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Proposing and Techno-Economic Study of Smart and Integrated Electric Transportation System

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A B S T R A C T

Electric transportation systems as huge demands of main electric networks, play major role in transferring passengers and goods throughout the world. Since the peak power consumption of these systems, have time overlap with the peak power demand of main electric networks, the supplying procedure causes negative impacts on their upstream grid. One of the best solutions to alleviate the negative impacts is the utilization of regenerated energy of braking trains as a distributed generation in electric transportation system as well as the solar energy sources in other power systems. The distributed generations will penetrate into the supply chains more effectively in benefit to the energy storage systems. The scope of this study is shaving the peak power consumption of electric transportation system by proposing an integrated electric transportation system containing electric railway system, fast charging station for electric vehicles, energy storages and distributed generations. A smart energy management system defines power flow strategies so that the shifting power demand from grid point of view can be proceeded. To clarify the issue, the smart configuration is compared with the traditional system by simulating the proposed configuration in HOMER software and analyzing results.

1. Introduction

With the rapid development of industry and urbanization, the energy crisis and emissions have become serious problems facing the world today. With regard to this, transportation is considered as a huge consumer of energy. As it can be inferred from Figure 1, the emission contribution of transportation in energy usage in the EU is about 27% of the total emission [1].

Therefore, studying the emission source of the transportation system is a necessity. The electric transportation system is being the most applicable transportation mode in terms of environmental emission, economic, and energy sustainability circumstances. Hence, this mode of transportation can increase the capacity of transportation with eco-friendly energy consumption trend, if a systematic management approach could be taken into consideration. The most common and applicable systems of which are Electric Railway Systems (ERS) and Electric Vehicles (EV) [2].

Despite electric transportation benefits, some severe problems may threaten its upstream network. DC Fast Charging Stations (FCS) are one of the practical sorts of EV chargers in public places [3]. Due to the substantial required power causing undesirable peak demands, these stations though beneficial, stress their upstream grid, i.e., distribution network. Therefore,

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negative consequences such as expensive infrastructure, voltage deviation, and harmonic low load factor are imminent [4].

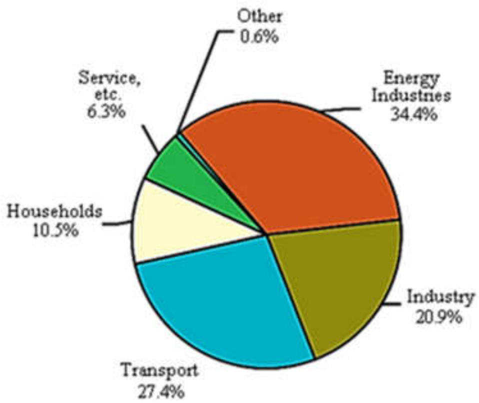

Figure 1. Total emissions by sector in EU [1]

The more EVs are penetrated into a network; the more negative impacts will appear since the penetrations may cause a demand more than the capacity limits of distribution network infrastructure. Concerning the impacts, studies on uncontrolled EV charging systems show the negative effects on transformers, for instance, the increase of EV penetration in distribution network from 17% to 31% causes a notable rise in the current of transformers from 37% to 74%.

Moreover, studies in Netherland show that the increment of EV penetration with uncontrolled charging system begets to augment national peak load from 7% to 30%. Studies in the UK also indicate that the 20% EV penetration with uncontrolled charging system, ends up to peak load up to 35.8% [4]. Consequently, predictions show that 2 million EV penetrations will occur up to 2020 in France; a typical distribution network must provide about 21 GWh per day to support the chargers of that much EVs. Nevertheless, the capacity of the existing infrastructure could not cover the level of energy mentioned above. Besides, the growing rate of renewable energy sources is lower than the EV penetrations [5].

Therefore, for alleviating these problems, in [4], the utilization of aggregators is issued to manage the EV power consumption properly. Although this approach may result in reduction of charging and discharging costs in the system, it leads to a restriction for EV owner's latitude. Moreover, using V2G is proposed as a solution, but proceeding the V2G procedures result in high aging cost of EV batteries, and uncertainties of consumer behaviors also could limit this hypothesis. On the other hand, some communication systems like Bluetooth, Z-wave, and ZigBee are proposed to make bidirectional communication between consumers and aggregators by informing consumers about real-time prices and the power quality of charging stations in a specific territory. These kinds of policies will restrict the latitude of end users by forcing them to charge their cars in specific charging stations and times. Lately, the application of Distributed Generations (DG) in the transportation sector that was investigated in [6], and [7] illustrates that the employment of Energy Storage Systems (ESSs) in a FCS reduce the negative impacts of such charging stations. These contributions help to damp the negative impacts, but they are depending on load terms and must be generalized by utilizing both DGs and ESSs in an integrated configuration.

Thanks to the development of power electronic engineering, the concept of a new DG known as Regenerative Braking (RB) appeared in ERS. This technology is about the regeneration of electrical energy during the braking procedure of trains [8–10]. As a consequence, the ERSs can exchange energy bilaterally. In [11], using time management of train headways is proposed, so that the energy regenerated from a train could be utilized for accelerating of the near train. Hardly ever, this procedure can be performed, mainly because of the incompatibility of accelerating with braking times of two near trains. In another study [12], using the regenerated energy for auxiliary loads of railway station is proposed. At this stage, a considerable amount of this energy remains as surplus energy wasting by converting into thermal energy. Therefore, researching energy storage devices (batteries, super-capacitor [13], flywheel [14], [15]), for storing the mentioned surplus energy, are hotly debated topics [16], [17].

From the review of literature, it is found that by considering the Photovoltaic panel (PV), RB, and ESSs as DER s in a new structure, a smart and integrated configuration can be proposed to improve the operation of the whole electric transportation system. The scope of this study is shaving the peak power consumption of the electric transportation system by proposing an integrated electric transportation system containing the traction power consumption of a metro station, power consumption of fast

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charging station for electric vehicles, energy storages and distributed generations. A Smart Energy Management System (SEMS) defines power flow strategies so that the shifting power demand from the grid point of view could proceed. Alleviating the negative impacts on the upstream network, cost reduction, and decreasing the size of network elements are the consequences of peak shaving.

The organization of this article is to propose the integrated system; explain the items of proposed configuration, simulation of the proposed and traditional system in HOMER software is also discussed and the results are analyzed.

2. Integrated System

To commence, the essential trait of the smart system –proposed in this context– is high level controllability of supply chain power flows. The controllability can be achieved by using SEMS as the heart of the system. Such a management system makes it possible to adapt the operations in order to respond to the demands and to make a decision about oncoming events originated inside or outside the system in real-time steps. The function of the management system is assigning each load or component, whether they should charge, discharge, supply, or be supplied. As ERSs have their power supply substations, their negative impacts on the upstream networks are less severe than FCSs, which are usually supplied by public distribution systems without specific substations. Therefore, this is recommended to both ERSs and FCSs to be supplied from the regenerated energy originating from braking trains. Coming up with a conclusion, for five items of the configuration, possibilities of power flows are as follows:

- Grid: Supplying
- PV: Supplying
- FCS: Consuming
- ERS: Consuming and regenerating (Supplying)
- ESSs: Charging and discharging

In order to integrate the whole system, an integrated configuration must be considered. Since all loads and components are working with DC voltage, a DC link is taken into account as an interface for power exchange among them as shown in Figure 2. Also, constructing DC FCSs for EVs through the city requires a massive investment while there are a lot of DC ERSs all over the city with short distances in between. Therefore, assigning a structure – supplying both loads- in this research is being proposed so that the railway infrastructure is also used for FCSs. To elaborate more, it is suggested the FCSs to be placed on the floor, located beneath the platform of the metro station. PV panels and ESSs are also placed on the roof of the station and inside the station, respectively.

Regarding the cost reduction, in a comparison between liberalized and traditional centralized markets, the former -covering DER benefits- is regarded as an economic structure to reduce the costs of the electric transportation system. Furthermore, by considering an appropriate economic infrastructure, the efficiency of energy consumption in the whole electric transportation system will improve indirectly [18].

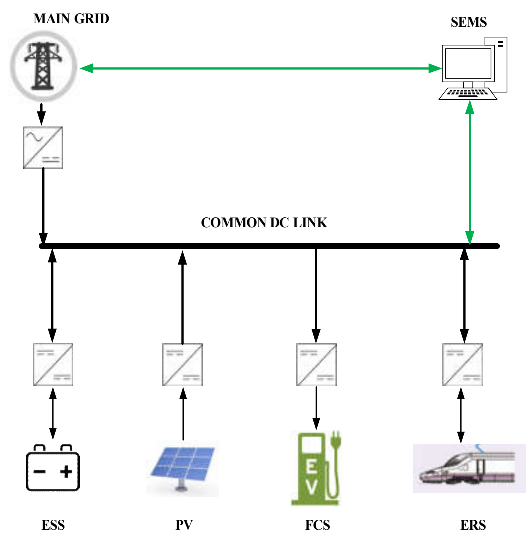

Figure 2. Proposed configuration of the smart system

3. Items of the Integrated System

3.1. Electric Railway System (ERS)

Power consumption in different steps of railway electrification is comprised of infrastructure losses, traction load, auxiliary load, motion resistance, and braking losses. A fraction of total traction energy is dissipated in braking, the amount of which depends on the type of system and its configuration. However, generally, half of the total input energy is not usable. This fraction of total energy can be increased with the frequent stops, and it has an augment in urban ones (DC railway systems) in comparison with commuter trains (AC railway systems) [19].

3.2. Fast Charging Station (FCS)

For many years, the Society of Automobile Engineers has been working on j1772 standard, which classifies charging station into three categories [20]:

Level 1: on-board charger with 120V AC voltage, which provides the maximum current of 20A and a maximum power of 1.9kW.

Level 2: on-board charger with 208 to 240V AC, which provides a maximum current of 80A and a maximum power of 19kW.

Level 3: off-board charger with a direct connection to the battery, which provides a maximum power of more than 100kW [21].

Level 3 chargers are fast chargers. Level 1 and 2 chargers are known to be slow because they obtain their power from a single AC grid. In the future, level 3 stations play the same role as gas stations today [3]. As a result, level 3 is the most applicable charger, since it enables easier integration of EVs into the market.

3.3. Energy Storage System (ESS)

The developments in power electronic and practical researches in energy storage technologies have empowered ESSs to become an excellent supplementary interface in the electrification supply chain of electric transportation. For choosing the appropriate storage in the proposed configuration, the issue can be better tracked by a comparison between batteries and supercapacitors. Batteries and supercapacitors enjoy the best energy density and power density among the storages, respectively [22]. As the concentration of this study is around alleviating the negative impacts of FCSs on their upstream grid, batteries are chosen as ESSs. Because EVs need to be supplied for about half an hour in FCSs.

3.4. Photovoltaic Panels (PV)

Local energy generation is required as an alternative solution to the proposed configuration in order to reduce pollution and optimize the power demands from the main electric network. Solar power generation around the charging station for electric vehicles and electric railway system can potentially be introduced by utilization of them on platform roofs, along the track of railways, station roofs, sound or windbreak walls, and roof of maintenance depots [10], [23].

4. Simulation and the Result Analysis

In this section, the proposed system is simulated in HOMER software. Figure 3 illustrates the designed configuration of the proposed system in HOMER software, according to Figure 2. The objective of the simulation is peak shaving by applying the smart strategies of power flows to the integrated configuration, including the ERS and FCS loads, solar generations, and regeneration of trains. Since the cost reduction is the constraint by which the scope of peak shaving can proceed (the price of electricity in peak hours is higher), the cost modeling is explained in order to elaborate the procedure.

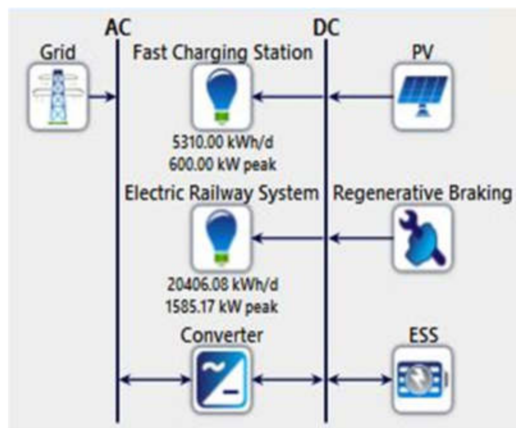

Figure 3. Proposed configuration in HOMER software

4.1. Cost Modeling

The total cost of the project, C_T must be minimized in Equation (1).

$$C_T = \sum_{t-1}^{T} C_{(t)} \times P_{Grid(t)} + C_{Component} \quad (1)$$

In Equation (1), P_{Grid}, $C_{(t)}$ and T denotes the power purchased from the grid in each time step, the hourly power price, and total operation time, respectively. $C_{Component}$ is the cost of components with consideration of maintenance expenses during operation time, while the capital cost contains just the initial investment. In order to convert the initial capital cost into the annual capital cost, Capital Recovery Factor (CRF) is defined in Equation (2) [24].

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$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (2)$$

n is the life span of the system, and i stands for the interest rate. The information for the component parameters is given in Table 1.

Table 1. Component parameters [24]

Parameter	Value
i	5%
n	25 years
η_{pv}	12%
$\eta_{Rectifier}$	95%
$\eta_{Battery}$	90%
$\eta_{Regenerative\ Braking}$	90%

4.2. Peak Shaving

The aim of peak shaving is followed by defining the state of power flow for all the loads and components by SEMS at each step time, as discussed in part II (supplying, consuming, charging, and discharging). Therefore, Equation (3) is issued with resulting in the best strategy for each parameter during the day.

$$P_{Grid} = P_{Fast-Chariging} + P_{Railway} + P_{ESS} - P_{PV} - P_{Regen} \quad (3)$$

P_{Grid}, $P_{Fast-Chariging}$, $P_{Railway}$, P_{ESS}, P_{PV} and P_{Regen} represent the power purchased from the grid, the load of FCS, the load of ERS, battery State of Charge (SOC) , generation of PV, and regenerations of braking trains, respectively. The variables of Equation (3), i.e. P_{Grid} and P_{ESS} are calculated by applying Multi Objective Particle Swarm Optimization (MOPSO) to the equation through the constraints which are demand meeting, battery controlling strategy and minimization of C_T in Equation (1). The other four parameters have the daily power curve.

Regarding the battery controlling, different constraints are defined according to the price of electricity during the day, as shown in Figure 4. In off-peak times (Green), the price of electricity is 0.04$ per kWh. In these times, the battery is prohibited from discharging, so that the battery can be charged during these hours -having a lower price- and consequently discharge it during peak hours -having a higher price. Subsequently, in peak hours (Red) -pricing 0.12$ per kWh- the battery is discharging and prohibited from any charging scenario. As for shoulder times (Blue) -pricing 0.06$ per kWh- the battery is prohibited from charging. Lately, the sell back to grid scenario is also prohibited in this study. Therefore, the demand is shifting from the grid point of view by consuming the battery as a load for the grid in off-peak times and providing energy instead of the grid in peak-time. Therefore, the peak loads can be shaved by applying this charging strategy.

As for consumptions, the daily traction load profile ($P_{Railway}$) of a sample 750 V ERS is shown in Figure 5. The FCS daily load profile ($P_{Fast-Chariging}$) also by considering five chargers (each one 120kW) is presented in Figure 6.

Figure 4. Green: Off-Peak – Red: Peak – Blue: Shoulder

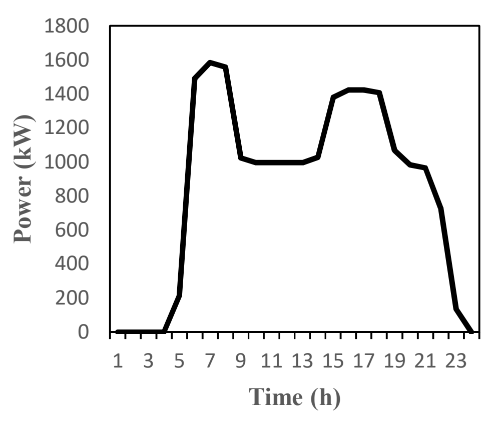

Figure 5. Electric Railway System daily load curve

The output power of PV can be calculated according to Equation (4).

$$P_{PV} = S_{PV} \times I_r \times \eta \quad (4)$$

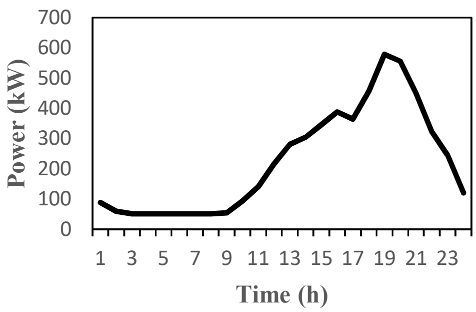

Figure 6. Fast Charging Station daily load curve – $P_{Fast\text{-}Charging}$

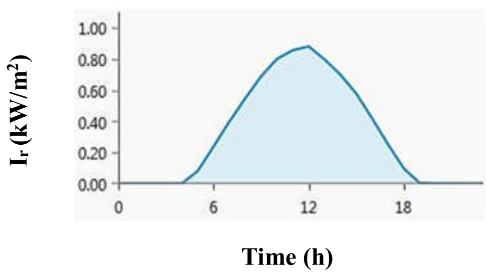

Figure 7. Radiation index during the day

In this equation I_r and S_{PV} represent the daily radiation index and available area, respectively. The efficiency (η) is 12% in the proposed system. Since the discussed sample metro station has about 800m^2 space for installing PV panels, the system can generate a maximum of 100kW at maximum radiation during the day that is depicted in Figure 7. Monthly average radiation and cleanness indexes are also shown in Figure 8. Ultimately, the daily output power of PV (P_{PV}) during the year is shown in Figure 9.

In the middle of the day, solar generations are more than other times, but the SEMS restricts the possibility of consuming this power. It may be stored in the battery and consequently discharged at the peak time according to the optimized value of power flow at each step time.

About the regenerative braking, the passenger capacity of trains in 750 V sample metro station is 1500 people at full load state, and headways are between 2 to 5 minutes depending on the demand. By considering different mass and headways during the day, the regeneration of braking trains is simulated in MATLAB environment so that the daily power generation curve of this DG could be entered into the Equation (3).

Consequently, the output of the MATLAB file is input as a custom resource module in

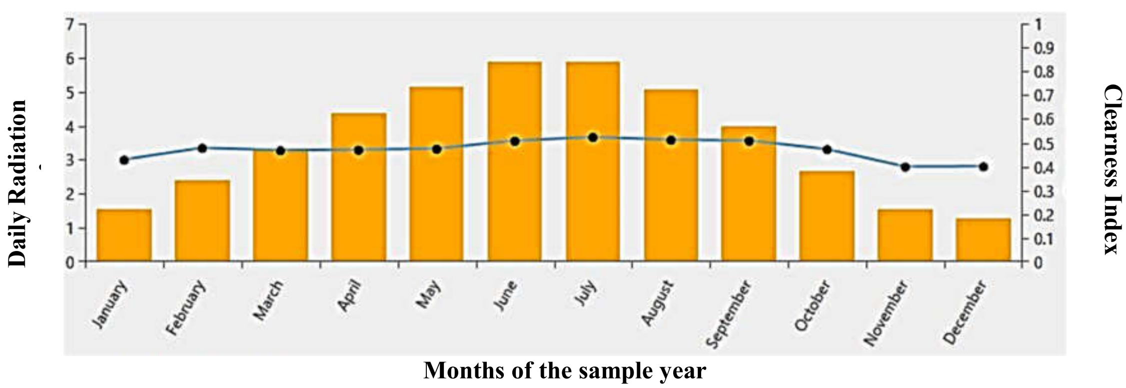

Figure 8. Monthly average solar radiation and cleanness

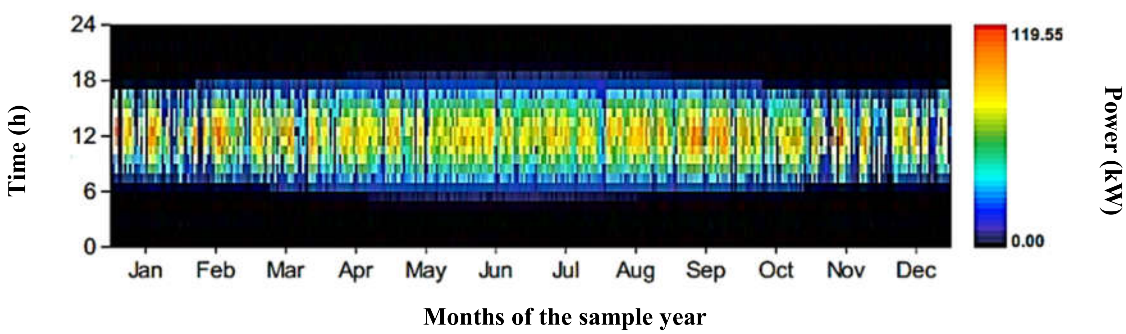

Figure 9. PV output power daily graphic curve during the year

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HOMER software. Figure 10 depicts the daily regeneration curve of braking trains.

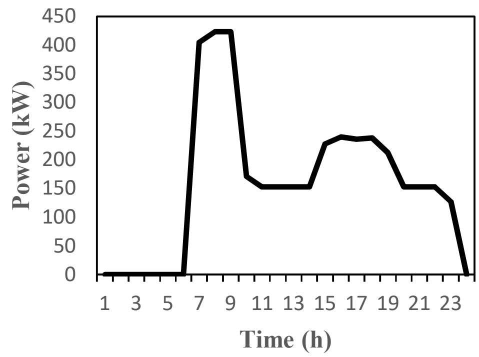

Figure 10. Regenerated power of braking trains daily curve

Different kinds of batteries are simulated in HOMER software. A 2000 kWh battery is found as the most suitable one for this configuration. As a result of the simulation, the batteries with lower capacity cannot respond to the needed energy during peak hours. The daily behavior of the battery as a variable of Equation (3), during the year, is presented in Figure 11. The SOC of the battery during the day varies between 40% to 80%. As it is shown in Figure 11, the controller forces the battery to be charged in off peak times according to the battery controlling strategy defined for the management procedure. This makes the SOC of battery increased (orange color illustrates the 80 percent state of charge) through the off-peak times by considering the battery as a load from the grid point of view.

Consequently, the transportation loads can be partly supplied by the battery during peak times. As the green color shows the 40 percent state of charge, it can be inferred that the battery is playing a supplementary role by supplying a noticeable amount of energy during the peak times. Therefore, the aim of peak shaving can be followed.

Ultimately Figure 12 indicates the absorbed power from the grid in the smart (a) and the traditional (b) system. Due to the DG utilization (PV and regenerative braking), the total purchased energy from the grid during the year is reduced about 25%. Moreover, the orange color shows the power consumption in peak times (about 18 o'clock), which is reduced around 20% in the smart proposed system in comparison with the traditional system. In order to shave the peaks, the portion of demand from the grid point of view has been shifted from peak hours to early morning (off-peak time).

Alleviating the negative impacts, reduction of cost, optimizing the size of network elements (transformer capacity, cable sizing, ventilating components) are the consequences of peak shaving proceeded in this study. Additionally, the procedure of peak shaving increases the converter lifetime. The postponement of converter replacement also reduces the total cost of operation during the lifetime of the project.

From an economic point of view, two million USD was invested in the new proposed system, the capital of which was recovered after nine years. After that, the system mentioned above would make a profit. Following the results arising from the simulation, the volume of this profit will have amounted to approximately three million USD in the 25th year.

5. Conclusions

In this research, an integrated, smart, and sustainable electrified transportation system is proposed which is consisting of electric railways system and fast charging station benefiting from solar generation and regenerated energy of braking trains for their power supply chain. The

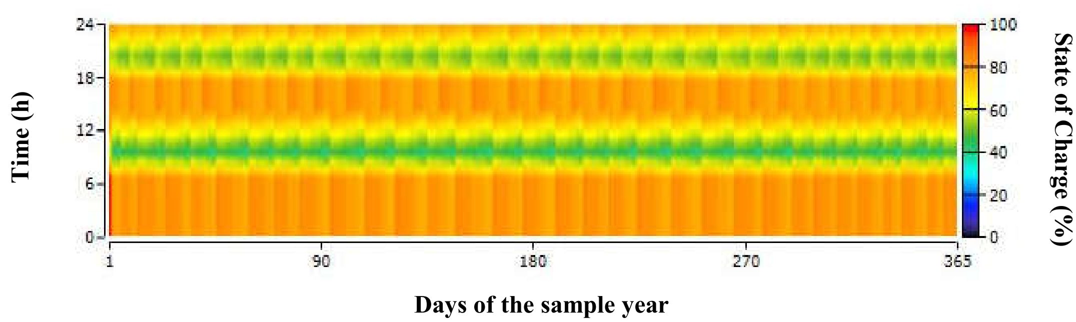

Figure 11. Daily Battery state of charge during the year

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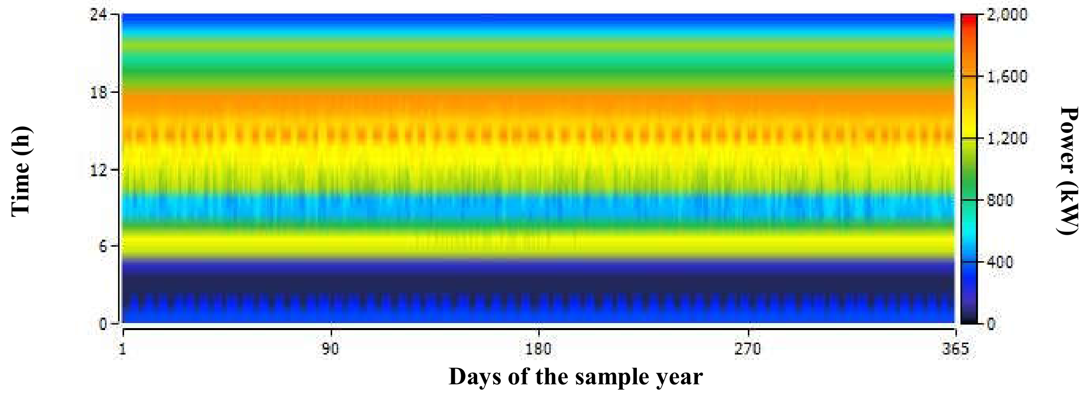
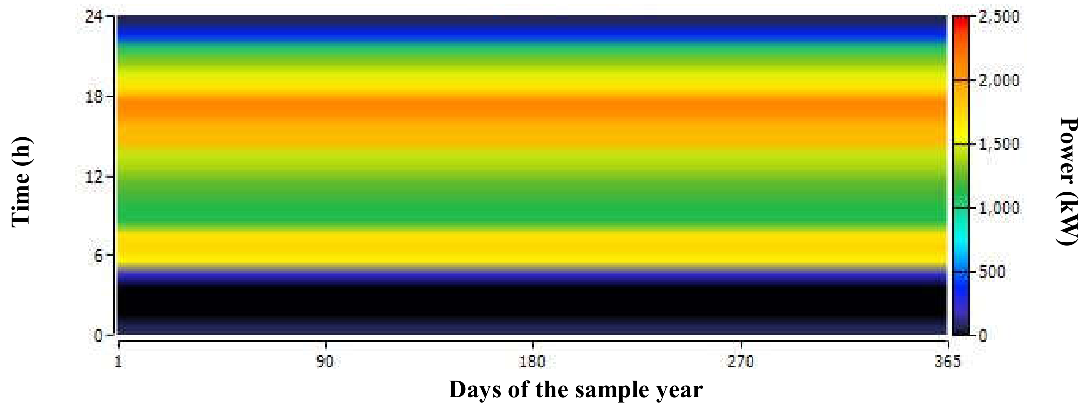


(a)



(b)

Figure 12. Daily purchased energy from the grid in the proposed system (a) proposed system (b) Traditional system

techno-economic comparison was made by using HOMER software between the traditional and proposed systems. The proposed system demanded less power in comparison with traditional systems at peak times about 20% by applying the control strategy to the battery and defining a cost reduction equation through a smart energy management system. Besides, the utilization of DGs proposed in the article caused the reduction in annual purchased energy from the grid about 25% and from the costs. By considering all of the issues mentioned above, and the cumulative cash flows, the initial investment of this project is also justifiable.

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