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OPTIMIZATION OF DAILY SCHEDULE FOR ELECTRIC VEHICLES CHARGING TO MINIMIZE THE ENERGY COSTS

Abstract: In this paper, an optimization problem of the daily schedule for charging/discharging of electric vehicles (EVs) is solved in order to minimize the energy costs. Results are obtained for the microgrid with renewable energy sources and the savings are calculated based on daily curves of non-deferrable load demand, photovoltaic and wind energy production and variable buying/selling energy prices from the energy market. The optimization results are given for different battery capacities of EVs fleet, charger power and types of renewable energy sources. Lingo program is used to solve this optimization problem.

Keywords: optimization, electric vehicle charging, energy costs, renewable energy sources.

INTRODUCTION

Renewable energy sources, new transportation systems and other clean technologies together with energy management and innovations in existing infrastructure present efficient tools to mitigate global warming, environmental pollution and emission of green-house gasses, with the aim to achieve sustainable development.

Smart grids combine traditional electricity grids and microgrids with contemporary communication and information technologies. Deferrable loads such as heating/cooling devices and charging/discharging of electric vehicles are good opportunities at demand-side management using innovative energy storage devices, photovoltaic and wind energy production. Vehicle-to-grid (V2G) technology enables an important advantage of electric vehicles in smart grids to be used both as flexible demand sources and storage units [1-6].

PROBLEM FORMULATION

Microgrid structure

The main components of the microgrid analysed in this paper are non-deferrable loads, wind turbines, PV panels, storage devices and charging stations for electric vehicles with the available V2G technology. These components are connected to the main grid and controlled by the energy management system (Fig.1).

Optimization problem

The intermittency of renewable energy sources and day-ahead energy prices available at the energy market provide an interesting possibility to reduce energy costs and investments in improvements and maintenance of power systems. Optimization and scheduling in using the V2G option may be done on a daily basis, using prices for a 24-hour period and daily curves of estimated energy production by PV and wind generators at a certain location. The characteristics of storage devices constantly improve as well as energy management systems based on new communication and information

technologies. Bidirectional power flow inside microgrid is available for storage devices and batteries of electric vehicles.

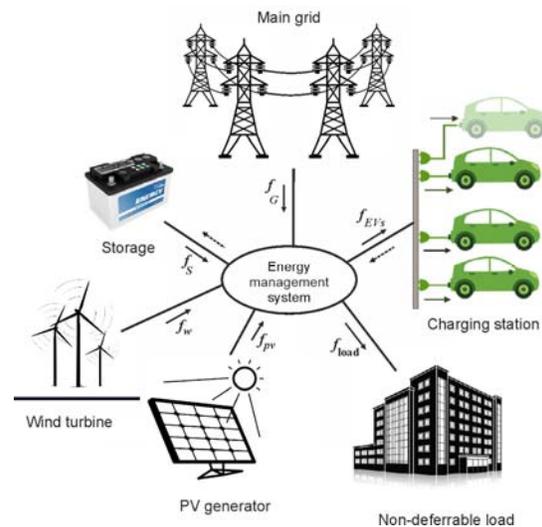


Figure 1. Microgrid structure

Parameters in using V2G technology which should be taken into account are: defined time intervals for driving the vehicles, number of chargers at the charging station, chargers power capacities, maximum driving ranges of the vehicles, battery capacities, state-of-charge (SoC), battery lifetime and degradation based on the maximum depth-of-discharge (DoD), number of charging cycles, operation temperature, total energy withdrawn, etc.

The mathematical model of this problem results in the goal function which should be minimized with the given constraints. Optimization is done by using Lingo [7] in this paper; however, other programs may be also used, such as MATLAB (e.g. in [8]), Yalmip, Excel Solver, etc.

One microgrid structure with renewable energy sources is presented in Fig.1. Storage devices, except batteries of electric vehicles, are not considered in this paper.

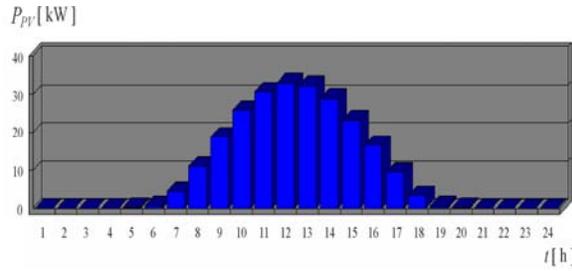


Figure 2. The daily curve of PV energy production

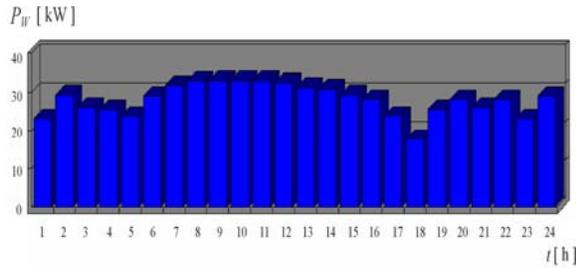


Figure 3. The daily curve of wind energy production

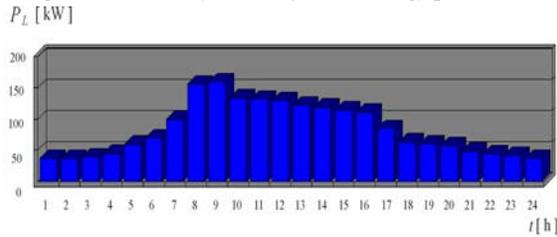


Figure 4. The daily curve of non-deferrable load

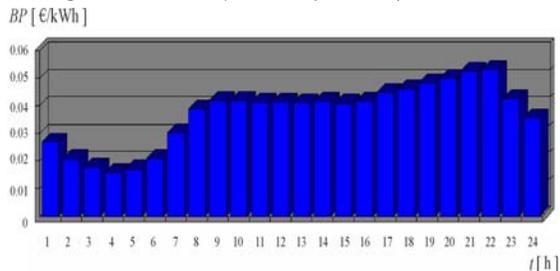


Figure 5. The daily curve of buying prices at SEEPEX electricity market [15] for Monday, July 6th, 2020

The list of variables used in this paper is as follows:

$P_{PV}(i)$ – power produced by photovoltaic (PV) panels in the i -th hour, for $i=1, \dots, 24$;

$P_W(i)$ – power produced by wind turbines in the i -th hour, for $i=1, \dots, 24$;

$P_L(i)$ – power of non-deferrable loads in the i -th hour, for $i=1, \dots, 24$;

$P_{EV}(i)$ – total charging demand power of all electric vehicles (EVs) in the i -th hour, for $i=1, \dots, 24$;

$P_G(i)$ – total power demand from the main grid in the i -th hour, for $i=1, \dots, 24$;

$P_{tot}(i)$ – optimized total power demand from the main grid in the i -th hour, for $i=1, \dots, 24$;

$SOC(i)$ – state of charge at the beginning of the i -th hour interval, for $i=1, \dots, 24$;

$BP(i)$ – buying price in the i -th hour, for $i=1, \dots, 24$;

$SP(i)$ – selling price in the i -th hour, for $i=1, \dots, 24$;

$x_B(i)$ – the discrete variable equal to 1 if the energy is bought from the main grid in the i -th hour, 0 if not, in the i -th hour, for $i=1, \dots, 24$;

$x_S(i)$ – the discrete variable equal to 1 if the energy is sold from the main grid in the i -th hour, 0 if not, in the i -th hour, for $i=1, \dots, 24$;

$x(i)$ – the discrete variable equal to 1 if the energy is bought from the main grid, -1 if the energy is sold from the main grid, 0 if the vehicle is either driving or staying at the station, neither charging nor discharging in the i -th hour, for $i=1, \dots, 24$.

For the chosen scenarios, the PV panels have a peak power of 33kW. The daily curve of energy production is estimated based on solar irradiation in Bavanište, South Banat, Serbia [9] for the average day of the year 2009. $P_{PV}(i)$, for each hour $i=1, \dots, 24$, is given in Fig. 2.

Wind turbines also have a peak power of 33kW. The daily curve of energy production is obtained by WASP software (Wind energy industry-standard software) [10] for parameters in [11], for the year 2011, in Banat, Serbia. $P_W(i)$, for $i=1, \dots, 24$, is given in Fig. 3. The peak power is chosen the same as for PV panels in order to estimate which type of renewable energy source is more suitable for minimizing the energy costs in this microgrid.

The daily curve of non-deferrable loads for one company [12-14] is given in Fig. 4 as $P_L(i)$ in each hour $i=1, \dots, 24$.

In [13] and [14], EVs are treated as a fleet, whereas in this paper for some vehicles different battery capacities are chosen in order to consider which achieves greater savings. Besides, the costs are optimized for various charger power. There is the charging station in this microgrid with $n=5$ chargers of power $P_{ch}=3.3$ kW or $P_{ch}'=9.9$ kW, available for V2G service. $P_{EV}(i)$, for $i=1, \dots, 24$, has to be optimized in order to minimize the costs.

Total power demanded from the main grid is

$$P_G(i) = P_L(i) - P_{PV}(i) - P_W(i) + P_{EV}(i). \quad (1)$$

This power has limited value so that the constraint is $P_G(i) \leq P_{G \max}$. The daily curve of the buying prices $BP(i)$ is given, for each hour $i=1, \dots, 24$, in Fig. 5. It is taken from the website [15] of SEEPEX electricity market operator, for Monday, July 6th, 2020. It is assumed that the selling prices are 75% of the buying prices so that $SP(i)=0.75 BP(i)$.

The goal function for optimization is the costs function

$$C_{COST} = \min \left\{ \sum_{i=1}^{24} P_{ch} \cdot n_V \cdot [BP(i) \cdot x_B(i) - SP(i) \cdot x_S(i)] - SP(i) \cdot n_{PV} \cdot P_{PV}(i) - SP(i) \cdot n_W \cdot P_W(i) + BP(i) \cdot P_L(i) \right\}, \quad (2)$$

to be minimized by optimal EVs charging/discharging. However, EVs are used for driving at specified time intervals during the day when they are not available at the charging station. The vehicles are used for driving from 10 am to 4 pm (for 6 hours within the working time of the company). In this paper, $n_W=1$, $n_{PV}=1$ have been chosen.

Various scenarios of electric vehicles fleet

Variable SoC is defined in percentages of battery capacity at the beginning of the i -th interval. In each interval, SoC of the electric vehicle battery should be from 20% to 100%, so this is the constraint:

$$20 \leq SOC(i) \leq 100, \quad i = 1, \dots, 24. \quad (3)$$

Scenario 1: there are 5 vehicles available for driving and charging/discharging. Small EVs such as Nissan Leaf with the battery capacity of $en_{EV}=30\text{kWh}$ have range distances from 100km to 200km with their fully charged batteries. If one vehicle makes 166.7km with its full battery capacity, then for 55km it needs 33% of its capacity. For 6 hours of driving and 55km distance, it means that SoC decreases on average 5.5% per hour. If EVs were fully charged, SoC decreased to 67% after the driving period. For the next 18 hours (from 4 pm to 10 am) all EVs are available for charging/discharging at the station. If the charger power is $P_{ch}=3.3\text{kW}$ and $P_{ch}/en_{EV}=0.11$, it means that SoC increases/decreases by 11% per hour when charging/discharging. It is assumed that there is the same efficiency of charging and discharging. Each EV has to be charged for a minimum of 3 hours to get the energy of 9.9kWh (in total 49.5kWh for 5 vehicles i.e. 33% of 150kWh).

Scenario 2: there are 3 vehicles available with the battery capacity $en_{EV}=50\text{kWh}$ which results in 150kWh in total as in Scenario 1. If the vehicle makes 277.8km with its full battery capacity, then for 91.67km it needs 33% of its capacity. Consumption of energy for the same driving distance differs for lesser than 10% for these and small EVs [16]. For example, energy consumption for Tesla S vehicle with the battery capacity 85kWh is 0.233kWh/km and for Nissan Leaf with the capacity 24kWh, it is 0.211kWh/km, which differs by 9.44%. Thus, it may be considered that the same distance of 275km is driven by these 3 vehicles as by 5 with smaller capacity in the first scenario. For 6 hours of driving and 91.67km distance per vehicle, it means that SoC decreases on average 6.6% per hour. If the battery was fully charged, SoC decreased to 67% after the driving period. In that case, EVs have to be charged for a minimum of 5 hours during the next 18 hours at the station by the chargers of power $P_{ch}=3.3\text{kW}$ to get the energy of 16.5kWh (in total 49.5kWh for 3 vehicles).

SoC at the beginning of the i -th interval is calculated based on the SoC at the beginning of the $i-1$ interval and added or subtracted energy in that interval as $x(i-1)$

is of value 1 or -1. If there is neither charging nor discharging, SoC does not change.

$$SOC(i) = SOC(i-1) + x(i-1) \cdot P_{ch} / en_{EV} \cdot 100. \quad (4)$$

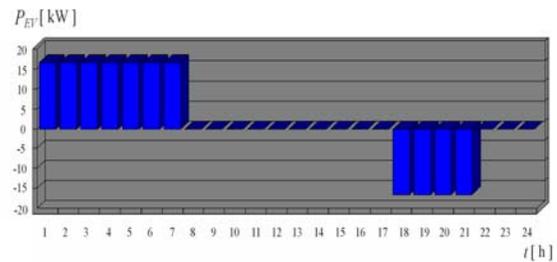


Figure 6. Optimized daily schedule for Scenario 1 case a) charging/discharging 5EVs with $en_{EV}=30\text{kWh}$ and $P_{ch}=3.3\text{kW}$

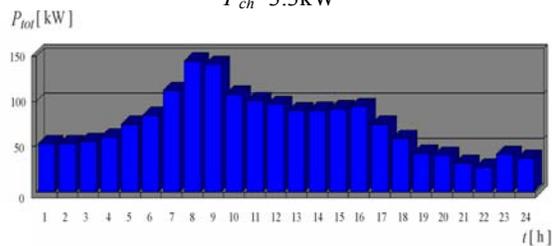


Figure 7. The daily schedule of total energy demand after optimization of charging for Scenario 1 case a)

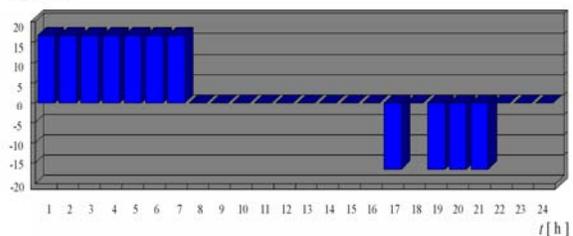


Figure 8. Optimized daily schedule for Scenario 1 case b) charging/discharging 5EVs with $en_{EV}=30\text{kWh}$ and $P_{ch}=3.3\text{kW}$

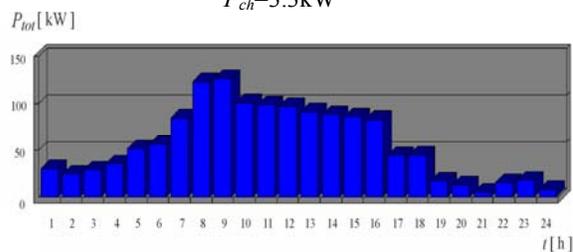


Figure 9. The daily schedule of total energy demand after optimization of charging for Scenario 1 case b)

Scenario 3: there are 3 EVs available, one of these with the battery capacity of $en_{EV1}=30\text{kWh}$ and two with $en_{EV2}=60\text{kWh}$ which results also in 150kWh in total as in previously discussed scenarios.

For the lower capacity vehicle, a minimum of 3 hours is needed for charging whereas for the higher capacity vehicles a minimum of 6 hours with the chargers of power $P_{ch}=3.3\text{kW}$.

Scenario 4: the same as Scenario 1, but for the chargers of power $P_{ch}'=9.9\text{kW}=3P_{ch}$, so that each EV takes at least 1 hour to charge.

Scenario 5: the same as Scenario 3, but for the chargers of power $P_{ch}'=9.9\text{kW}$, so that for the lower capacity EV minimum of 1 hour is needed for charging and for the higher capacity EVs at least 2 hours.

RESULTS OF OPTIMIZATION

Various types of renewable energy sources

For each of these scenarios the optimization is done for two cases: a) PV panels are working, wind generators are not working, b) wind generators are working, PV panels are not working. For Scenario 1 case a) the optimized daily schedule of EVs charging/discharging is obtained as given in Fig. 6. The daily schedule of the total energy demand to the main grid $P_{tot}(i)$ is given in Fig. 7. For Scenario 1 case b) the optimized daily schedule is obtained as given in Fig. 8, and the daily schedule of $P_{tot}(i)$ in Fig. 9.

Per each hour the sum of non-deferrable load demand $P_L(i)$ and EVs charging demand $P_{EV}(i)$ is greater than the production of renewable energy sources, as can be noticed in Figs. 7 and 9. The results of optimization for Scenario 2 cases a) and b) are given in Figs. 10 and 11, whereas for Scenario 3 in Figs. 12-15. It can be concluded that wind generators provide greater savings than PV panels if calculated per peak power installed.

Various chargers' power

Scenarios 4 and 5 are the same as Scenarios 1 and 3 except that the chargers are with three times greater power so that charging/discharging is three times faster.

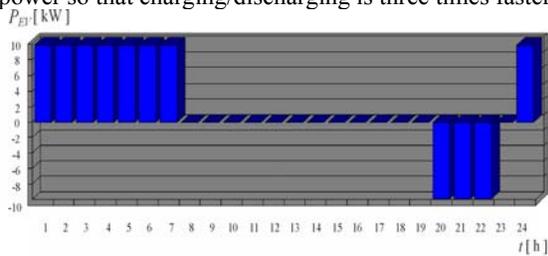


Figure 10. Optimized daily schedule for Scenario 2 case a) charging/discharging 3EVs with $en_{EV}=50\text{kWh}$ and $P_{ch}=3.3\text{kW}$

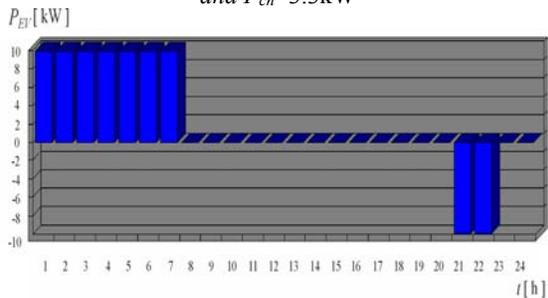


Figure 11. Optimized daily schedule for Scenario 2 case b) charging/discharging 3EVs with $en_{EV}=50\text{kWh}$ and $P_{ch}=3.3\text{kW}$

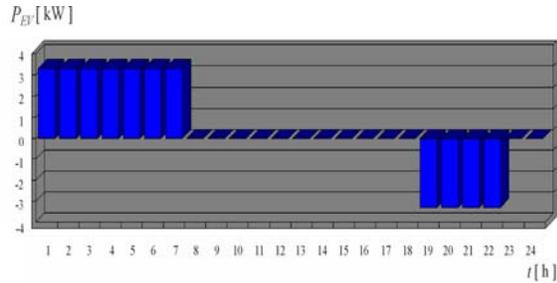


Figure 12. Optimized daily schedule for Scenario 3 case a) charging/discharging 1EV with $en_{EV1}=30\text{kWh}$ and $P_{ch}=3.3\text{kW}$

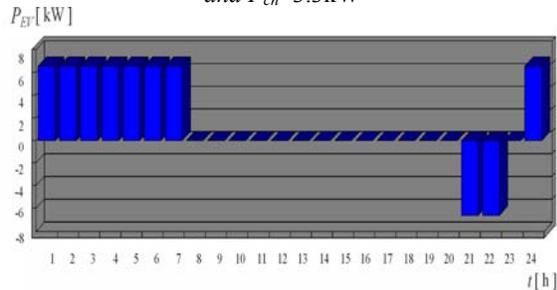


Figure 13. Optimized daily schedule for Scenario 3 case a) charging/discharging 2EVs with $en_{EV2}=60\text{kWh}$ and $P_{ch}=3.3\text{kW}$

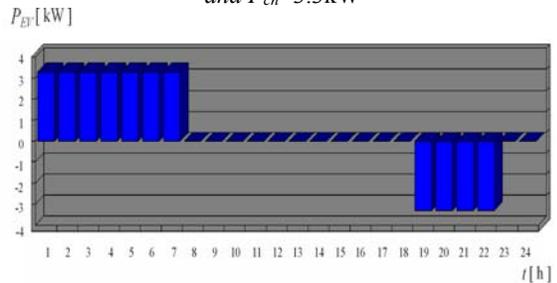


Figure 14. Optimized daily schedule for Scenario 3 case b) charging/discharging 1EV with $en_{EV1}=30\text{kWh}$ and $P_{ch}=3.3\text{kW}$

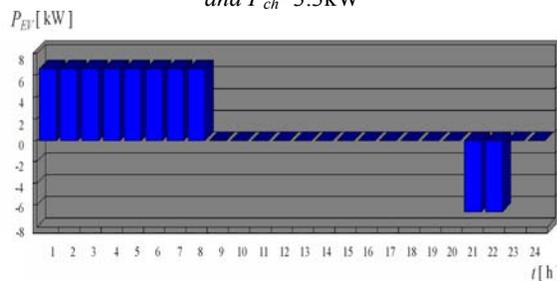


Figure 15. Optimized daily schedule for Scenario 3 case b) charging/discharging 2EVs with $en_{EV2}=60\text{kWh}$ and $P_{ch}=3.3\text{kW}$

The same results are obtained for both Scenarios 4 a) and b), as given in Fig. 16. Results for Scenarios 5 a) and b) are given in Figs. 17-20. Costs are reduced in case b) if compared to case a) for 16.21% in Scenario 1, for 16.16% in Scenario 2, for 16.15% in Scenario 3, for 16.35% in Scenario 4, and for 16.33% in Scenario 5.

The savings for scenarios with different EVs power capacity (for the same total energy used) do not differ significantly. However, the greatest savings are

obtained for Scenarios 4 and 5 for charging/discharging by more powerful chargers.

Charging strategy for electric vehicles should be also considered for the various energy buying prices at the market for different days in a week.

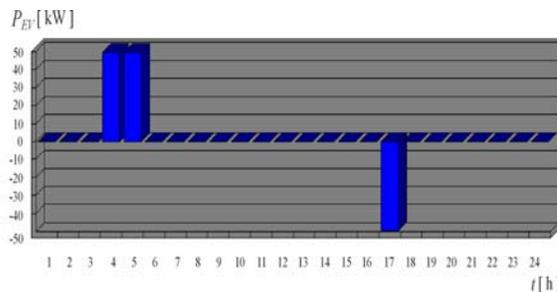


Figure 16. Optimized daily schedule for Scenario 4 both cases a) and b) charging/discharging 5EVs with $en_{EV}=30kWh$ and $P_{ch}'=9.9kW$

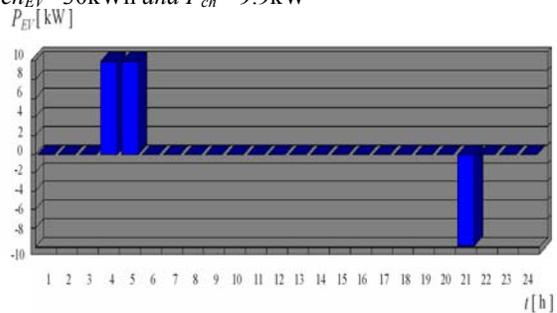


Figure 17. Optimized daily schedule for Scenario 5 case a) charging/discharging 1EV with $en_{EV1}=30kWh$ and $P_{ch}'=9.9kW$

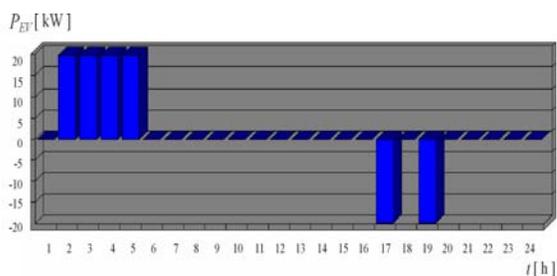


Figure 18. Optimized daily schedule for Scenario 5 case a) charging/discharging 2EVs with $en_{EV2}=60kWh$ and $P_{ch}'=9.9kW$

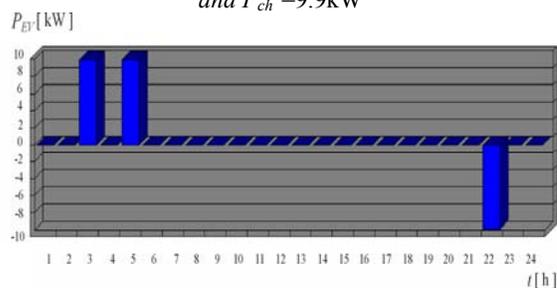


Figure 19. Optimized daily schedule for Scenario 5 case b) charging/discharging 1EV with $en_{EV1}=30kWh$ and $P_{ch}'=9.9kW$

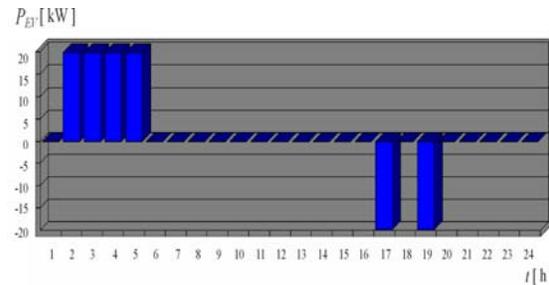


Figure 20. Optimized daily schedule for Scenario 5 case b) charging/discharging 2EVs with $en_{EV2}=60kWh$ and $P_{ch}'=9.9kW$

If compared to Wednesdays or Thursdays, buying prices may be about twice lower on Sundays and Saturdays. This is concluded based on buying prices from the SEEPEX power exchange market [15]. It makes days of the weekend (especially Sunday) preferable for charging if a vehicle was not driven meanwhile or DoD did not reach 80%.

CONCLUSION

The day-ahead offered variable energy buying prices at the energy market to enable reducing the energy costs in the case of using V2G technology of EVs.

Wind generators provide greater savings than PV panels per peak power installed but require greater investments. EVs are treated as a fleet. It is concluded that a fleet with a greater number of EVs of lower battery capacity results in somewhat greater savings than a lesser number of EVs of greater battery capacity, for the same energy consumption and the same driving distance in total. However, this is not as significant as the charger power. More powerful chargers result not only in consumer satisfaction but also in reduced costs. It is interesting to take into account variable energy prices during weekdays and to charge preferably on Sundays. In future work, battery lifetime and its degradation, based on the number of charging/discharging cycles and total energy withdrawn, should also be considered.

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His main areas of research include renewable energy sources, smart grids, energy efficiency, optimization methods, electromagnetic compatibility, etc.

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OPTIMIZACIJA DNEVNOG RASPOREDA PUNJENJA ELEKTRIČNIH VOZILA RADI MINIMIZACIJE TROŠKOVA ELEKTRIČNE ENERGIJE

Dario Javor, Dejan Krstić, Nebojša Raičević

Rezime: U ovom radu je rešen optimizacioni problem za dnevni raspored punjenja/praznjenja električnih vozila (EV) kako bi se minimizirali troškovi za električnu energiju. Rezultati su dobijeni za mikromrežu sa obnovljivim izvorima energije, a uštede su sračunate na osnovu dnevnih dijagrama neodložne potrošnje, proizvodnje fotonaponskih izvora i vetrogeneratora, kao i kupovnih/prodajnih cena električne energije na tržištu. Rezultati optimizacije su dati za različite kapacitete baterija električnih vozila u floti, različite snage punjača i tipove obnovljivih izvora energije. Program Lingo je korišćen da se reši ovaj optimizacioni problem.

Ključne reči: optimizacija, punjenje električnih vozila, troškovi električne energije, obnovljivi izvori energije.