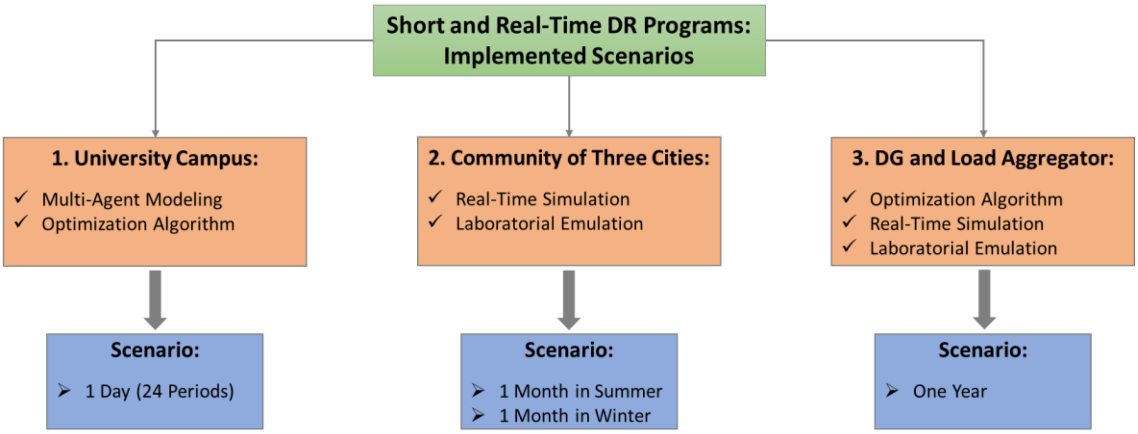


Figure 1. Implemented scenarios for short and real-time DR programs.

Additionally, Table 1 gives an overview of the implemented scenarios presented in this work.

Table 1. The detailed information regarding the implemented scenarios.

	Resources		*Modeling*				*Scenarios*
	No. Consumers	***No. Producers***	***Multi-Agent***	***Optimization Model***	***Real-Time Simulation***	***Laboratorial Emulation***	
University Campus	20	26	★	★			1 Day (24 Periods)
Community of three cities	56	8			★	★	1 Month in Winter; 1 Month in Summer
DG and Load Aggregator	100	100		★	★	★	1 Year

After providing a brief introduction in Section 1, the rest of this deliverable is organized as follows. Section 2 describes and applies a model of low voltage distribution network of a university campus with multi-agent modelling and an optimization algorithm for performing DR programs and resource scheduling. Section 3 presents a community of three cities simulated by a real-time simulator and several laboratory equipment. Section 4 describes a Distributed Generation (DG) and a load aggregator model also implemented in real-time using the emulation level. Finally, Section 5 provides the main conclusions of this deliverable.

2. University Campus

This section focuses on modelling the distribution network of a university campus in order to perform DR programs, aggregation, and resource scheduling. For this purpose, an optimization algorithm is developed for optimal management of small and medium scale DRERs and DR resources. The optimization algorithm uses clustering to define remunerations. Furthermore, a multi agent-based platform is considered in this scenario, which is utilized by the network aggregator to perform resource scheduling. Finally, the results and performance of the developed model for 24 periods (1 day) are demonstrated.

2.1. Distribution Network Model

In this section, the model of university campus´s distribution network is explained, and then, the scheduling, aggregation and remuneration process is detailed. For this purpose, a low voltage distribution network of a university campus in Porto, Portugal is considered. This network consists of 21 buses, one bus for each building, connected via underground electrical lines with a total length of 3.350 km. There is an MV/LV transformer in BUS 21, that connects the campus network to the external supplier [1]. Figure 2 shows the network architecture indicating the location of the buildings, buses, and transmission lines.

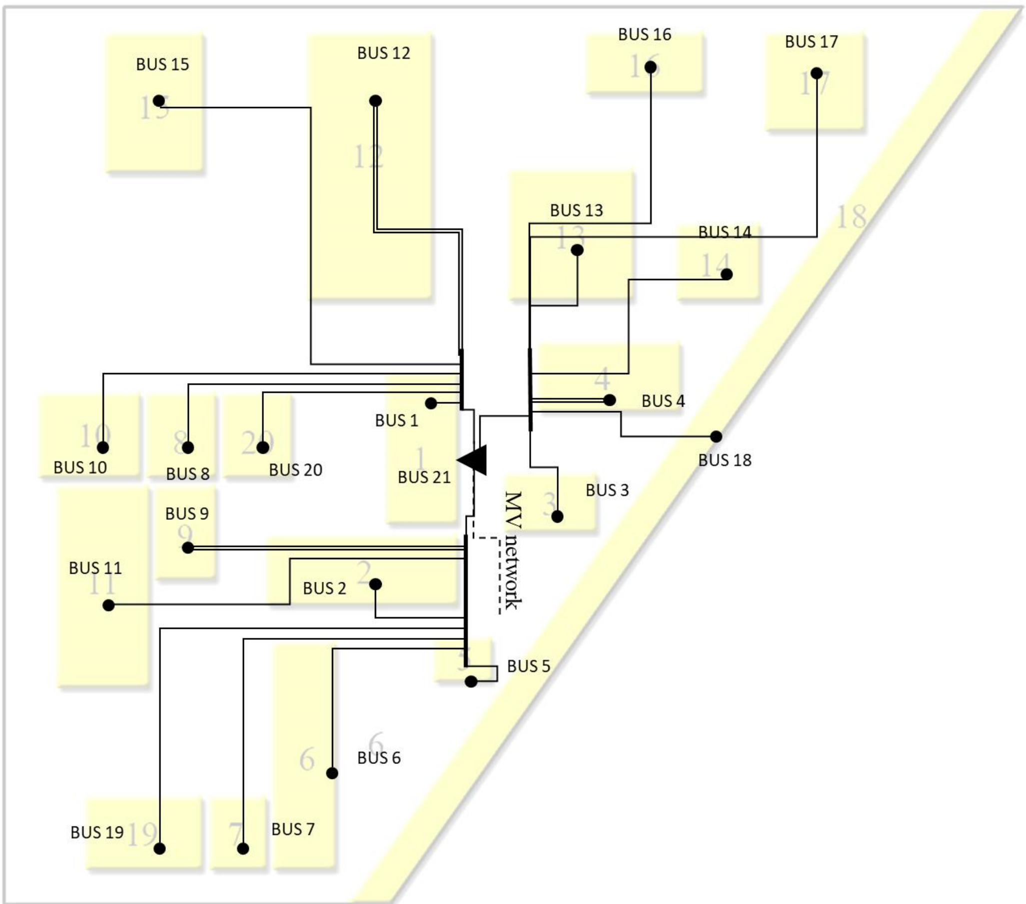


Figure 2. Internal low voltage distribution network of the university campus.[1]

In this network, we supposed that there are 20 consumers and 26 producers. The producers include 18 Photovoltaic (PV) units, 7 wind turbines, and 1 biomass with a maximum capacity of 40 kW. Also, it is considered that there is an external supplier with a capacity of 500 kW for supporting the network in the critical moments. Regarding the consumers, it is supposed that there are 10 residential houses, 2 office buildings, 5 commercial shops, 2 commercial centers, and 1 industrial unit. Figure 3 and Figure 4 show respectively the consumption and generation profiles considered for this network in different sectors. The classifications of the consumers and producers are performed based on their average daily consumption/generation rates.

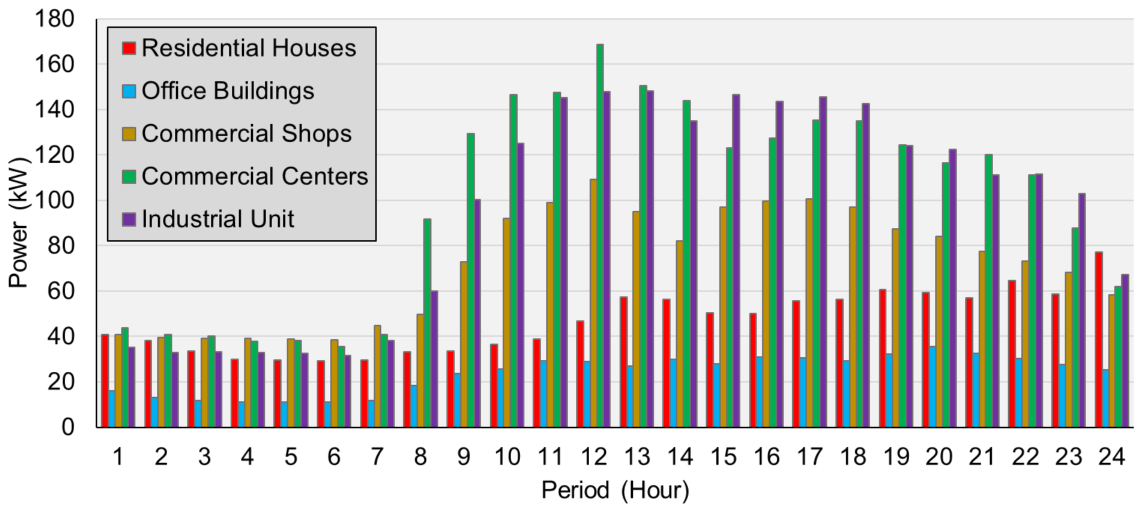


Figure 3. Consumption profile of the network for a day.

As Figure 3 shows, commercial centers and industrial unit are two sectors with a high rate of consumption during the working hours. Also, in Figure 4, since a winter day is selected, there is a low generation rate in the PV producers and high rate in the wind turbines.

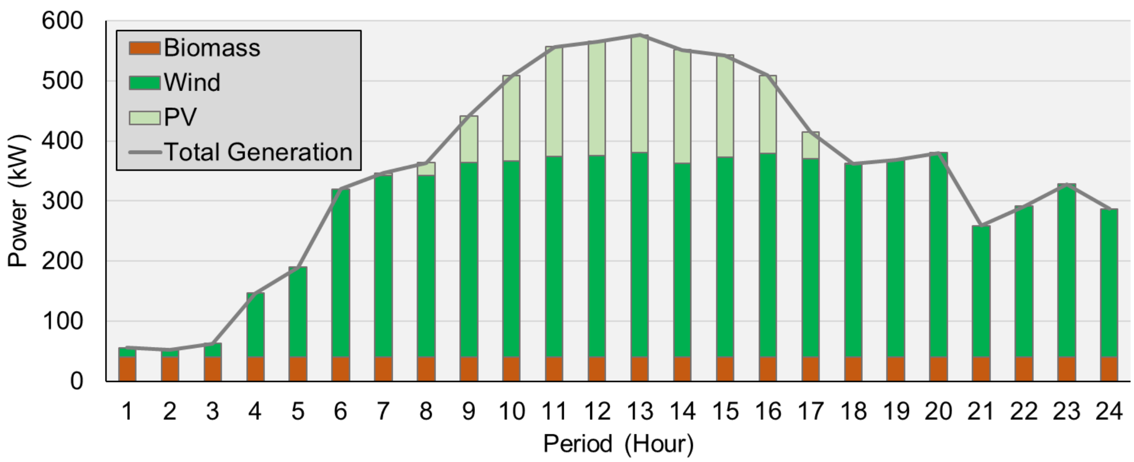


Figure 4. Generation profile of a winter day considered for the network.

Regarding the scheduling of resources, it is considered that DRERs and active consumers can participate in the scheduling process, and external suppliers support the network in critical moments. For the generation resources, the methodology considers a linear cost function for both distributed generators and external suppliers. Also, for the active consumers, it is considered that they can be enrolled in three different types of DR, including load reduction, curtailment, and load shifting. Only the load reduction and curtailment flexibilities are considered by the network operator to be scheduled and negotiate in the energy market. The cost considered is also linear for reduction and curtailment, while load shifting is free. Table 2. presents these linear costs, classified by the type of resource. In this model, 6% of the initial load is considered as the maximum reduction capacity, and 10% for load curtailment and shifting.

Table 2. Linear costs for load reduction and curtailment (m-u./kWh).

Consumers / Periods	Residential Houses	Office Buildings	Commercial Shops	Commercial Centers	Industrial Units
1	0.04	0.07	0.07	0.06	0.08
2	0.04	0.07	0.07	0.06	0.08
3	0.04	0.07	0.07	0.06	0.08
4	0.04	0.07	0.07	0.06	0.08
5	0.04	0.07	0.09	0.06	0.08
6	0.04	0.12	0.09	0.06	0.08
7	0.11	0.12	0.09	0.06	0.08
8	0.11	0.12	0.09	0.1	0.08
9	0.11	0.12	0.07	0.1	0.08
10	0.11	0.07	0.07	0.1	0.08
11	0.11	0.07	0.07	0.1	0.08
12	0.11	0.07	0.07	0.1	0.08
13	0.11	0.07	0.07	0.1	0.08
14	0.11	0.07	0.07	0.1	0.08
15	0.04	0.12	0.07	0.1	0.08
16	0.04	0.12	0.07	0.1	0.08
17	0.04	0.12	0.07	0.1	0.08
18	0.04	0.12	0.07	0.06	0.08
19	0.11	0.07	0.07	0.06	0.08
20	0.11	0.07	0.09	0.06	0.08
21	0.11	0.07	0.09	0.06	0.08
22	0.11	0.07	0.07	0.06	0.08
23	0.11	0.07	0.07	0.06	0.08
24	0.11	0.07	0.07	0.06	0.08

Aggregation of resources is made using K-Means clustering algorithm, considering the observations of the energy scheduled and the discriminated cost of that scheduling. It is important to notice that the aggregation is only made considering the resources with participation in the scheduling. If the resource is not affected by the scheduling provided by the network operator, then it is not considered in the aggregation process.

The remuneration of resources is determined after the aggregation process since the groups need to be made to define a group tariff. In this way, the resources belonging to a given group are remunerated at the same price. In this case, it is considered that the maximum price in the group is assigned as the group tariff, which will result in paying the most expensive consumers with a fair amount. Therefore, the cheapest resource is motivated to participate in the scheduling since the payment is superior to their initial suggested price. This ensures that most of the consumers are encouraged to participate in the scheduling performed by the network operator.

Each of the formed groups will represent a bid made by the network operator in the energy market (seen as a bid group), which considers the energy obtained from the resources within that group, and the respective group tariff as the minimal acceptance rate for the bidding. The energy in each group corresponds to the sum of the scheduling obtained for the distributed resources in that same group. This type of analysis facilitates the activities developed by the aggregator, namely, by providing a simple decision strategy based on the financial balance computation of its participation in the market.

2.2. Optimization Algorithm

The scheduling optimization is formulated as a Mixed-Integer Linear Problem (MILP) since it involves continuous and discrete variables. Equation (1) presents the objective function implemented for the aggregator's cost minimization. The resources considered for the objective function are: the energy bought from the external suppliers ($P_{(s,t)}^{Sup}$), the obtained energy from the DG ($P_{(p,t)}^{DG}$), and the demand flexibility (reduction - $P_{(c,t)}^{Red}$, curtailment - $P_{(c,t)}^{Cut}$, and shifting - $P_{(c,t,d)}^{Shift}$)

$$MinOC = \sum_{s=1}^{S} P_{(s,t)}^{Sup} \cdot C_{(s,t)}^{Sup} + \sum_{p=1}^{P} P_{(p,t)}^{DG} \cdot C_{(p,t)}^{DG} + \sum_{c=1}^{Cs} \left[\begin{array}{l} P_{(c,t)}^{Red} \cdot C_{(c,t)}^{Red} + P_{(c,t)}^{Cut} \cdot C_{(c,t)}^{Cut} \\ + \sum_{d=1}^{T} P_{(c,t,d)}^{Shift} \cdot C_{(c,t,d)}^{Shift} \end{array} \right] \quad \forall t \in \{1,...,T\} \tag{1}$$

The constraints of the proposed optimization problem consist of:

- The energy balance to assure the consumers are supplied according to their consumption needs:

$$\sum_{c=1}^{Cs} \left[\begin{array}{l} P_{(c,t)}^{Load} - P_{(c,t)}^{Red} - P_{(c,t)}^{Cut} \\ - \sum_{d=1}^{T} \left(P_{(c,t,d)}^{Shift} - P_{(c,d,t)}^{Shift} \right) \end{array} \right] - \sum_{s=1}^{S} P_{(s,t)}^{Sup} - \sum_{p=1}^{P} P_{(p,t)}^{DG} = 0 \qquad \forall t \in \{1,...,T\} \tag{2}$$

- Technical generation limits of the external suppliers and distributed generators:

$$P_{(s,t)}^{Sup\min} \le P_{(s,t)}^{Sup} \le P_{(s,t)}^{Sup\max} \quad \forall s \in \{1,...,S\}, \forall t \in \{1,...,T\} \tag{3}$$

$$P_{(p,t)}^{DG\min} \leq P_{(p,t)}^{DG} \leq P_{(p,t)}^{DG\max} \quad (4)$$
$$\forall p \in \{1,...,P\}, \forall t \in \{1,...,T\}$$

- Technical limitations of DR programs:

$$P_{(c,t)}^{Red\min} \leq P_{(c,t)}^{Red} \leq P_{(c,t)}^{Red\max} \quad (5)$$

$$P_{(c,t)}^{Cut\min} \leq P_{(c,t)}^{Cut} \leq P_{(c,t)}^{Cut\max} \quad (6)$$

$$P_{(c,t)}^{Cut} = P_{(c,t)}^{Cut\max} \cdot X_{(c,t)}^{Cut}$$
$$X_{(c,t)}^{Cut} \in \{0,1\} \quad (7)$$
$$\forall c \in \{1,...,C\}, \forall t \in \{1,...,T\}$$

- Limitations regarding the maximum amount of energy shifted out and into a given period:

$$P_{(c,t,d)}^{Shift\min} \leq P_{(c,t,d)}^{Shift} \leq P_{(c,t,d)}^{Shift\max} \quad (8)$$

- The maximum price of the resources belonging to each group:

$$\sum_{d=1}^{T} P_{(c,t,d)}^{Shift} \leq P_{(c,t)}^{Shift\_out} \quad (9)$$

$$\sum_{d=1}^{T} P_{(c,d,t)}^{Shift} \leq P_{(c,t)}^{Shift\_in} \quad (10)$$
$$\forall c \in \{1,...,C\}, \forall t,d \in \{1,...,T\}$$

Therefore, the key components of the proposed methodology, regarding the scheduling and remuneration of resources managed by the aggregator have been presented. In the next section, it is detailed the case study used to validate the presented methodology

2.3. Multi-Agent Platform

This section describes a multi-agent platform that is employed by the network operator in order to perform the resource scheduling process. The system integrates an energy resource management (ERM) platform that is used as an optimization tool for management of the distributed energy resources in the network. The ERM platform is a part of Multi-Agent Smart Grid Simulation Platform (MASGriP) developed by GECAD for simulating the operation of the smart grids and microgrid and survey the performance of them [2][3]. In the ERM, all type of energy resources, such as DGs and DR resources, electric vehicles, energy storage systems, can be considered. Also, it supports the negotiations with other markets and external suppliers. Figure 5 illustrates the architecture of the ERM platform, which is a part of MASGriP.

The ERM performs the scheduling in three levels: day-ahead, hour-ahead, and real-time. In the first level, the ERM executes the day-ahead resources scheduling by relying on the day-ahead forecast for each resource. In the hour-ahead, all generation and consumption resources would be forecasted for each period (one hour), and then, all the resources affected by the hour-ahead scheduling are managed based on the day-ahead scheduling results as well as the results of previous hour´s scheduling. In the real-time scheduling, the resources are optimized and updated for the next five minutes. After the real-time forecasts, the optimal scheduling process is performed for the next five minutes by relying on the hour-ahead forecasted results, the results of the previous five minutes schedule, and the forecasted values from the following 5 periods of five minutes.

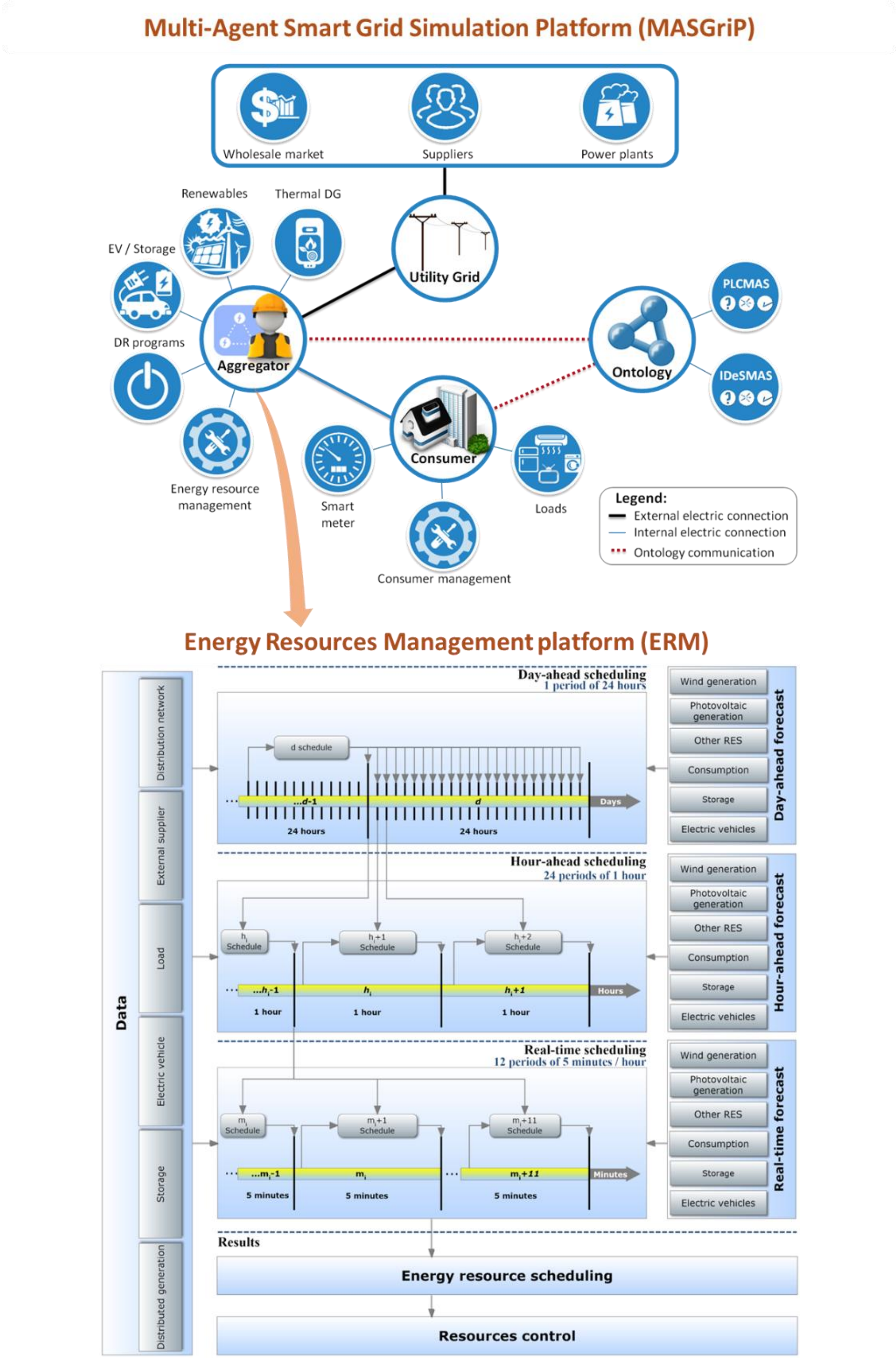


Figure 5. The multi-agent platform used by aggregator for resources scheduling [3].

Through the ERM platform, the network operator is able to optimally schedule the resources to minimize the operational costs and gain more profits by selling energy with the external suppliers.

2.4. Scenarios and Results

In this section, the results and the performance of the network model and scheduling process is surveyed. The results of market negotiations are also presented to observe the performance of the network operator while intending to present a bid. In this scenario, it is considered that the university network faces an energy shortage from the external suppliers in the first four periods being able to support only 10% of the capacity, which is around 50 kW. Therefore, the network operator should execute the scheduling process. Figure 6 shows the results of resource scheduling of the network for 24 hours.

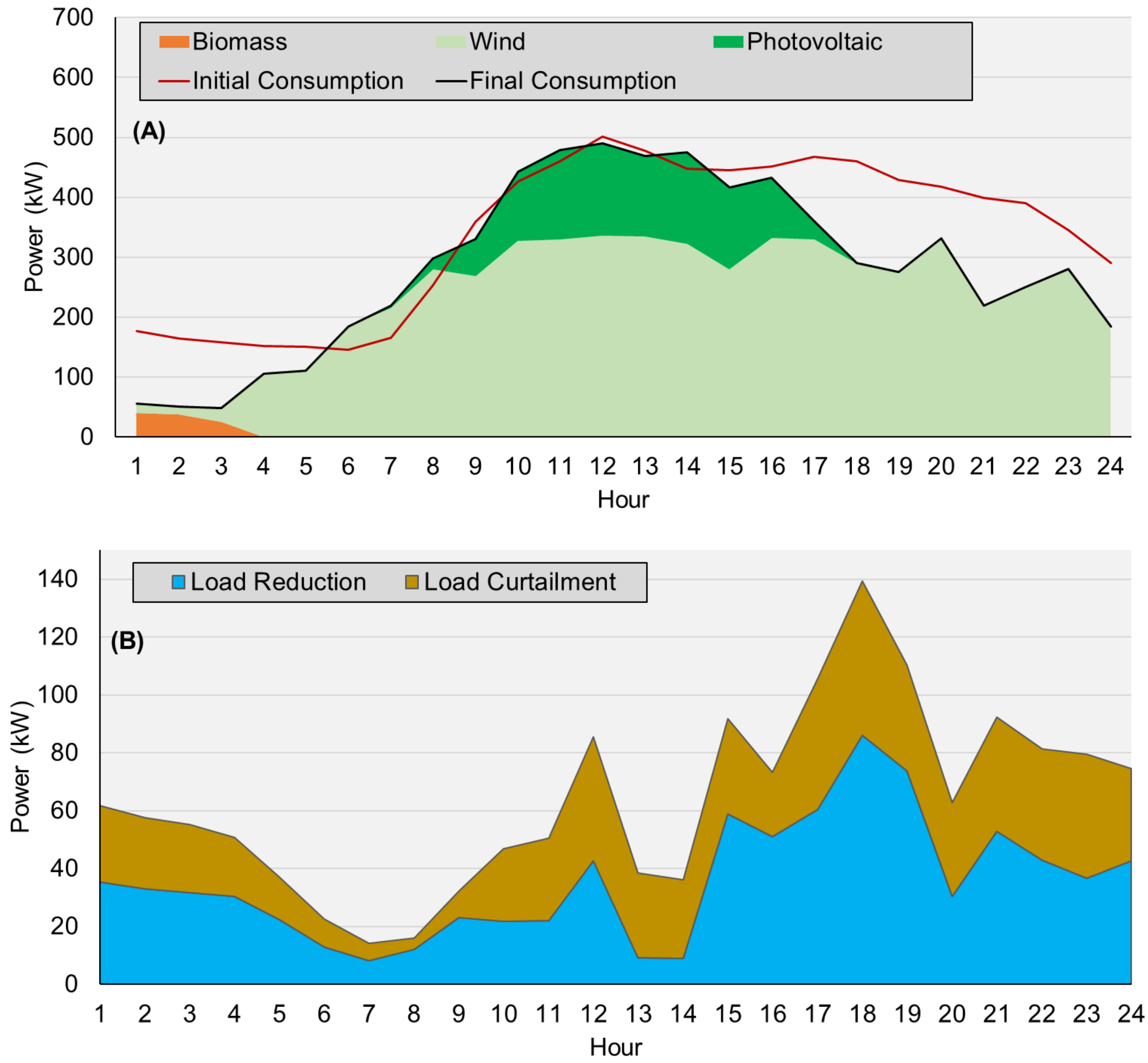


Figure 6. Resources scheduling results; (A) Consumption and production, (B) DR.

While the network has an energy shortage, the operator applies for DR programs in order to balance the rate of consumption and generation. The high penetration of renewable resources is obvious in Figure 6, which validates the performance of the scheduling process since the costs of DGs is lower comparing to the external supplier. Furthermore, the differences of the initial consumption and final consumption profiles shown in Figure 6-A, are related to the DR implementation, such as load reduction and load curtailment, as Figure 6-B demonstrates. Moreover, during the periods of energy shortage from an external supplier, while all the resources were used with full capacity, the rest of demand has been supplied by the biomass, which is cheaper compared to purchasing energy from the external supplier.

Regarding the market bidding results, Table 3 shows the outcomes of optimization for the aggregation and remuneration of the resources for a randomly selected period (period #12). In fact, the minimum bid tariff is from the remuneration process, while the total energy and the number of resources is the result of the aggregation process.

Table 3. Aggregation and remuneration results of one period.

Bid group	1	2	3	4	5
Energy in DR groups (kWh)	6,09	9,49	4,04	17,18	3,55
Number of DR resources	1	1	1	2	1
Group tariff (m.u./kWh)	0,05	0,05	0,05	0,05	0,05
Energy in DG groups (kWh)	30,73	250,58	16,02	37,72	114,21
Number of DG resources	2	3	4	2	7
Group tariff (m.u./kWh)	0,03	0,05	0,06	0,03	0,05
Total Energy	**489,62**				

Further on, a comparison is made regarding the influence of load shifting in the costs. The comparison is made between the total costs of the aggregator in the current scenario (with shifting - WS), and in one when instead of load shifting availability, there is enough energy available from the external suppliers (without shifting - WOS). In Table 4, the results of the scenarios comparison show that the influence of load shifting availability affects considerably the total costs of the aggregator since these are mostly balanced by the contributions that distributed generators and external suppliers provide for the scheduling. In the scenario without load shifting the energy imported from external suppliers is raised in 50 kW in the first four periods, obtaining a total of 100 kW. This is performed so energy balance can be obtained without load shifting.

Table 4. Cost comparison with and without load shifting.

Scenario		Value (m.u.)	Total (m.u.)
WS	Total costs using distributed resources	286,41	286,41
	Total costs using external suppliers	0	
WOS	Total costs using distributed resources	279,87	300,27
	Total costs using external suppliers	20,40	

The calculations and results shown on the above tables are for a single period with a limited number of consumers and producers. More resources in a longer period of time, enable the aggregator to gain more financial profits. However, the profitability of the aggregator is dependent on the offers and capability of negotiations in the market.

In summary, the results demonstrated in this section proved that the aggregator can perform the scheduling according to the resources contribution, that has been applied through different programs such as demand-side resources. Therefore, the aggregator is able to perform network balance and the participation of each resource. Moreover, the aggregation and remuneration results proved that the developed methodology affect the outcome of benefit for the aggregator. However, the aggregator can obtain the operation balance and fair usage of distributed energy resources for its activities by using this methodology.

3. Community of Three Cities

This section describes the second implemented scenario in the scope of this deliverable. This scenario focuses on a community of three cities including various types of consumers and producers. The developed community model is validated in two levels:

- Real-Time Simulation: developing a MATLAB/Simulink model for the community and executing and obtaining the results in real-time;
- Laboratory Emulation: Test and validate the model through the laboratory consumption and generation resources.

Therefore, the community model and the details regarding the community players are presented first. Then, the real-time simulation and emulation models implemented in real-time simulator machine (OP5600) are demonstrated. Finally, the results obtained from the simulation and emulation are presented in order to survey and validate the performance of the model.

3.1. Community Model

The community model presented in this work is referred to a group of consumers and producers that have an agreement with a management entity, such as community manager. The community manager is able to manage, control, and organize the community player´s consumption and generation rate. The community can be considered as an aggregator; however, the main difference is aggregator is profit-based with lots of players and the community is interest-based with a few numbers of players. Figure 7 shows an overview of the community model presented in this work.

Figure 7. The community model of three cities.

As Figure 7 shows, the community model contains three cities, where each city has a local controller connected to the main community manager. In this model, the community manager is not owning any resources of the network. In fact, it is only responsible for managing the rate of consumption and generation in the players to maintain the network balance. Also, the community manager can offer some strategic network plans, such as DR programs and resources scheduling, for minimizing its operational costs. In other words, the community manager always tends to supply its electricity demand from the internal and local energy resources since the external suppliers usually sell electricity to the community with a higher rate of price. Therefore, it is affordable for the community manager to firstly supply the demand from the local resources, and secondly, apply DR programs to the members to reduce the rate of consumption, comparing to purchasing energy from the external suppliers.

As it was mentioned above, there are three cities in the community grid:

- **City 1**: 27 consumers including 23 residential buildings and 4 public buildings equipped with 4 PV installations;
- **City 2**: 16 consumers including 12 residential buildings and 4 public buildings equipped with 4 PV installation;
- **City 3:** 13 consumers including 13 residential buildings.

Therefore, there are 56 consumers and 8 PV installations in the community in total. All community members should transmit the rate of consumption/generation to the local manager and community manager as well, which enables the community to have management and forecast for consumption and generation. In this network, all PV producers are accountable to produce electricity and provide it to the community network and in exchange, they will receive payments from the community manager based on the tariffs mentioned in the agreements. Also, the consumers should be able to participate in the DR programs and reduce or shift their consumption, and in exchange, they will receive incentive payments based on the agreements.

3.2. Real-Time Simulation and Emulation

This section describes the real-time simulation model developed for the three cities of the community. The model has been designed using MATLAB/Simulink tools and is executed in real-time capable to control and manage the real hardware resources outside of the simulation environment. In other words, the real-time simulation model integrates the emulation and simulation results in a unique model that can be used for the management and control scenarios, such as DR programs and resources scheduling. The integration of emulation and simulation results enable the system to have more reliable results to verify the business models and prevent future problems.

The model developed in this section contains two main subsystems:

- Computational subsystem: including all mathematical and logistical Simulink blocks and computations;

- Interface subsystem: including all monitoring and controlling blocks enabling the user to control the model through this subsystem.

Figure 8 to Figure 10 show the main bodies of the Simulink model placed in the Computational subsystem for the three cities. As can be seen in these figures, all consumers are modeled by a three-phase dynamic load model, where all of them are connected and supplied by a three-phase source model. Furthermore, there are several three-phase series RLC branch blocks simulating the impedance of each line in the network. By this way, the model can provide the most accurate and near to real results.

All residential consumers in three cities are indicated by dark green color, as shown in Figure 8 to Figure 10, and all public buildings are shown by red. Also, the PV installation in each public building is demonstrated by light green. While this model is embedded in the real-time simulator (OP5600), the user has no access to the computational subsystem when the model is running in real-time. In order to control the model in real-time mode, the Interface subsystem is provided to the user through a host PC connected to the OP5600 machine via Ethernet. Therefore, the user is able to control and manage the model through the Interface subsystem.

In the Interface subsystem, there are three main sections specified for each city, as Figure 11 shows. By clicking on each city on this subsystem, a set of controlling and monitoring blocks appears to control consumers or PV producers. As an example, on the right side of Figure 11, there are controlling and monitoring blocks for a public building, 2 residential buildings, and a PV installation in City 2. These sets of blocks are available in the Interface subsystem for all consumers and producers in all three cities.

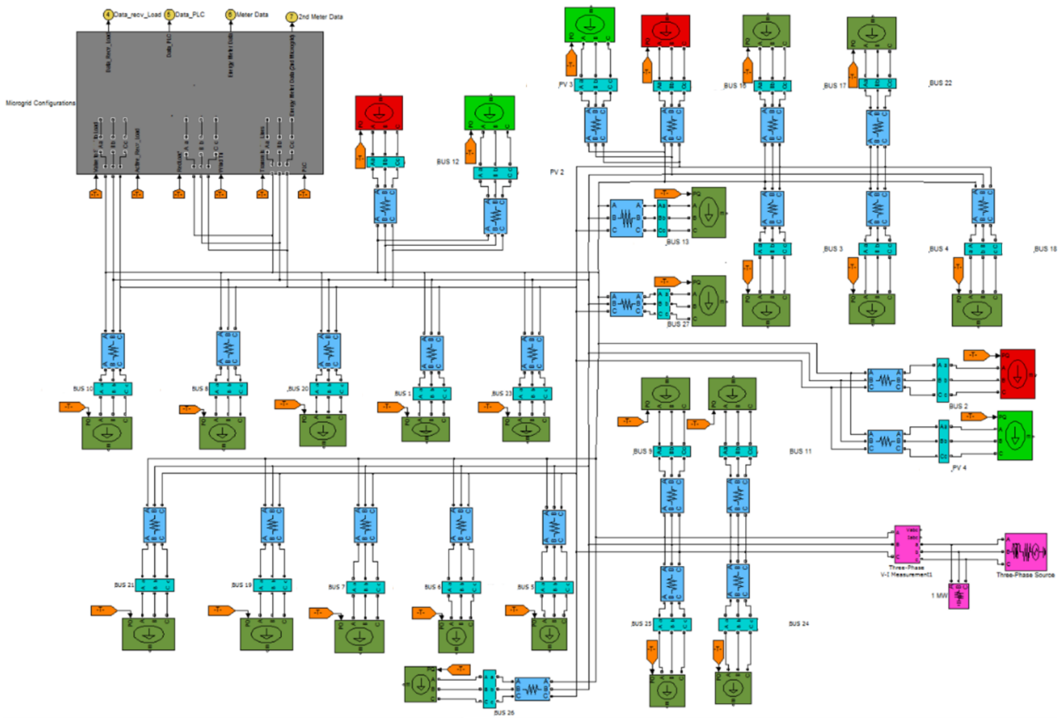


Figure 8. Simulink model of network in City 1 for 27 consumers and 4 producers.

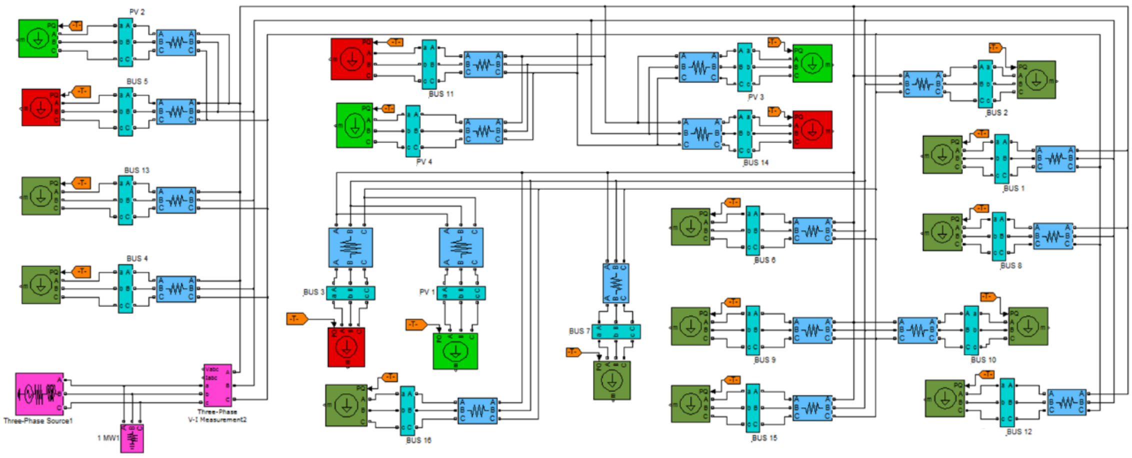


Figure 9. Simulink model of City 2 including 16 consumers and 4 producers.

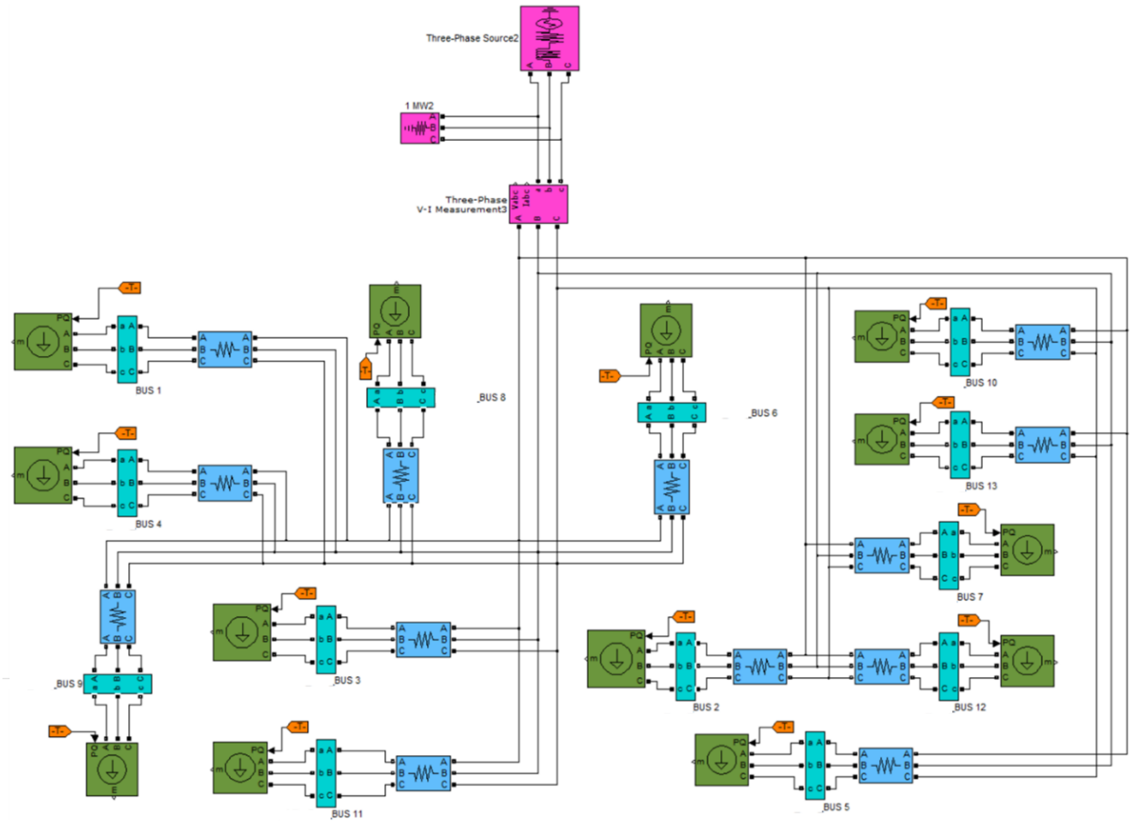


Figure 10. Simulink model of City 3, including 13 consumers.

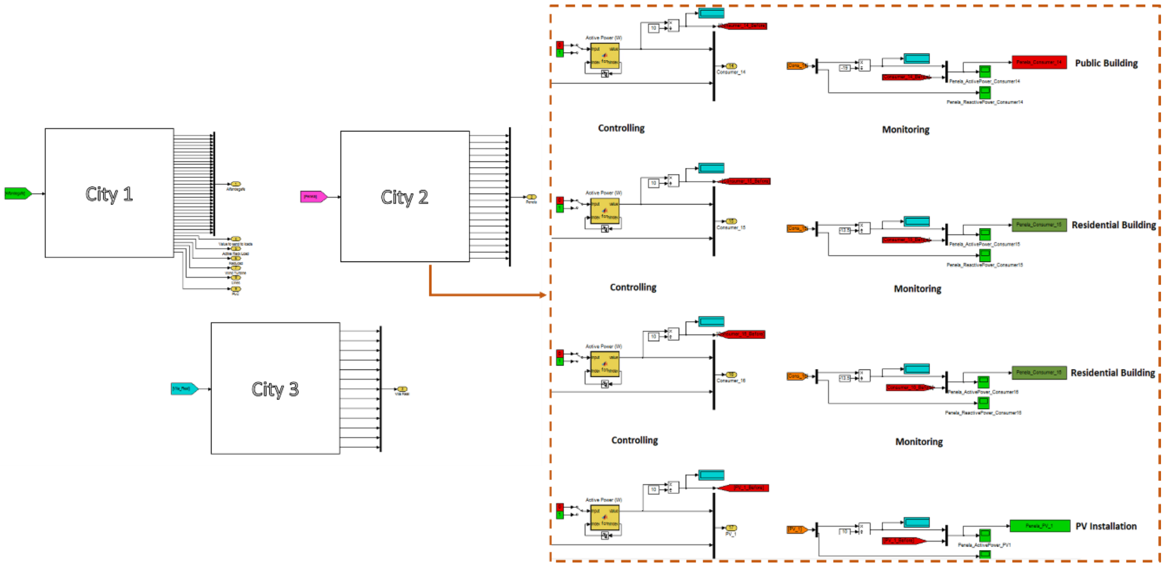


Figure 11. User interface subsystem of Simulink model for controlling and monitoring.

The most important part of the developed model is to integrate the real laboratory equipment to controlling and monitoring with this Simulink model. For this purpose, three network players of the City 1 are dedicated for this Hardware-In-the-Loop (HIL) implementation. The gray block in Figure 8 is related to the HIL configuration.

The developed HIL model to be integrated into this model is composed by four laboratory equipment, including:

- Consumer resources: 2 output sockets to be connected to two laboratory load banks;
- Producer resources: one three-phase and one single-phase PV Emulator.

In addition, several energy meters are employed in this model to transmit the real-time consumption/generation of the HIL devices.

Regarding the two consumer resources, there is a 30 kW load bank, and 4 kVA load bank considered as two HIL consumer devices in the model. In the 30 kW load, there are four relays that increase or decrease the rate consumption, and in 4 kVA load, there is an Arduino® (www.arduino.cc), which manages the amount of consumption. The relays in 30 kW load are connected to Digital Output board of OP5600, and Arduino® has been connected to OP5600 via Ethernet interface, with MODBUS TCP/IP protocol. Since the main focus of this work is not on the hardware configuration, only the most relevant information is mentioned, and more detailed explanation about these resources is available in [4], [5], [6]. Figure 12 illustrates the Simulink model, which OP5600 uses for controlling these consumer resources via HIL.

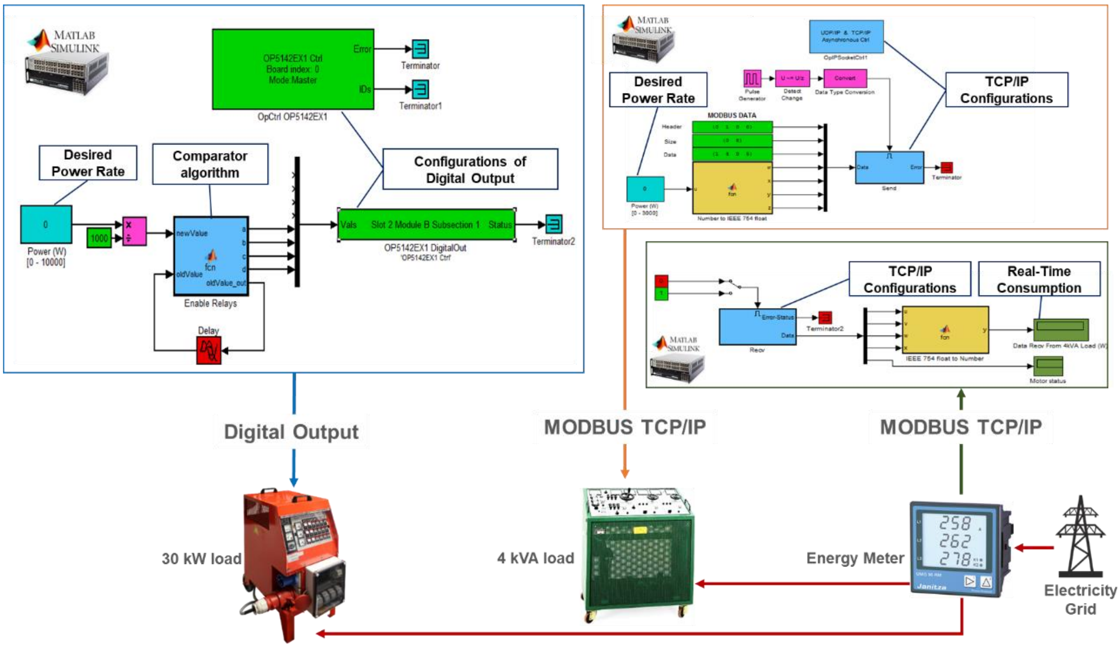


Figure 12. The Simulink HIL model for consumer resources in City 1.

As Figure 12 shows, two Constant blocks in Simulink indicate the desired consumption that OP5600 tends to be consumed by 30 kW and 4 kVA loads. In the case of 30 kW load, the output of Constant block will be divided into the four binary outputs through a comparator algorithm to be provided to the Digital Output board. In the case of 4 kVA load, the output of the Constant block will be converted to MODBUS TCP/IP format with IEEE 754 standard, which is four hexadecimal numbers. Furthermore, there is an energy meter for these two loads, which measures the consumed active power and transmit it to OP5600 in real-time via MODUS TCP/IP. By this way, OP5600 is able to transmit the favorable amount of power to the loads and simultaneously receive the real-time consumption of them.

Regarding the producer resources, two PV emulators are used, which in principle the Simulink model and HIL methodology are the same for both emulators. Therefore, in this work, only one of them is described. The only difference between these two emulators is the internal electrical configurations, which one is three-phase, and the other is single-phase. The nominal capacity of these two emulators is rated as 10 kW. In order to control these producer resources from OP5600, an Arduino® has been utilized in the DC power supply in order to manage the output power between 0-100% of capacity. In fact, the DC power source simulates the PV arrays, which provides DC power, and DC/AC inverter is a usual model that is utilized in real PV installations. The Simulink model for controlling and monitoring these emulators is shown in Figure 13. In this model, two groups of TCP/IP blocks have been employed, one for DC power source (Arduino®), and the other for DC/AC inverter. By this way, OP5600 transmits the desired value of PV generation to Arduino via a MODBUS TCP/IP request and receives the real-time AC power generation from the DC/AC inverter.

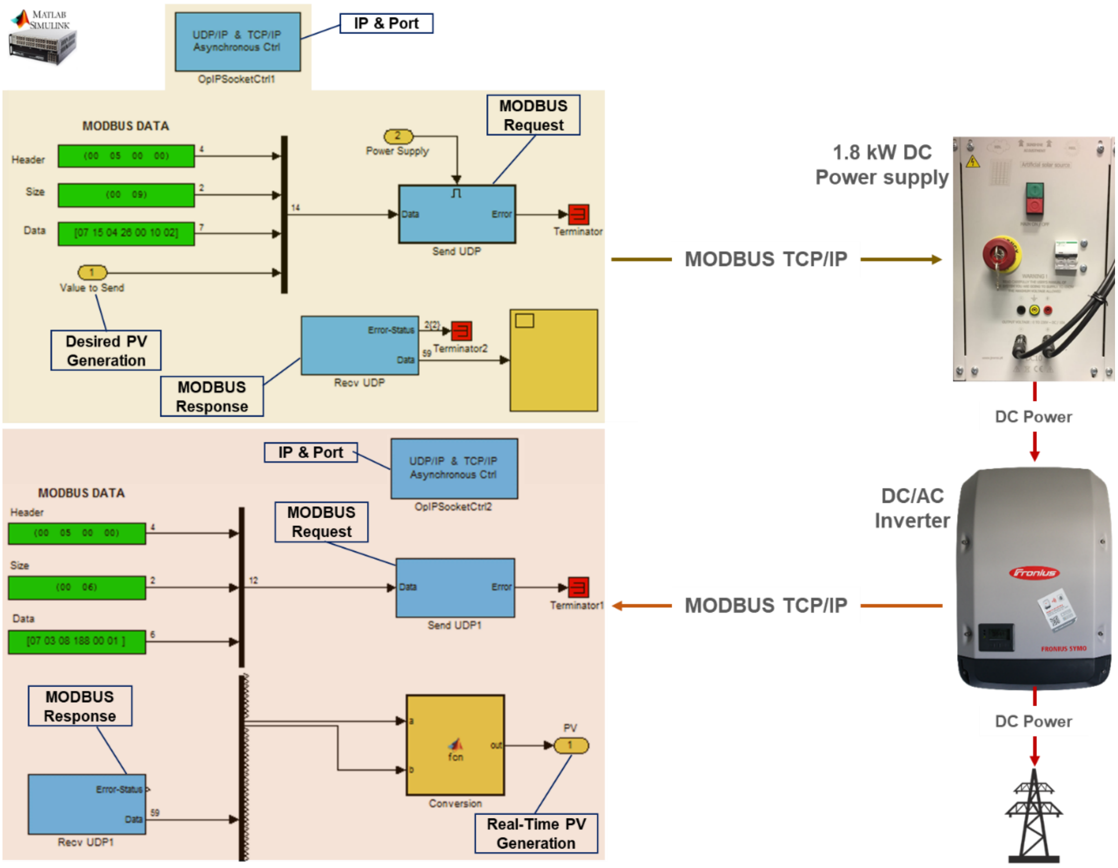


Figure 13. The Simulink HIL model for PV emulators.

The Simulink models shown in Figure 12 and Figure 13. are embedded on the gray block presented on Figure 8, which stands for the HIL configuration. However, since the computational subsystem is not available during the real-time simulation, a user interface has been designed and placed in the Interface subsystem, as Figure 14, illustrates.

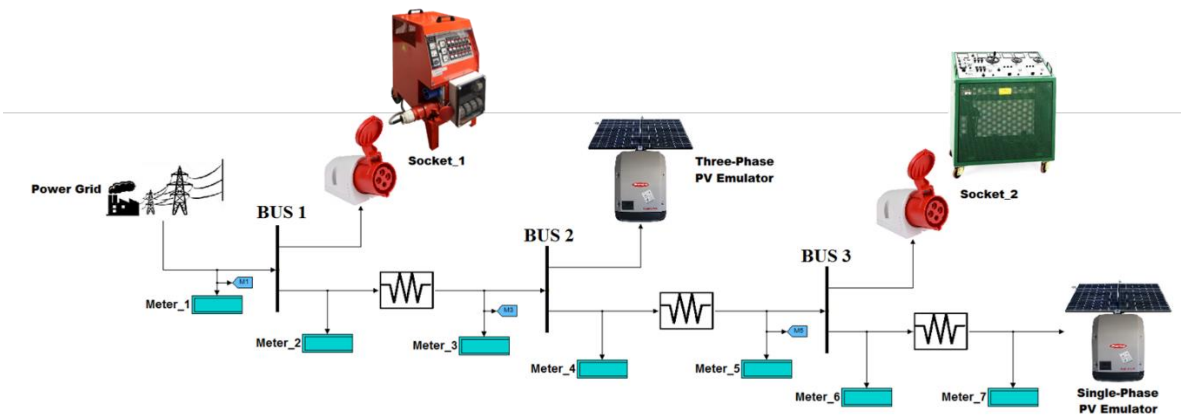
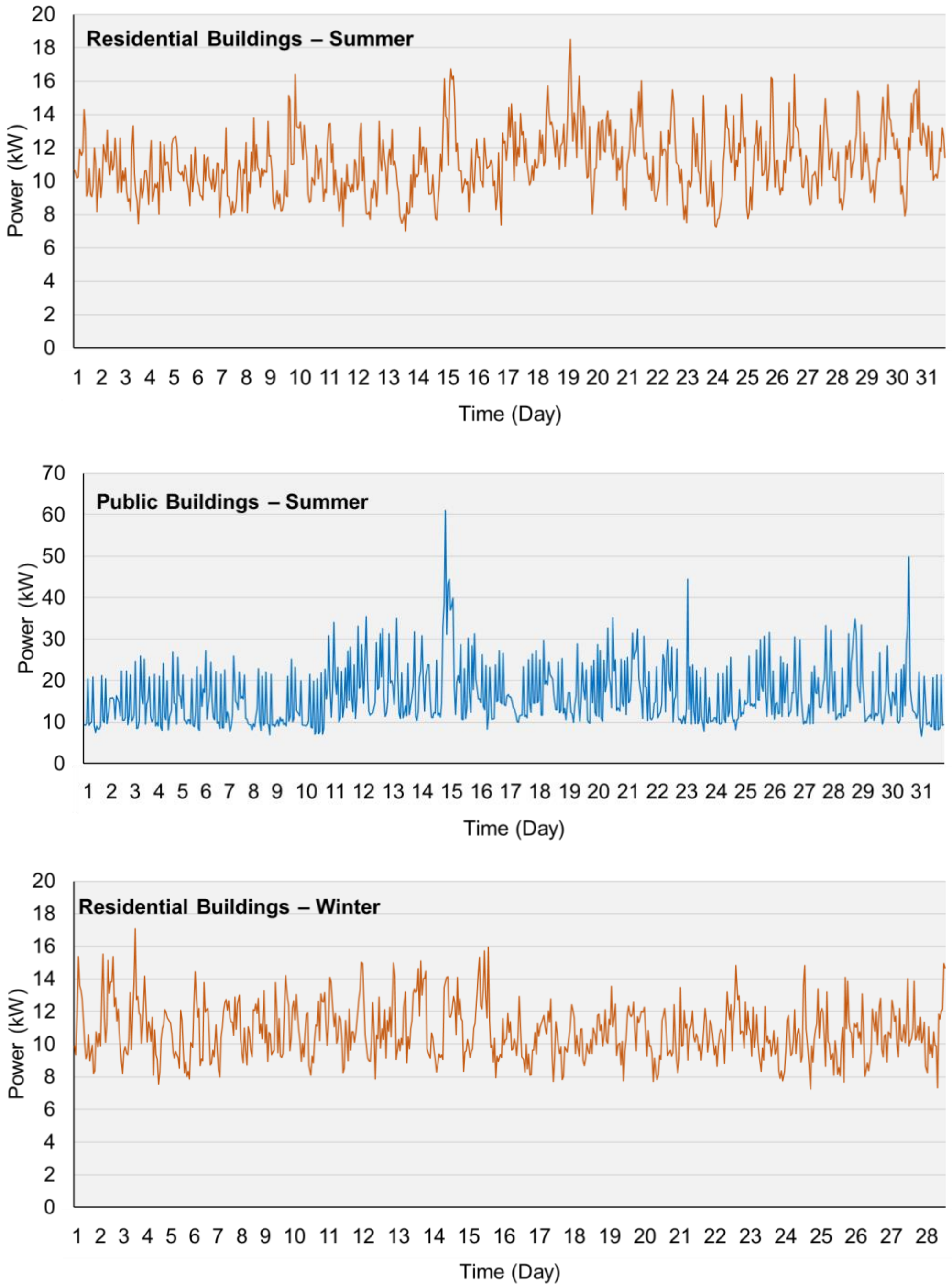


Figure 14. User interface model for controlling and monitoring HIL devices.

To sum up, by using the Simulink models shown above, the user can specify any rate of consumption and generation to be simulated and emulated through the full simulation models as well as the HIL devices, and compare the results obtained from the real equipment with the gained results from the full simulation models.

3.3. Scenarios and Results

This section focuses on a case study to test and validate the functionalities of the developed community model. For this purpose, two consumption and generation profiles are considered for the cities: one month in summer, and one month in winter. Since the main producers of the model are PV installations, it is appropriate to compare and validate the performance of them during the summer and winter. The coldest month in the year (February with 28 days) and the warmest month in the year (July with 31 days) are selected for this case study. Figure 15 shows the detailed consumption profiles of the City 1.



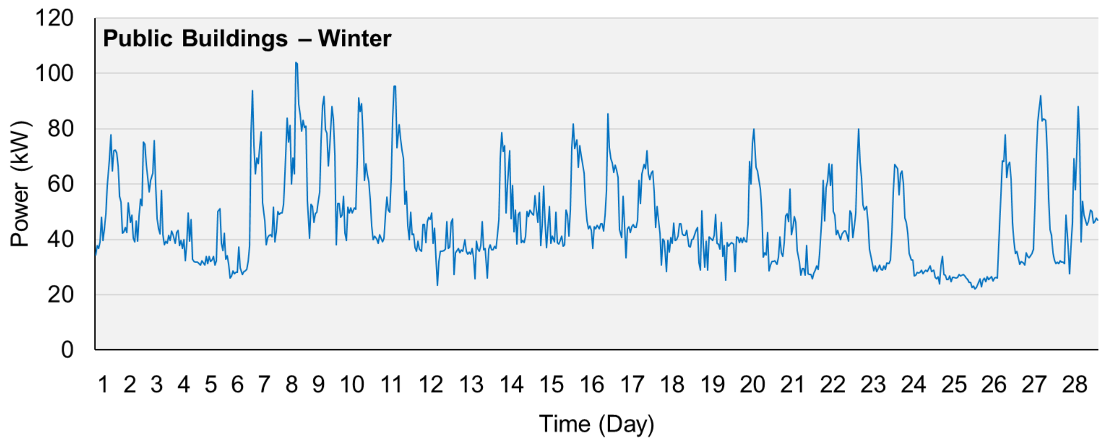


Figure 15. Consumption profiles of different sectors in City 1.

Also, the total consumption and PV generation in City 1 is illustrated in Figure 16. The difference between the PV generation in summer and winter is obvious.

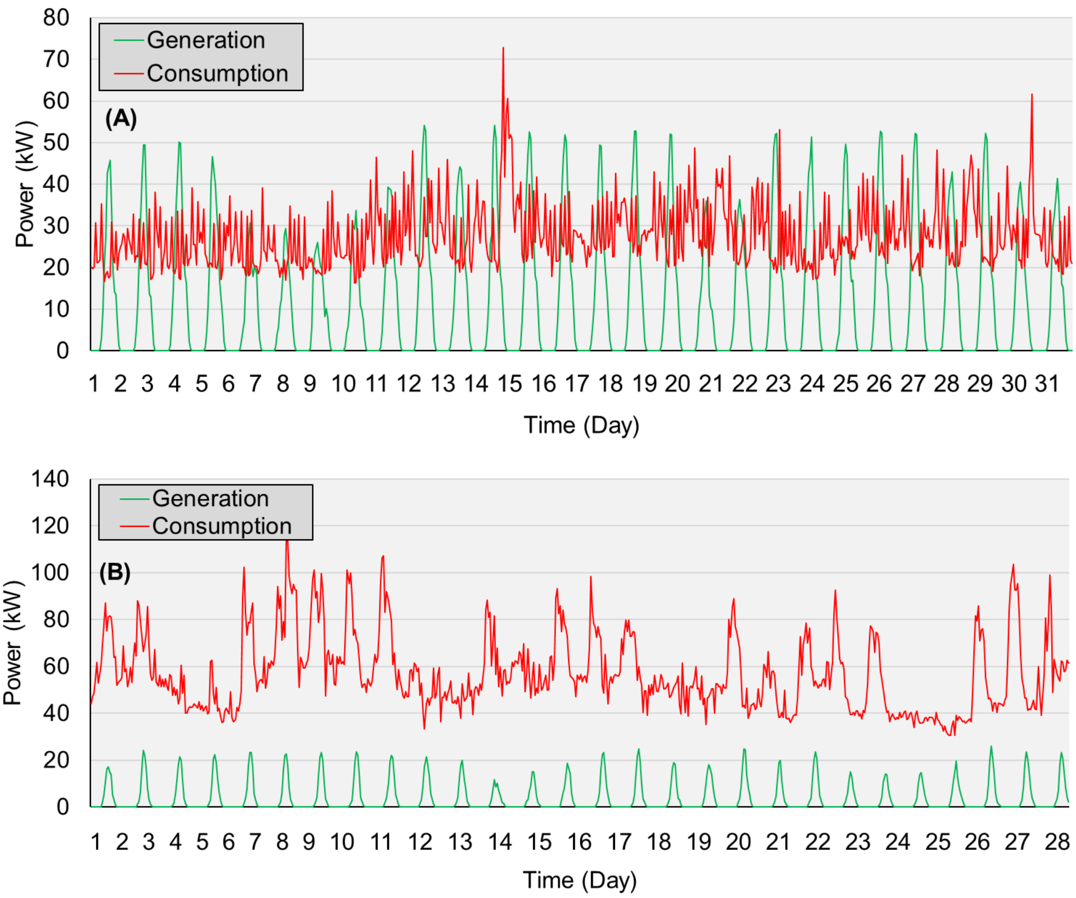


Figure 16. Total generation and consumption profiles of City 1. A) Summer month. B) Winter month.

The same approach is followed for City 2 and City 3, where Figure 17 and Figure 18 show the consumption and generation profiles of City 2, and Figure 19 demonstrates the total consumption rate regarding the residential buildings in City 3.

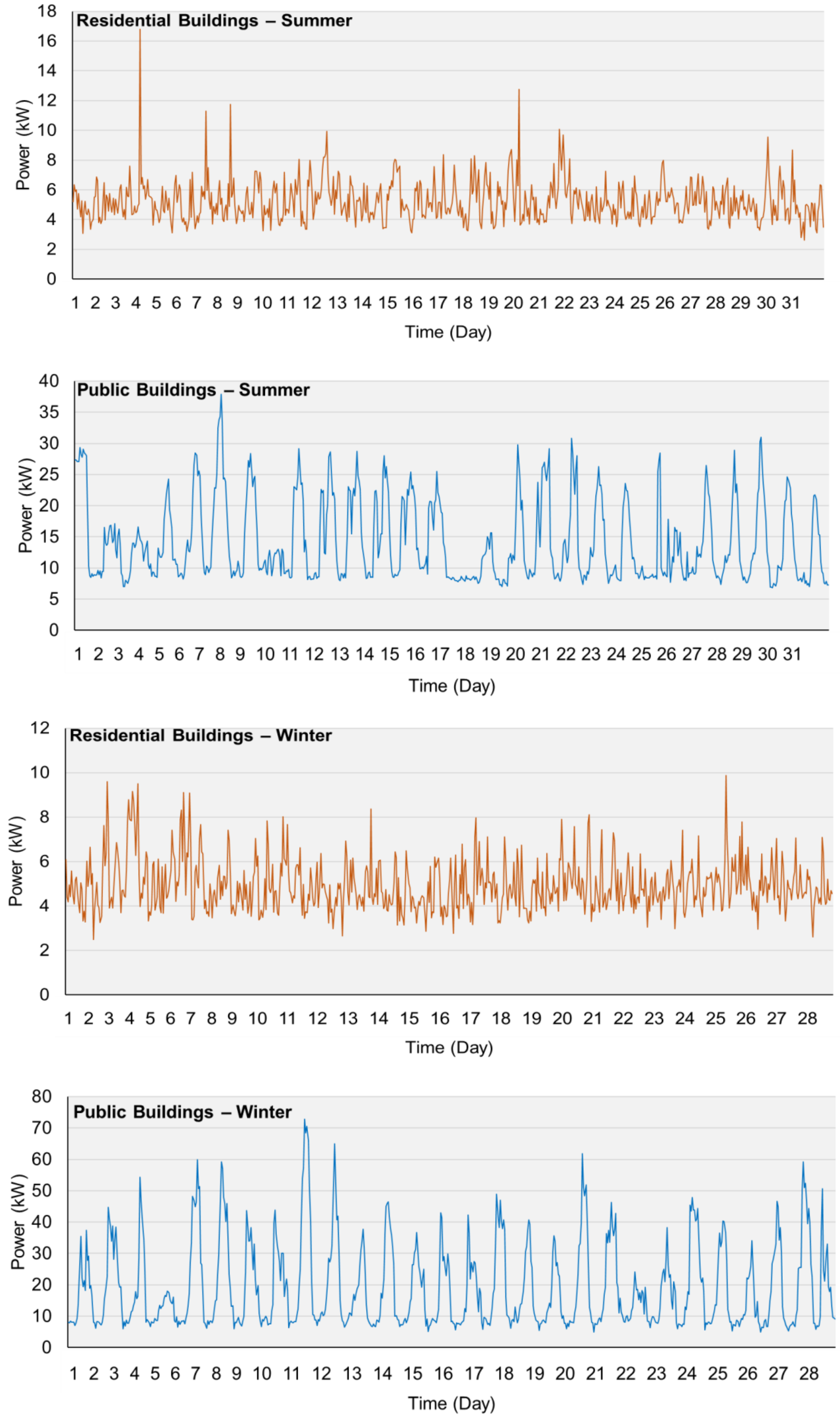


Figure 17. Consumption profiles of residential and public buildings in City 2.

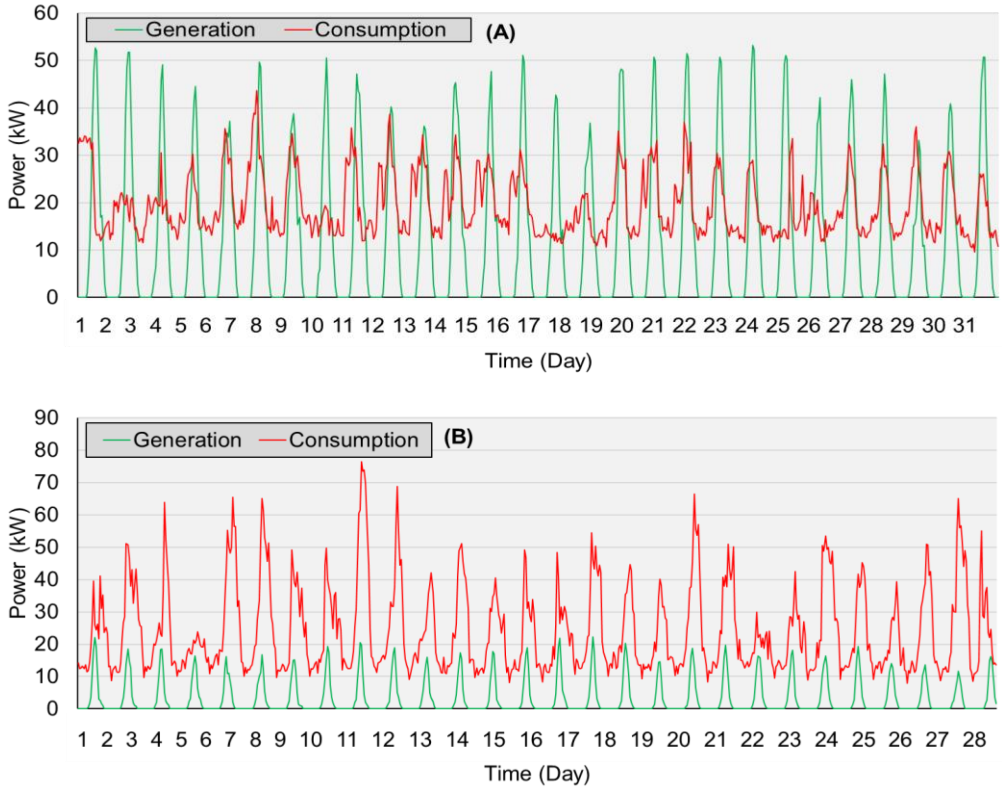


Figure 18. Consumption and generation patterns in City 2. A) Summer month. B) Winter month.

Figure 19. Total consumption profile related to the residential buildings in City 3.

All the profiles shown in Figure 15 to Figure 19 are for a month winter (February) and a month in summer (July), with a one-hour time interval. The significant generation rates in summers enable the community to not only supply the local from the local energy resources, but also it can transact energy with the external supplier and obtain financial profits. Also, in the winter, since the generation rate is low, the community can apply DR programs to reduce the consumption, especially in the residential buildings, to avoid purchasing energy from the external suppliers.

In fact, all the profiles shown in above are the inputs for the real-time simulation process. All those data would be provided to the input block of each consumer and producers, and the real-time results would be gained. In order to show the real-time simulation, 90 periods of 8 seconds (720 seconds in total) are selected. In principle, every 8 seconds in the real-time simulation is considered as 1 hour in reality. Since there are a lot of consumers and producers modeled in this section, only some sample results are demonstrated, and the others follow the same approach. Figure 20 and Figure 21 illustrate two random consumption profiles obtained from the real-time simulator.

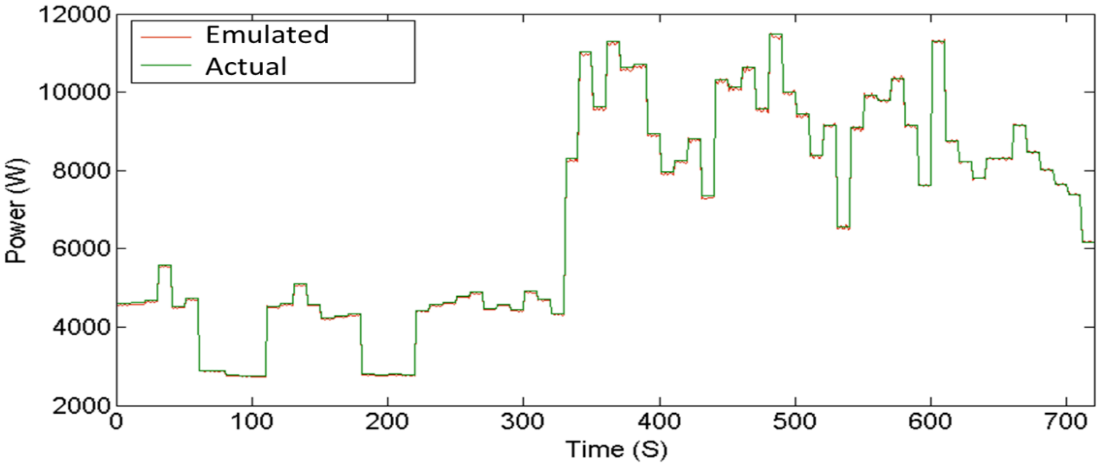


Figure 20. Real-Time consumption profile of a public building in City 1 during winter.

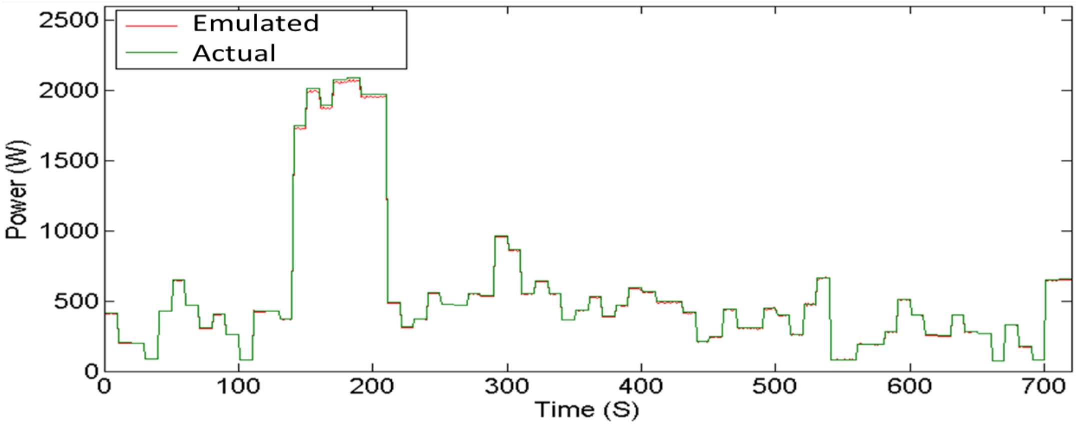


Figure 21. Real-time simulation results of a residential building in City 3 during summer.

In fact, the results shown in Figure 20 and Figure 21 are obtained from the full simulation model developed for the community. In the same figures, the red line indicates the desired rate of consumption that the OP5600 requested from the load model to be simulated, and the blue lines stand for the obtained results.

Furthermore, Figure 22 shows the real-time simulation results for a PV producer in the City 2. All the other PV producers have the same behaviour as Figure 22, and only the amount of generations is different. Also, in Figure 22, the generation profile contains the negative values indicating the energy production. By this way, firstly the produced energy is subtracted (supplied) by the local consumer, and then, if there is any surplus of generation, it is injected into the community grid.

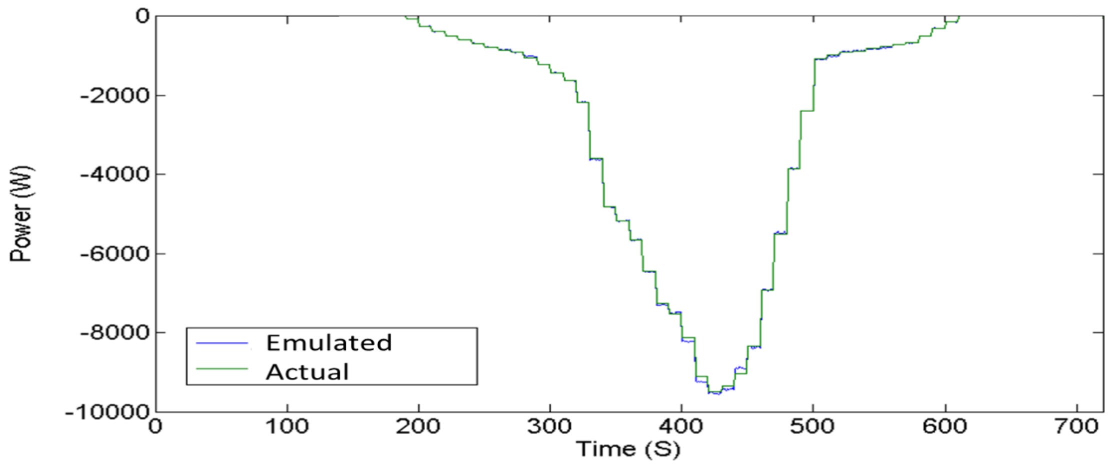


Figure 22. Real-time simulation of generation in a PV producer in City 2 during summer.

Regarding the HIL results, Figure 23 and Figure 24 demonstrate the final obtained results from the HIL devices and OP5600. The results shown in Figure 23 and Figure 24 correspond to 24 periods of 30 seconds (720 seconds in total). The time step in this model is considered 0.5 seconds in the real-time simulation. In other words, OP5600 transmits the desired consumption rates to laboratory HIL equipment with 30 seconds time interval and receives the real data from the equipment with 0.5 seconds time interval. In fact, the results shown in Figure 23 are the reaction of a public building in City 1 during winter emulated by the 30 kW and 4 kVA load banks.

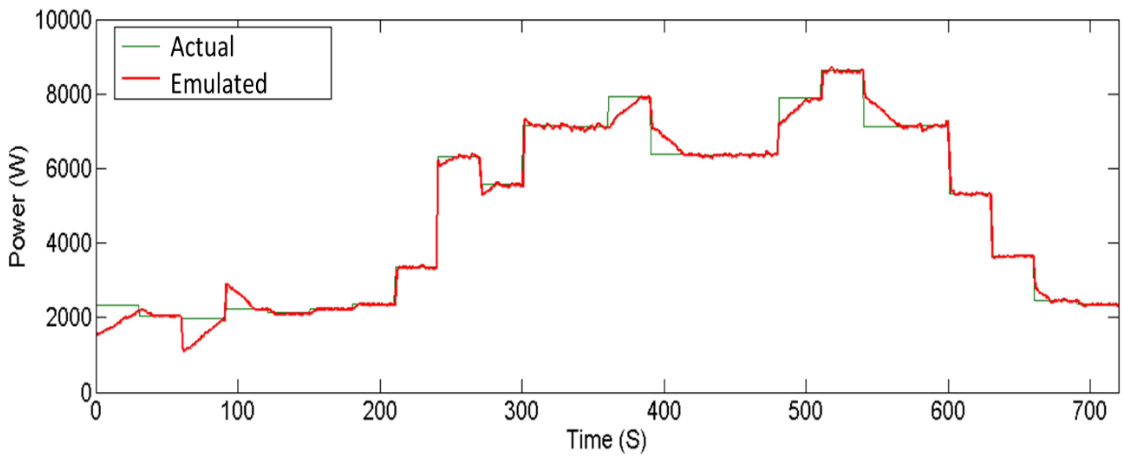


Figure 23. Real-time emulation results of a public building in City 1.

In Figure 23, the set point values are the ones that OP5600 transmitted to the laboratory emulators (30 kW and 4 kVA load banks) for emulating the consumption profile of the public building in City 1. The blue line in the same figure is the reaction of the emulators during the simulation. As it is clear in Figure 23, while the rate of consumption is changed, the emulators require some time to reach the desired consumption rate. In fact, this is the main advantage of using HIL devices comparing to the fully computational results.

Focusing on the generation results, Figure 24 shows the results of PV emulator presented the results of a producer in City 1. In Figure 24, the set points are the desired rate of power that OP5600 transmits to the emulator to be generated, and the blue curve is the real generation profile of the emulator, which is transmitted back to the OP5600.

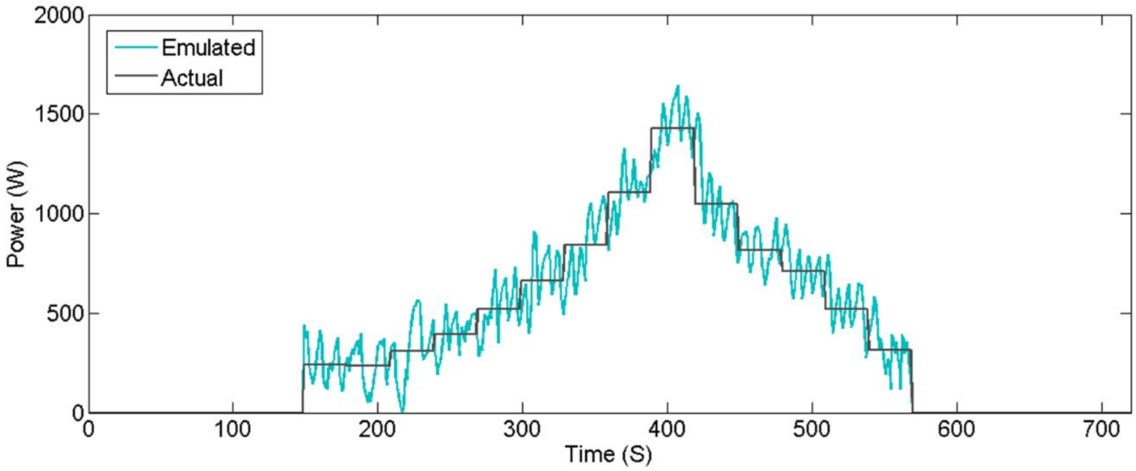


Figure 24. Real-time results of PV emulator for a producer in City 1.

As a summary for this section, the results of real-time simulation and emulation model of a community containing three cities were presented. The results proved and validated the functionalities and performance of the developed community model. In fact, the actual implementation of DR programs and resources scheduling for each community member depends on the electrical grid conditions. The use of real-time simulation and laboratory HIL devices allow us to validate the actual DR programs and resources scheduling using the simulation environment based on the actual electrical grid conditions.

4. DG and Load Aggregator

This section describes an optimization-based distributed generation (DG) and load aggregator model. The model is validated by the real-time simulation and emulation through real consumption and generation data. In principle, the main functionalities of the aggregator model presented in this section are similar to the community model provided in Section 3. However, the main differences are in the number of consumers and producers and in the optimization algorithm for minimizing the operational costs of the network used by the aggregator.

In this aggregator model, it is considered that there is only a city including 100 consumers and 100 DG. To apply the model in real-time simulation, a MATLAB/Simulink model has been designed for the aggregator in order to survey and analyze the behavior of the entire network as well as some specific players. Furthermore, the aggregator employs an optimization algorithm to minimize its operational costs and also gain financial benefits from energy trading with the electricity markets. Finally, a case study is provided, which utilize one-year real data of consumption and generation, in order to survey the performance of the developed optimization-based aggregator model in real-time using real hardware resources.

4.1. Real-Time Simulation Model

This section describes the MATLAB/Simulink model developed for the aggregator in order to be used by the real-time simulator. As it was explained in Section 3.2, the Simulink model is divided into the two main subsystems: computational and user interface. In the computational subsystem, all the load modeling and network configurations are placed, whereas, in the user interface subsystem, all the monitoring and controlling blocks are placed. Figure 25 shows the network configuration developed for this aggregator model.

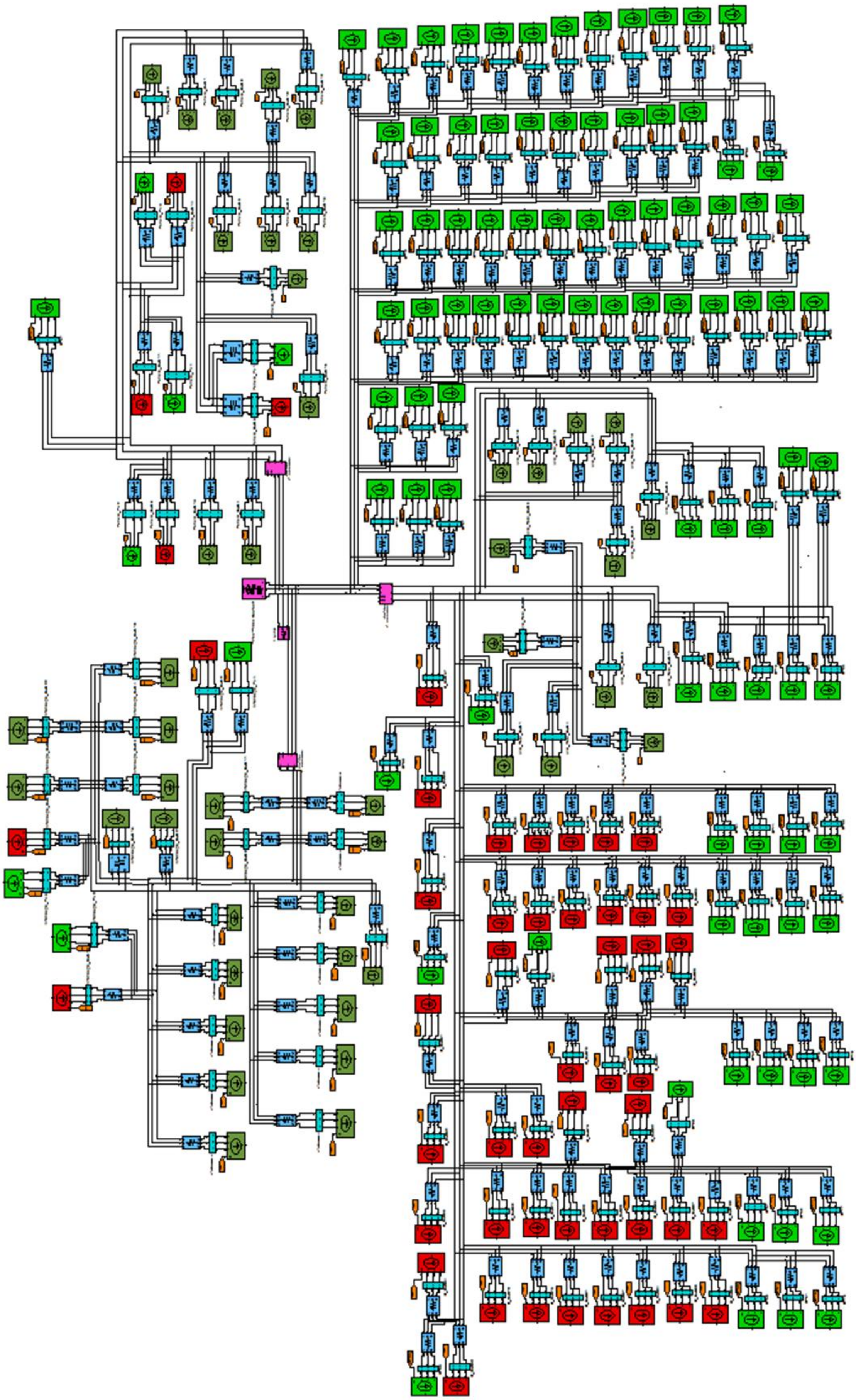


Figure 25. Simulink model for DG and load aggregator.

In this aggregator, it is considered that there are 100 consumers and 100 DG. The consumers consist of 79 residential buildings, 16 commercial shops, 3 commercial centers, and 2 industrial units. The DGs include 13 large-scale PV pilots, 22 small-scale PV pilots, and 47 PV arrays in residential buildings considered as 47 prosumers. These classifications are performed based on the average daily consumption and generation profiles of each player. In Figure 25, the red and dark green blocks are three-phase dynamic load model for the consumers, and light green blocks are dedicated to the DG resources. The HIL devices applied in the aggregator model are as same as the ones presented in Section 3.2. Therefore, they are not mentioned in this section.

4.2. Optimization Algorithm

In this part, an optimization algorithm is described to be used by the aggregator to minimize the operational costs. In fact, the aggregator would like to use the local energy resources and DGs to supply the demand of the network [7], [8]. In the peak periods, it also tends to provide incentives to the customers and apply for DR programs in order to reduce the consumption to avoid purchasing energy from electricity markets. Therefore, the aggregator model should be intelligent enough for managing and scheduling the loads and DGs. An optimization algorithm is developed in this section for minimizing the Operation Cost (*OC*) of the aggregator. The objective function of this optimization problem is:

$$\text{Minimize}$$
$$OC = \sum_{i=1}^{I}\Bigg(\left(P_{Buy(i)} \times C_{Buy(i)}\right) - \left(P_{Sell(i)} \times C_{Sell(i)}\right) + \sum_{m=1}^{M}\Bigg(\left(\left(P_{DG(m,i)} + P_{DG\ Surplus\ (m,i)}\right) \times C_{DG(i)}\right) + \sum_{n=1}^{N}\left(P_{DR(m,n,i)} \times C_{DR\ (m,n,i)}\right)\Bigg)\Bigg) \quad (11)$$

Regarding the constraints of this objective function, the first constraint stands for the load balance, as shown by (12). The power that aggregator purchased from the market, plus the sum of DG production and the DG surplus of prosumers and contractual DR capacity of aggregator´s members, should meet the amount of load consumption plus the power that aggregator sells to the market.

$$P_{Buy(i)} + \sum_{m=1}^{M}\left(P_{DG\ (m,i)} + P_{DG\ Surplus\ (m,i)} + \sum_{n=1}^{N} P_{DR(m,n,i)}\right) = Load(i) + P_{Sell(i)}\,; \quad \forall 1 \le i \le I \quad (12)$$

The second constraint, shown on (13), concerns about the prosumers, where indicates that DG production supplies the local demand first, and then, if there is any generation surplus, it will be injected to the community grid.

$$P_{DG\ Surplus\ (m,i)} = \begin{cases} P_{DG(m,i)} - P_{Cons(m,i)} & P_{DG(m,i)} > P_{Cons(m,i)} \\ 0 & P_{DG(m,i)} \le P_{Cons(m,i)} \end{cases} \quad \forall 1 \le m \le M, \forall 1 \le i \le I \quad (13)$$

In what concerns the capacity of each resource, the maximum capacity of DR resources and DGs are presented by (14) and (15) respectively.

$$P_{DR(m,n,i)} \leq P^{max}_{DR(m,n,i)};\ \forall 1 \leq m \leq M, \forall 1 \leq n \leq N, \forall 1 \leq i \leq I \quad (14)$$

$$P_{DRER(m,i)} \leq P^{max}_{DRER(m,i)};\ \forall 1 \leq m \leq M, \forall 1 \leq i \leq I \quad (15)$$

The maximum energy transaction capacity between the aggregator and electricity market is modeled in (16) and (17).

$$P_{Buy(i)} \leq P^{max}_{Buy(i)}; \forall 1 \leq i \leq I \quad (16)$$

$$P_{Sell(i)} \leq P^{max}_{Sell(i)};\ \forall 1 \leq i \leq I \quad (17)$$

4.3. Scenarios and Results

A scenario is developed in this section in order to survey the reaction of the aggregator model in real-time. For this purpose, the annual consumption and generation profiles of 100 consumers and 100 producers have been adapted from a smart metering company in Germany (www.discovergy.com), which is one of the participants of the project. The data are actual consumption and generation information adapted with 3 minutes time interval. Figure 26 shows the total consumption and generation profiles considered for the aggregator network. Also, detailed consumption profiles of aggregator are shown in Figure 27, which are related to residential buildings, commercial shops. Commercial centers, and industrial units.

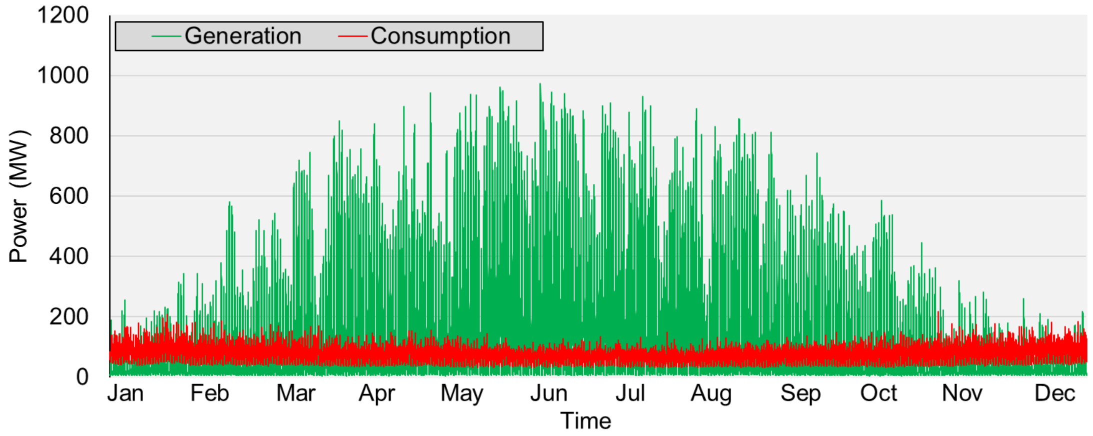


Figure 26. Total consumption and generation profiles considered for the aggregator.

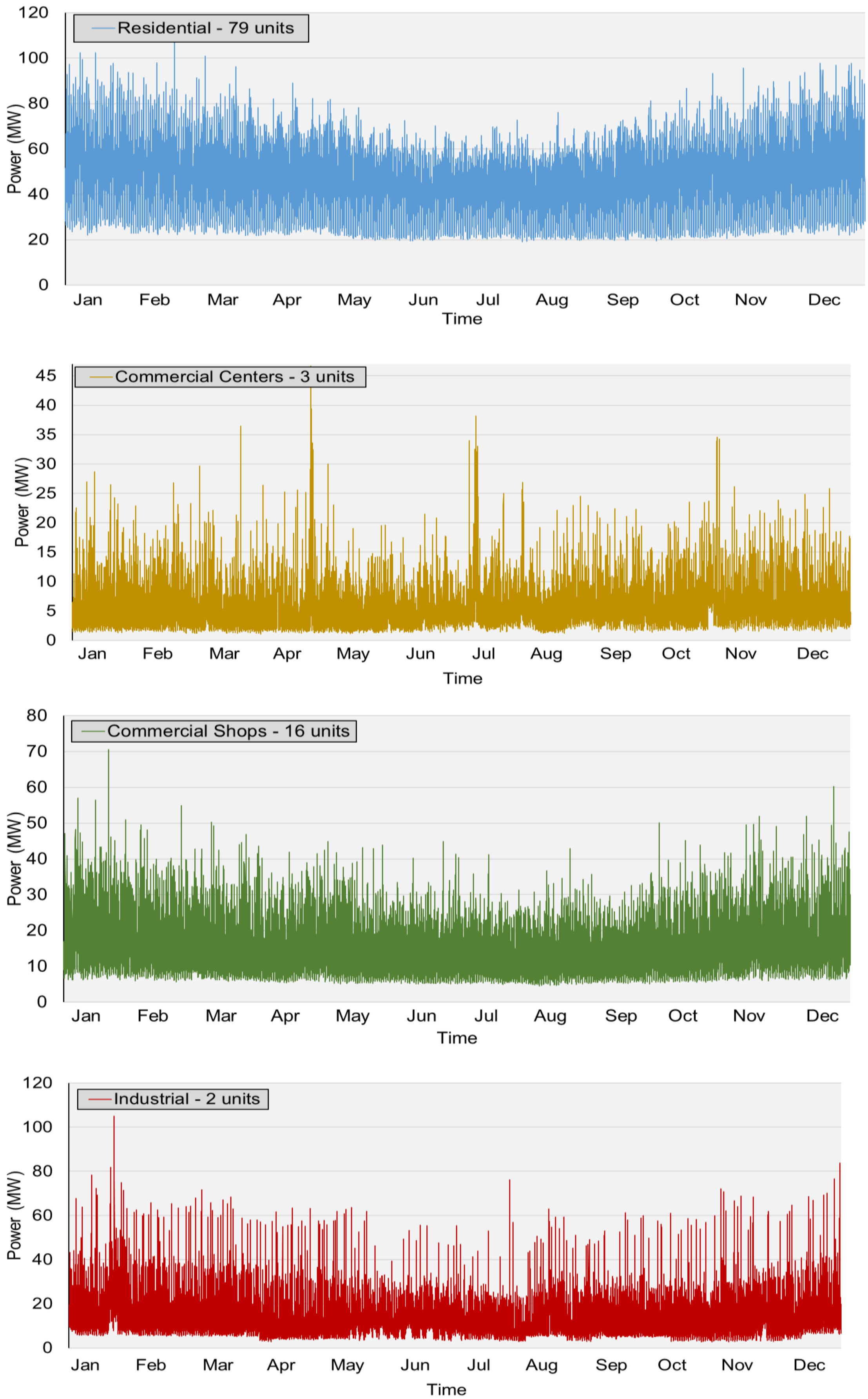


Figure 27. Consumption profile of the aggregator members.

As can be seen in Figure 26, the generation rate in summer is much higher than in the winter, which is due to the high generation rate of PV pilots. Since the rate of consumption is almost equal during the year, not only the aggregator is able to supply the demand via the local resources but also, it can participate in the market negotiations for selling energy during the summer. Furthermore, in Figure 27, the consumption profile of residential houses is a bit lower in summer comparing to the winter. This is due to the geographical areas and weather conditions. Also, in the same figure, the profile of commercial buildings in the working hours is higher than the nights. These points would be useful for the aggregator in order to perform DR programs or loads scheduling.

In order to perform the real-time simulation, the data showed in Figure 26 and Figure 27 are provided to the optimization algorithm as inputs. Then, the algorithm starts the optimization, and the results gained from the optimization algorithm are provided to the real-time simulator (OP5600). Consequently, the real-time simulator starts the simulation and it controls and manages the HIL equipment in order to implement the optimization results in real-time. The results of simulation and emulation are shown in the next section.

The results of the aggregator performance are organized in two subsections. The first subsection provides the results concerning the "real-time simulation", while the second subsection focuses on an "economic analysis". It is assumed that the aggregator model is implemented in two countries in Europe, Portugal, and Germany (two countries involved in the project).

- ***Real-Time Simulation***

This part shows the results of real-time simulation performed by OP5600 in Simulink. For this purpose, 90 periods of 8 seconds (720 seconds in total) are selected for performing the real-time simulation. The real-time simulation is performed for a short period of time due to the technical limitations of the real-time simulator machine. Figure 28 to Figure 31 illustrate the results of real-time simulation for different sectors of the aggregator network.

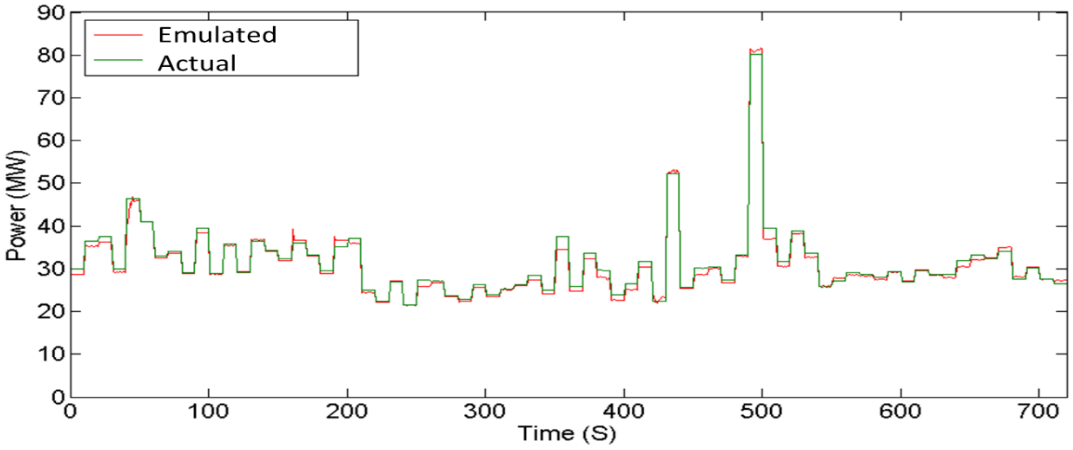


Figure 28. Real-Time simulation results of 79 residential buildings consumption.

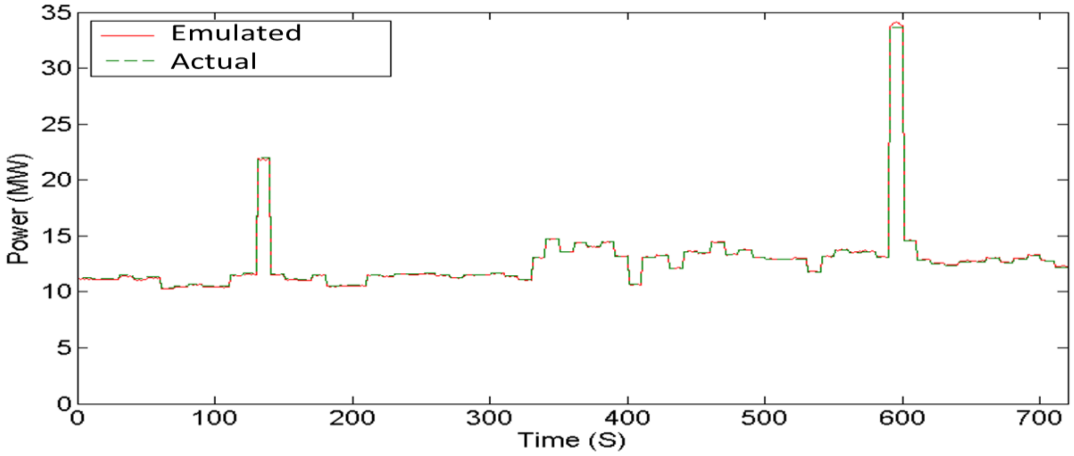


Figure 29. Consumption of 3 commercial centers in real-time simulation.

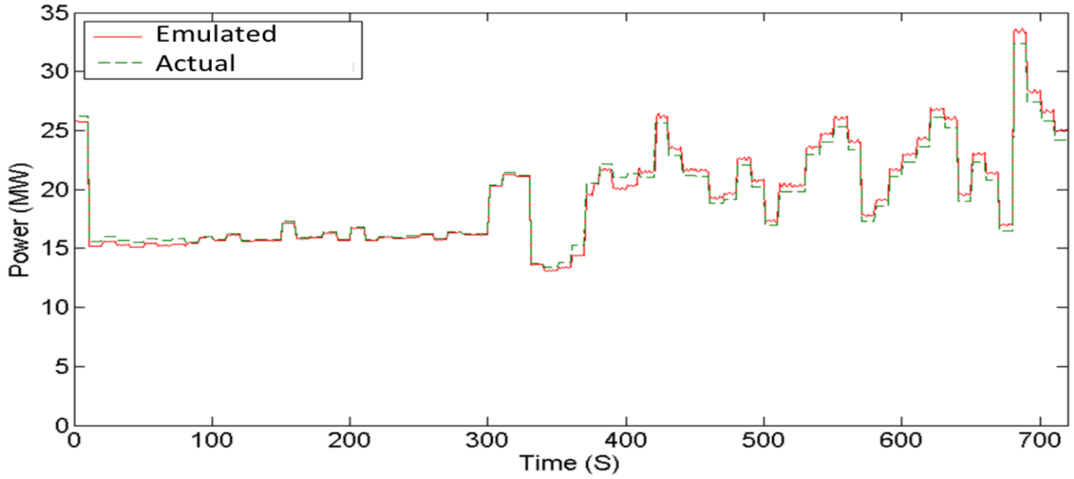


Figure 30. Real-Time simulation of consumption in 16 commercial shops.

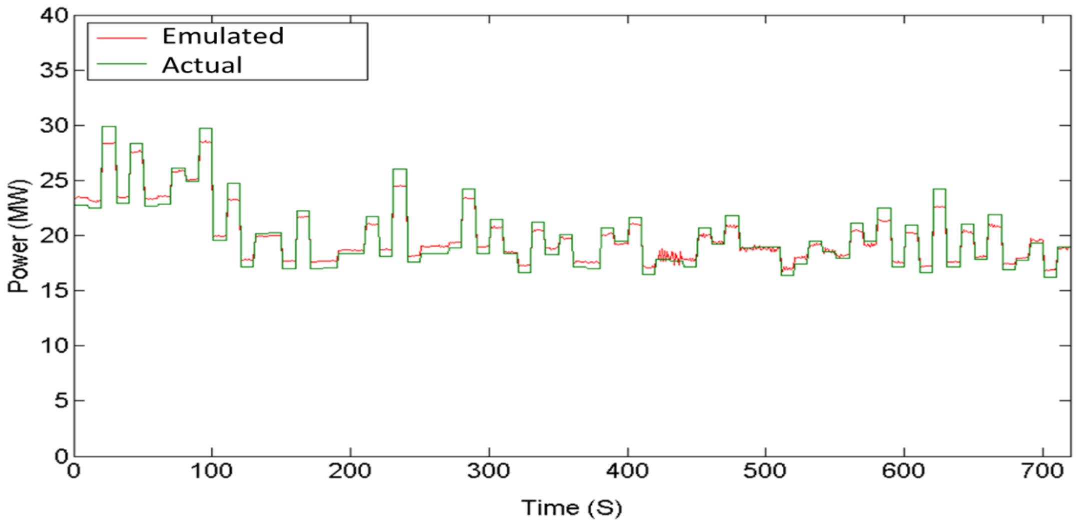


Figure 31. Real-Time simulation of consumption in 2 industrial units.

The results shown in Figure 28 to Figure 31 are the scheduled and optimized consumption profile, which is the output of the optimization problem.

- ***Economic Analysis***

As it was mentioned, this part focuses on the economic analysis of the aggregator model while it is considered that it is implemented in Portugal and in Germany. Therefore, the electricity prices and regulation of these two countries are applied in the aggregator model and the results are compared.

The first analysis was done using the Portuguese electricity prices to calculate the annual costs of the aggregator. Therefore, the electricity price for consumption has been adapted from [9], which is 0.15 EUR/kWh. Also, the price of electricity generation, Feed-In-Tariff, has been adapted from [10], which stands as 0.09 EUR/kWh. Figure 32 shows the calculated annual costs for Portugal. Furthermore, Table 5 demonstrates the detailed accumulated consumption costs for the different sectors of the community while it operates with Portuguese prices.

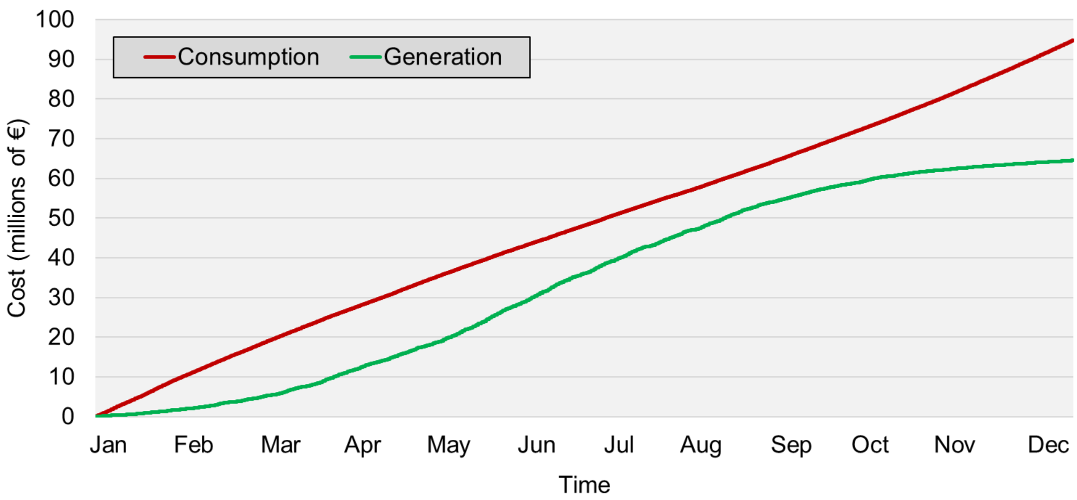


Figure 32. Accumulated costs of aggregator for one year with Portuguese prices.

Table 5. Accumulated consumption costs of aggregator with Portuguese electricity prices.

	Consumers				Producers
	Residential Houses	**Commercial Centres**	**Commercial Shops**	**Industrial Units**	**PV and wind turbines**
Cost (M€)	54.6	24.2	9.6	5.4	64.5
	Total: 93.8				**Total: 64.5**

Regarding the community costs with Germany electricity prices, Figure 33 and Table 6 show the economic analysis. In those results, the electricity price for consumption has been adapted from [11], which stands for 0.25 EUR/kWh, and the generation costs adapted from [12] stands for 0.09 EUR/kWh.

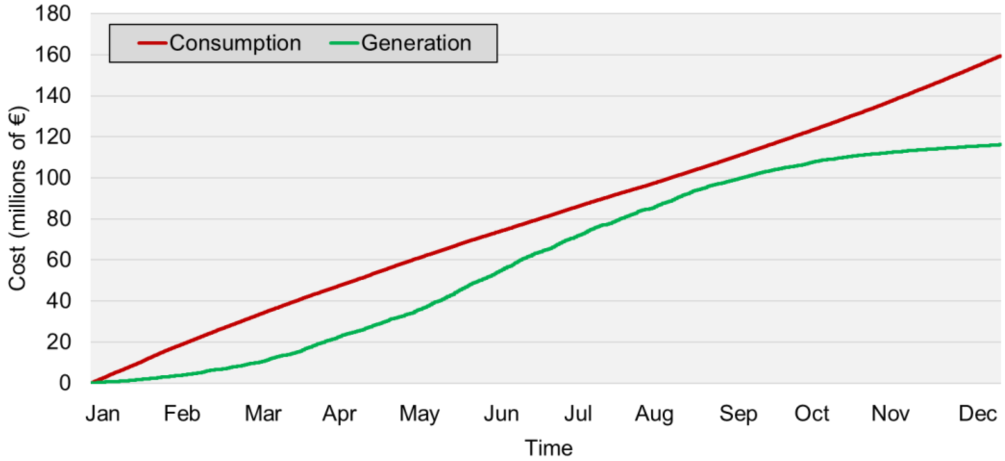


Figure 33. Accumulated costs of the aggregator for one year with prices in Germany.

Table 6. Accumulated consumption costs of aggregator with German electricity prices.

	Consumers				Producers
	Residential Houses	**Commercial Centres**	**Commercial Shops**	**Industrial Units**	**PV and wind turbines**
Cost (M€)	97.7	10.1	28.1	23.5	116.1
	Total: 159.4				**Total: 116.1**

The results of this section illustrate a comparison between the consumption and generation costs for an entire year while the pricing schemes of the two countries in Europe are applied. These kinds of analysis are very useful for network operators and management entities, such as aggregators, in order to identify the best and optimal situations for performing DR programs and loads scheduling.

5. Conclusions

In this deliverable, several case studies and scenarios concerning short and real-time DR programs are proposed, implemented, and analyzed. The work developed has been done in view of concerns and challenges that the electricity sector is facing nowadays, e.g., the daily increment of electricity consumption in the world, environmental issues due to the impact of greenhouse gases emission, low level efficiency of current power systems to accommodate DRER, among others. In addition, the lack of awareness from consumers in the demand side maximizes the impact of such issues.

Three case studies have been proposed and analyzed in this work:

- **University campus:** Energy management and DR impact considering a time horizon of 1 day with 24 hours granularity. Computational resources used for this case study comprises a multiagent system and an optimization algorithm.
- **Community of cities**: Energy management and DR impact considering two months with different weather and load profiles (i.e., one summer month and one winter month). Computational resources used for this case study span real-time simulation and real-time emulation.
- **Aggregator and distributed generation:** Energy management and DR impact considering one full year with one-minute granularity. Computational resources used for this case study encompasses optimization modeling, real-time simulation, and real-time emulation.

The advantages of using these three case studies lay in their generalization to different contexts, and in the added value that the results can bring to different stakeholders. For instance, it has been found that aggregators can perform optimal scheduling of resources depending on the contributions coming from different demand-side and DR programs. Also, through the use of real-time simulation and emulation, it has been proven the benefits that DR programs can bring to grid operators under actual grid conditions.

Finally, the work has also provided evidence about the feasibility on the use of advanced computational resources for energy efficiency management of resources. The computational resources used include a multi-agent system, mathematical optimization modeling, real-time simulation, and laboratorial emulation. From such computational resources, an especial emphasis in the laboratorial emulation has been posed since that kind of approach allows a more accurate validation on the actual DR programs and resources scheduling impact under actual grid conditions.

In light of the analysis and findings provided in this deliverable, it can be stablished and highlighted the crucial role that DR programs will play in the future of energy systems. Future research activities and initiatives are still needed in what concerns to real implementation and additional infrastructure requirements. The effect and impact of also new technologies, such as block chains or transactive energy systems, are also encouraged as further work.

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