Optimization-Based Home Energy Management System Under Different Electricity Pricing Schemes

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***Abstract*—This paper presents an optimization-based home energy management system, by taking advantages of renewable resources and energy storage system for optimally managing the energy consumption and generation of the house. The surplus of renewable generation will be stored in energy storage system or will be injected into the main grid. An optimization algorithm is developed for this system in order to minimize the electricity bill of the house considering electricity tariffs. Four home appliances are considered to be controlled by this system for reducing the consumption in critical periods. The outcomes of optimization problem are the optimal scheduling of the resources including renewable generation, energy storage system, consumption reduction, and power transactions with the grid. In the case study, the developed model will be employed in three different scenarios, which considers simple electricity prices and time-of-use tariffs in order to test and validate the performance of the developed model.**

***Index Terms*— Home Energy Management, Optimization, Time-Of-Use, Renewable Generation, Energy Storage.**

I. INTRODUCTION

The significant penetration of Renewable Energy Resources (RERs) for supplying electricity demand, became an irrefutable fact around the world [1]. In addition to supplying energy, RERs such as Photovoltaic (PV), and wind turbines, can be mentioned as nature-friendly resources against to disadvantages of fossil fuels [2]. According to [3], many buildings were persuaded to install rooftop PV system for supplying a part of their consumption. This leads to significant increment in global PV deployment by the end of 2014, and it is estimated that by 2050, 16% of world's electricity demand will be supplied by PV generation. Despite all benefits of RERs, the problem of stochastics, intermittent, and unpredictable production are some barriers [4]. Among all solutions to overcome this problem, most cost-effective way, seems to use Energy Storage System (ESS), and load scheduling in Demand Response (DR) [5].

Use of ESS beside the RERs can be considered as an effective solution to maximize the self-consumption, and take advantages from reducing their energy cost by storing the energy on the high generation periods, and release the stored energy when needed [6]. In the case of DR programs, the consumption pattern can be a function of total generation and §electricity price variation during a day. This makes the consumers to schedule the consumption based on these programs. They can control the consumption of appliances in response to electricity price variations, under the DR programs which encourage the consumers to shift their loads based on the time-of-use (TOU) scheme [7], [8]. Residential buildings can be considered as a proper case for participating in DR programs [9]. It is worth noting that the smart residential houses which are equipped with automation infrastructures have more potential for managing the energy [10]. For this purpose, each home appliances should be connected to an energy management system in order to be optimally controlled [9], [11]. Therefore, this paper represents an optimization-based Home Energy Management System (HEMS) by penetration of RERs and ESS. The developed optimization problem is a Linear Program (LP), which aims at minimizing the electricity bill of the house. The algorithm considers RERs, ESS, consumption reduction, and energy transactions with the electricity network, somehow the final results would be the optimal resources scheduling, by relying on the electricity tariffs of the grid. Four home appliances are considered in this model in order to be controlled by HEMS and participate in optimization problem as reduction resources.

There are a significant number of research works that implemented HEMS and building optimization, however, only a few numbers of them have been mentioned in this part. In [11], an innovative HEMS has been presented and its performance during a DR event has been surveyed by considering comfort level of users, and [12] presents a HEMS with considering an electric vehicle and small-scale RERs. Reference [13] provides an independent management for minimizing the electricity bill and purchased power from the grid by employing PV and ESS. An optimization methodology for PV, wind generation, and ESS has been proposed in [14], which is completely based on RERs and is isolated from the grid. In [15], the authors proposed an optimization algorithm for the lighting system of an office building based on the user preferences and comforts, with respect to the RERs. In [16], an optimization problem has been presented for the air conditioner of an office building in order to be applied for DR programs, such as Direct Load Control (DLC).

However, the main goal of this paper is firstly to propose an optimization-based HEMS by considering RERs and ESS in order to optimally schedule the consumption and generation of the house. And then, the performance of the developed

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system will be surveyed and compared under different electricity tariffs. The rest of the paper is organized as follows. The architecture of the model regarding HEMS is described in Section II. Section III represents the optimization algorithm. The case studies and its final results are represented in Section IV. Finally, section V details the main conclusions of the work.

II. Model Description

The main purpose of this paper is to optimize the energy consumption of a residential house, with using the renewable energies as much as possible. The overall view of this work can be seen in Fig. 1. In addition to the power distribution network, there are local energy resources, which contain a PV system, a wind turbine, and an ESS to supply the home energy demand. In this system, a distinct priority level has been specified for each resource. PV system and wind turbines are the first priority for the developed HEMS since they have no cost for the power generation.

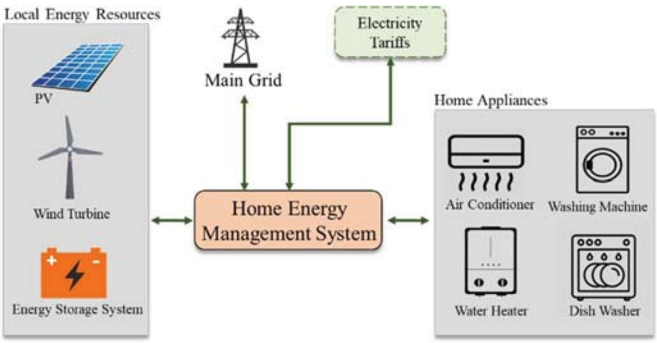

Fig. 1. Overall view of the HEMS functionalities.

As it can be seen in Fig. 1, there is an ESS in this system for storing the surplus of energy production and release the energy in critical periods. The main task of this model is to use the entire production of RERs first, and then it comes to buy energy from the grid or utilize the reduction resources. This depends on the scheduling results of the optimization algorithm implemented in HEMS. In fact, the optimization algorithm is obligated to check the real-time status of energy resources in order to make a decision to perform the optimization. This means, in each period, generation level of RERs, state of the charge of ESS, available consumption reduction capacity, consumption of the house, and the electricity price, would be considered as inputs for the optimization algorithm, and the outcomes will be efficient and optimal resources scheduling of the house, by aiming at minimizing the daily energy cost. In order to clarify the optimization process, we consider an example. Suppose that the produced energy is more than the consumption of the house, therefore, the priority is given to charge the ESS with the generation surplus, and then if there is any excess of power, it will be injected to the grid. However, if the produced energy is not adequate for the house consumption, the algorithm should survey three different situations:

1. Using the stored energy in ESS;
2. Applying consumption reduction for home appliances;
3. Purchasing energy from the grid.

The decision making in this situation depends on the electricity tariffs in each period. In the periods with high electricity prices and a lower rate of RER generation, the solutions are to utilize the reduction resources or use the store energy in ESS, in order to buy a few amounts of energy from the grid. However, in the periods with lower electricity price, not only the entire consumption can be met by the grid, but also the ESS can be charged by the grid in order to be utilized in the periods with high electricity prices.

Regarding the periods that the algorithm needs to apply consumption reduction, there are four home appliances, including Air Conditioner (AC), washing machine, dishwasher, and water heater, considered as the loads that can be controlled by HEMS. These controllable loads considered as curtailment loads, therefore the system is not able to reduce their consumption, and it has discrete control on them. During the optimization process, a weight of priority is specified for each appliance in order to respect the user comfort and preferences.

III. Mathematical Formulation

This section represents the mathematical formulation of proposed optimization methodology. This optimization algorithm is considered as a Linear Problem (LP) optimization, which has been formulated in order to be modeled in RStudio tools (www.rstudio.com) using LPSolve and LPSolve API packages. Equation (1) represents the objective function of optimization algorithm aiming at minimizing the electricity bill considering the rate of generation in RERs, available consumption reduction, available stored energy in ESS, and the electricity tariffs of the network.

$$Minimize$$
$$EB = \sum_{t=1}^{T} \left[\left(P_{(t)}^{buy} \times COST_{(t)}^{buy} \right) - \left(P_{(t)}^{sell} \times COST_{(t)}^{sell} \right) \right] \tag{1}$$

Where T is the number of periods, $P_{(t)}^{buy}$ indicates the purchased power form electricity network and $P_{(t)}^{sell}$ shows the injected power to the network by HEMS. P^{Buy} and P^{sell} are two determinative parameters that are effective for the electricity bill. The $COST_{(t)}^{buy}$ is the price of purchasing energy from the grid in each period, which is an essential factor for performing the optimization process, and several decisions are based on the value defined in this parameter. $COST_{(t)}^{sell}$ is the price of selling energy to the grid in each period. Furthermore, there are several constraints that should be considered for this objective function. Equation (2) represents the definition of the power that should be purchased form grid, and (3) is the mathematical form of the total production of local renewable energy resources.

$$P_{(t)}^{buy} = P_{(t)}^{load} - P_{(t)}^{RER} + P_{(t)}^{ch} - P_{(t)}^{dch} - P_{(t)}^{red} \quad \forall\, t \in \{1, \dots, T\} \tag{2}$$

$$P_{(t)}^{RER} = P_{(t)}^{PV} + P_{(t)}^{wind} \quad \forall\, t \in \{1, \dots, T\} \tag{3}$$

$P_{(t)}^{load}$ is for the total power consumption of the house, $P_{(t)}^{RER}$ stands for the total power production of renewable energy resources. $P_{(t)}^{ch}$ shows the power that is consumed for charging the ESS, and $P_{(t)}^{dch}$ is for the discharged power of ESS. Moreover, $P_{(t)}^{PV}$ and $P_{(t)}^{wind}$ indicate the power production of PV system and wind turbine respectively, and finally, $P_{(t)}^{red}$ indicates the amount of power reduction which is reduced to meet desired power consumption rate.

Equation (4) shows the constraint for consumption reduction, which indicates the respect of optimization process for user preferences and comfort by specifying a weight of priority for each device (W). In this constraint, D is the number of devices available for HEMS to be controlled, and $P_{(t,d)}^{device}$ stands for the consumption of each device. Moreover, (5) demonstrates the technical limitation for the consumption reduction in each device, which should be less or equal to a maximum rate ($P_{(t,d)}^{max.device}$).

$$P_{(t)}^{red} = \sum_{t=1}^{T} \sum_{d=1}^{D} P_{(t,d)}^{device} \times W_{(t,d)} \tag{4}$$

$$0 \le P_{(t,d)}^{device} \le P_{(t,d)}^{max.device} \quad \forall\, t \in \{1, \dots, T\}, \forall\, d \in \{1, \dots, D\} \tag{5}$$

Equation (6) and (7) shows the limitations regarding the maximum amount of RER generation in each period ($P_{(t)}^{max.PV}, P_{(t)}^{max.wind}$).

$$0 \le P_{(t)}^{PV} \le P_{(t)}^{max.PV} \quad \forall\, t \in \{1, \dots, T\} \tag{6}$$

$$0 \le P_{(t)}^{wind} \le P_{(t)}^{max.wind} \quad \forall\, t \in \{1, \dots, T\} \tag{7}$$

The ESS is an effective tool for this optimization algorithms since it brings flexibility for managing the consumption and generation. Equation (8) shows the limitation for the maximum capacity of ESS ($P_{(t)}^{max.stor}$) for storing the energy ($P_{(t)}^{stor}$). Furthermore, (9) and (10) represent the technical constraints for the rate of charging and discharging the ESS, which should not exceed a maximum rate ($P_{(t)}^{max.ch}, P_{(t)}^{max.dch}$). In (9)- (11), $S_{(t)}^{ch}$ and $S_{(t)}^{dch}$ are two factors for showing the impossibility of charging and discharging the ESS in the same period. In other words, they demonstrate that in each single period, the ESS should be charged or discharged. Finally, (12) represents the stored energy of ESS in each period is based on the stored energy in the previous period.

In sum, this part represented the mathematical formulation for the developed optimization algorithm in order to have efficient and optimal scheduling results for the consumption and generation resources available in the HEMS. This optimization problem will be employed in the next section for case studies in order to test and validate the performance of the system in various electricity tariffs.

$$0 \le P_{(t)}^{stor} \le P_{(t)}^{max.stor}, \forall\, t \in \{1, \dots, T\} \tag{8}$$

$$0 \le P_{(t)}^{ch} \le P_{(t)}^{max.ch} . S_{(t)}^{ch} \quad S_{(t)}^{ch} \in \{0, 1\}, \forall\, t \in \{1, \dots, T\} \tag{9}$$

$$0 \le P_{(t)}^{dch} \le P_{(t)}^{max.dch} . S_{(t)}^{dch} \quad S_{(t)}^{dch} \in \{0, 1\}, \forall\, t \in \{1, \dots, T\} \tag{10}$$

$$S_{(t)}^{ch} + S_{(t)}^{dch} \le 1, \forall\, t \in \{1, \dots, T\} \tag{11}$$

$$P_{(t)}^{stor} = P_{(t-1)}^{stor} + P_{(t)}^{ch} - P_{(t)}^{dch}, \forall\, t \in \{1, \dots, T\} \tag{12}$$

IV. CASE STUDIES

This section represents the case studies, which implemented for evaluating the proposed methodology. The case studies consider the developed optimization-based HEMS with RER generation, the ESS, and four controllable loads under different electricity tariffs.

The day-ahead consumption and generation profiles considered for HEMS during the case studies are demonstrated in Fig. 2. These profiles are for a full day including 24 periods of 1 hour. In this system it is considered that the PV arrays has the maximum generation capacity of 4.5 kW, the wind turbine has 1 kW, and the ESS is capable to store 2 kW.

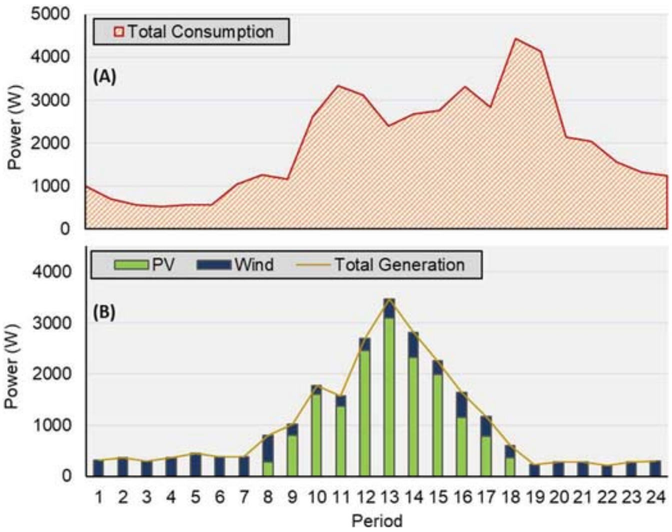

Fig. 2. Day-ahead profiles considered for HEMS: (A) Consumption, (B) Generation.

As it can be seen in Fig. 2, there are some periods during the day that the generation is more than the consumption. Therefore, the optimization makes a decision for the generation surplus based on the input factors to be stored in the ESS or to be injected into the grid to gain profits. Moreover, there are some periods that RER generation is not adequate for the demand, therefore the optimization process makes the decision to purchase power from the grid, or utilize reduction resources, or release the stored energy in ESS. However, all these processes depend on the electricity tariffs. In order to validate the performance of the developed model in different conditions, three scenarios are implemented for comparing the daily electricity bill of the house based on the outcomes of the optimal resource scheduling of the model. The first scenario considered as a base case, where it is considered that HEMS has no RERs generation, no ESS, and has no capability of consumption reduction. Therefore, it is obligated to supply all demand from the utility grid. It is true that in this scenario there is no scientific contribution, however, the main purpose is to demonstrate the advantages of an optimization-based HEMS, and how this system can be effective to reduce the daily electricity bill of the house. The second scenario considers there is no ESS in HEMS, however, it is equipped with RER, and reduction resources. The house is contracted with the electricity retail company with simple tariff price. The last scenario is similar to the scenario 2, however, in the third scenario, it is considered the house has a contract of tri-hourly price scheme under TOU program. Fig. 3 shows the different pricing schemes considered for the three scenarios. The simple tariff and tri-hourly price scheme have been adapted from incumbent Portuguese electricity retailer in the liberalized market (EDP Commercial – www.edp.pt), for a residential consumer with 5.75 kVA contract in a typical weekday.

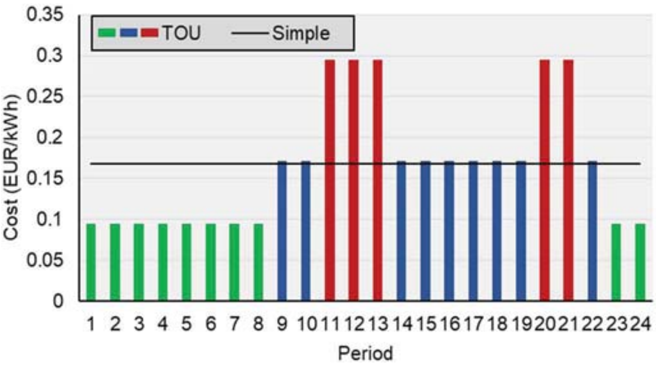

Fig. 3. Electricity costs under different pricing schemes for three scenarios.

As it can be seen in Fig. 3, in the simple tariff there is not any variation during the day, and a fixed price is defined for all periods. Also, TOU scheme includes three levels of pricing, which are normal (red), economic (blue), and super economic (green). Furthermore, the price of selling energy to the utility grid is considered as 0.16 EUR/kWh, adapted from [15]. Price variation in TOU scheme makes better challenges for the developed HEMS to schedule consumption and generation in expensive periods, and take advantage of ESS and optimization algorithm outcomes

A. Scenario 1

This scenario is considered as a base case for the other scenarios, in order to compare it with the developed methodologies. For this purpose, Fig. 4, shows the consumption of the building in a base case. In fact, the aim of this scenario is to calculate the daily electricity price of this residential house, while there are no HEMS equipped with RERs and ESS. This scenario shows the functionalities of the typical houses, which always rely on the utility grid for supplying the electricity demand. As it can be seen in Fig. 4, all power consumption of the house is supplied from the grid, and no PV or wind applied in this scenario. By the way, with considering simple tariff, the electricity cost in this scenario is 7.45 EUR. This will be considered as a base case, in order to be used by other scenarios for the comparison.

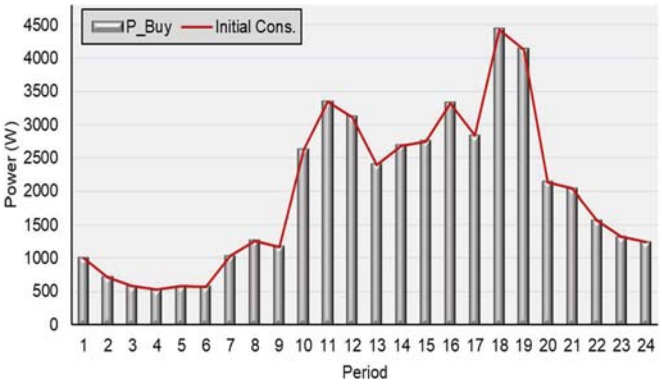

Fig. 4. Consumption profile of the house without any schedule.

B. Scenario 2

This scenario surveys about the impact of the proposed methodology in the electricity bill, based on the simple tariff considering there is no ESS in HEMS. Fig. 5 demonstrates the obtained results after running the algorithm. As it was mentioned in previous parts, each resource has a specific priority to operate. In other words, the system automatically makes the decision to specify a priority for each resource in various periods and situations based on the input data.

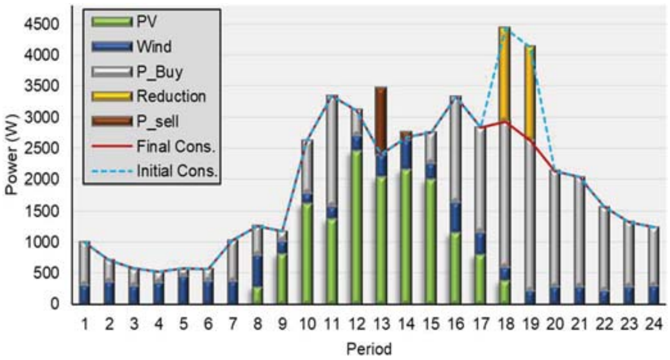

Fig. 5. Scheduling results under simple electricity tariff.

As it can be seen in Fig. 5, PV system and wind turbine, are the first suppliers of electricity demand. According to defined priorities by the system, the remaining energy demand has been supplied by the grid, and the system decided to purchase energy from the network, instead of reducing the consumption. Furthermore, according to selling and buying prices considered in this scenario and also since ESS is not considered in this scenario, the system prefers to sell the surplus of generation to the grid. As Fig. 5 illustrates, in periods 13 and 14, the RERs generations are more than the consumption of the house, and therefore, the algorithm decided to sell this surplus to the grid. Also, in periods 18 and 19, although there are not significant RERs generation, the total power consumption is high. Therefore, the system decided to reduce total consumption of the house by controlling the four controllable appliances considered for the reduction resource. It should be noted that this power reduction has itself constraints and limitation, and each device has specific priority defined by the house inhabitants, and algorithm respects these priorities in order to maintain the user comfort and preferences level. In this condition, the daily electricity cost for the house in this scenario calculated in HEMS by considering the optimal usage of RER generation and reduction capacity is 3.28 EUR. Although the electricity price in this scenario is the same as scenario 1 (simple tariff), this proves the impact of using home-scale RERs and employing an optimization-based HEMS for resource scheduling.

C. Scenario 3

This subsection presents the obtained results of running the optimization algorithm, based on TOU tariff with full equipment of HEMS including ESS. In the previous scenario, the optimization algorithm was implemented in simple tariff, and there was not any price variation during all periods. However, in this scenario (according to the prices in Fig. 3) there are three different prices in different periods of a day, therefore, employing ESS would be profitable in order to reduce the daily electricity bill. One of the effective functionalities of the developed model can be utilized in this scenario, which is ESS can be charged in the period with low electricity prices and discharge it in the critical periods or in the periods with high prices. Different priorities are defined for the resources in different periods. This priorities and preferences will change, based on the price variations in order to minimize the electricity bill as much as possible. Fig. 6, represents the obtained scheduling results, for a full day based on the price variation in TOU scheme pricing.

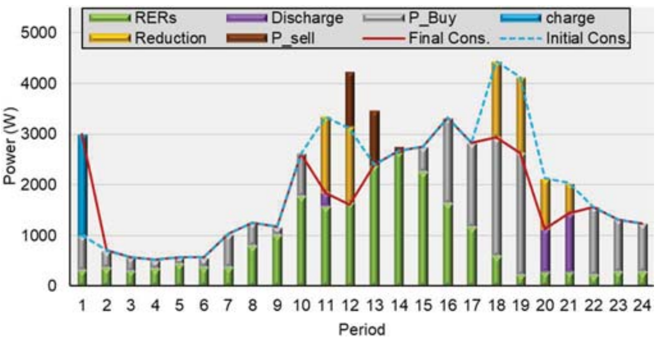

Fig. 6. Scheduling results under TOU pricing scheme.

In this scenario, the initial charge of ESS is considered equal to zero. As Fig. 6 shows, in the first period, according to the low price of electricity, the HEMS decided to purchase power from the grid and fully charges the ESS. Similar to the previous scenario, the RERs are the first priorities of the HEMS to supply the demand in all period. Therefore, HEMS requests RERs to provide their maximum generation capacity. In the periods that electricity price is low, after utilizing all RERs generation, the system purchased energy from the grid and it did not utilize the reduction resource in order to maintain the comfort of users, since interrupting the appliances and reducing consumption in the periods with low electricity prices, is not a reasonable solution. Moreover, in the periods that the consumption is too much higher than the RERs generation, the algorithm reduces the power consumption, by applying the reduction resource and interrupt the controllable appliances in the home. Different situations and different decisions of the algorithm can be seen in Fig. 6. In periods 11 and 12, since the electricity price is high, the algorithm must use all its capability to avoiding purchasing electricity from the grid. Therefore, in these periods, after using the RERs generation, the system reduced the power consumption from the appliances and discharged the ESS in period 11, to avoid buying energy from gird. It is clear that the priority for the surplus energy is to charge the ESS, however, while the ESS is full of charge, the next priority belongs to sell to the grid. That's why in periods 12-13, regarding the significant RERs generation and power reduction in period 12, the system was able to sell the surplus of RERs generation to the grid. Moreover, in periods 18 to 21 in Fig. 6, according to high power consumption compared with power generation, the system reduced the total power consumption by interrupting one or more controllable loads. Also, in periods 20 and 21, since the electricity price is high, and the RERs generation is not sufficient, so the system first decided to discharge the ESS, and then it utilized the reduction resources to prevent to purchase electricity from the grid. In this scenario, the developed system applied all available resources and capabilities that it could perform in order to reduce and minimize the electricity bill as much as is possible. Therefore, the daily energy bill in this scenario under TOU pricing scheme has been calculated by HEMS, which is 2.14 EUR for the entire day. This reduction of the cost validates the performance of the HEMS by considering the price variations in 24 hours.

D. Results Comparison

The main idea of this part is to have an overview of the obtained results in the three described scenarios. The first scenario demonstrated an ordinary residential house without any HEMS and any RERs generator. The other two scenarios presented a house that equipped with HEMS, PV system, wind turbine, ESS, and an optimization algorithm for optimally scheduling the available resources with the aim of minimizing the electricity bill. Fig. 7 shows the comparison of the final scheduled consumption profiles during three scenarios

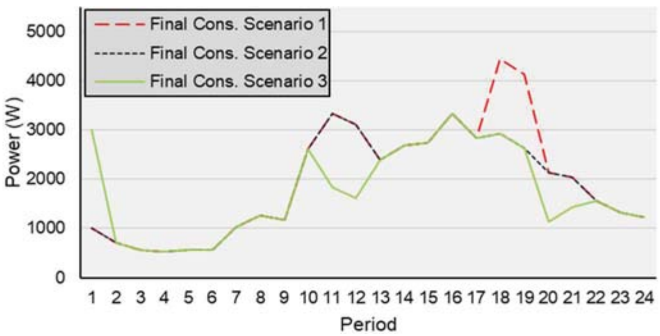

Fig. 7. Consumption profile comparison during three scenarios.

As it can be seen in Fig. 7, in the third scenario the reduction resources are more employed comparing with scenario 2. However, a peak of consumption between period 17 to 20 has been reduced in scenario 2. Furthermore, Fig. 8 illustrates the accumulated price comparison for the three scenarios for a day. The benefits of using optimization-based HEMS equipped with RERs can be seen obviously in Fig. 8.

The electricity cost from 7.45 EUR, has 4.17 EUR decrement in scenario 2, and 5.31 EUR reduction in scenario 3. For more clarifying this cost comparison, Table 1 demonstrates the details of daily electricity price during the three scenarios.

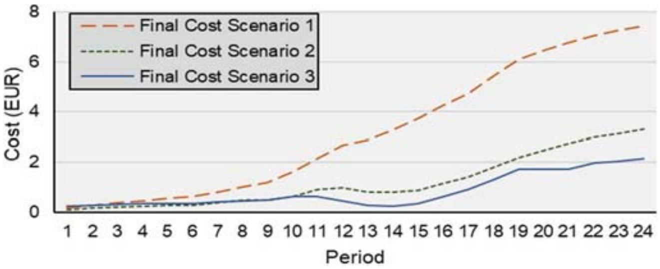

Fig. 8. Accumulated costs for one day in three implemented scenarios.

TABLE I. COSTS COMPARISON FOR THREE SCENARIOS

Scenario	*Tariffs/ Features*	*Daily Cost (EUR)*	*Cost Reduction (Compared to Scenario 1)*
1	No HEMS Simple Tariffs	7.45	–
2	HEMS without ESS Simple Tariffs	3.28	56 %
3	Full HEMS TOU scheme	2.14	71 %

As it is clear in Table I, the amount of cost reduction in scenario 2 is 56 % comparing with scenario 1, and 71 % in scenario 3 comparing with scenario 1. This proves the functionalities and capabilities of the developed optimization-based HEMS, which has acceptable performance while there is variation in the electricity prices schemes, such as TOU or real-time pricing.

V. CONCLUSIONS

Increasing electricity demand and the current state of electricity production, need to investigate more than before about energy optimization and using renewable energy resources on the demand side. Residential houses are suitable for energy consumption management and they can be optimized through mathematical optimization problems.

An optimization-based home energy management system has been proposed in this paper with the aim of minimizing daily electricity bill. The methodology was considered that the system is equipped with renewable energy resources, including a photovoltaic system as well as a wind turbine, an energy storage system, and also it is capable to transact energy with the grid. Furthermore, four home appliances were considered in the model, which can be controlled by the home energy management system. The final results of the optimization problem were the optimal resources scheduling, by relying on the electricity tariffs of the grid. In the case study, three different scenarios examined and validated the performance of the system in various situations. Simple electricity tariffs and time-of-use pricing schemes were utilized in the case study as the pricing programs. The final results show that how much an optimization-based home energy management system would be effective for reducing the daily electricity bills of the house, while there is variation in the electricity prices schemes, such as time-of-use or real-time pricing.

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