1. Aleksander LULA[1], 2. Krzysztof ZAGRAJEK[2]

Warsaw University of Technology (1), Warsaw University of Technology (2)
ORCID: 1. 0000-0002-5765-6890; 2. 0000-0001-7034-9433

doi:10.15199/48.2022.10.02

A concept of using a private electric vehicle to optimize the costs of electricity in household equipped with a PV power plant

***Abstract**. Nowadays, a dynamic increase in the number of households equipped with photovoltaic (PV) systems is observed, driven by the willingness to optimize the costs of electricity purchase. Considering also the growing share of electric vehicles (EV) in the automotive market in Poland, it is necessary to consider how to effectively integrate both areas. Therefore, the main objective of this paper was to develop a household electricity management algorithm that would reduce the electricity consumption charges using PV system and EV. It also takes into account the daily variability of electricity prices, which can also be a future element of electricity market transformation suitable for prosumers. The study showed potential savings in electricity bills of up to several PLN per day.*

***Streszczenie.** Obecnie obserwuje się dynamiczny wzrost liczby gospodarstw domowych wyposażonych w instalacje fotowoltaiczną (PV), który wynika z chęci optymalizacji kosztów zakupu energii elektrycznej. Mając na uwadze również rosnący udział pojazdów elektrycznych (EV) w rynku motoryzacyjnym w Polsce, należy zastanowić się jak efektywnie zintegrować ze sobą oba obszary. W związku z tym głównym celem artykułu było opracowanie algorytmu zarządzania energią elektryczną w gospodarstwie domowym, który zmniejszałby opłaty za jej pobranie, wykorzystując do tego instalację PV oraz EV. Uwzględniono także w nim dobową zmienność cen energii elektrycznej, która może być także w przyszłości elementem transformacji rynku energii elektrycznej dostosowanym do prosumentów. W przeprowadzonych badaniach wykazano potencjalne oszczędności w rachunkach za energię elektryczną sięgające nawet kilkunastu złotych dziennie. **(Koncepcja wykorzystania prywatnego pojazdu elektrycznego do optymalizacji kosztów zużycia energii elektrycznej dla gospodarstwa domowego wyposażonego w instalację fotowoltaiczną)**.*

Keywords: prosumers, dynamic energy prices, electric vehicles, energy management algorithms.
Słowa kluczowe: prosumenci, dynamiczne ceny energii, pojazdy elektryczne, algorytmy zarządzania energią elektryczną.

Introduction

Retail electricity prices in European countries have been steadily rising due to increased costs of electricity generation, mainly in conventional power plants [1]. This growth is mainly driven by the surging prices of fossil fuels, such as coal, lignite, oil and natural gas [2], but also by the rapid increase in the prices of CO_2 emission permits under the European emissions trading system (EU ETS) [3]. In the case of Poland, both of the aforementioned factors are extremely noticeable for the end users, mainly due to the country's energy policy [4].

Therefore, end users are looking for opportunities to make savings on their electricity bills, particularly in households. These can be demonstrated, for example, by improving the energy efficiency of buildings, especially those whose heating is based on electricity [5]. One of the more popular solutions for demonstrating savings on electricity bills is to use households' own micro-sources for generating electricity for their own consumption, most often based on photovoltaic (PV) installations [6,7]. Such households then become renewables self-consumer or in other words prosumers. According to Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources, it is "*a final customer operating within its premises located within confined boundaries or, where permitted by a Member State, within other premises, who generates renewable electricity for its own consumption, and who may store or sell self-generated renewable electricity, provided that, for a non-household renewables self consumer, those activities do not constitute its primary commercial or professional activity*" [8]. It is important to note that it may store energy as part of its activities. The most common and at the same time the simplest solution is storing it via an energy storage facility installed in the building [9,10]. Nevertheless, pursuing for alternatives, one should consider other forms of battery energy storage. For instance, electric vehicles (EV) can be considered as mobile energy storage from the point of view of the power system [11, 12]. It should be noted that their share of the EV market in Europe is growing [13], and forecasts predict a sharp increase in EVs at a time when vehicle manufacturers are moving more boldly away from internal combustion engine cars [14,15]. This is due to the general trend of concern for air quality, particularly in highly urbanised areas [15,16]. Moreover, the development of electric vehicle market is positively influenced by the decreasing cost of production and purchase of batteries year by year [17]. All these factors cause the emergence of new business models that use electric vehicles as a backup power source - the so-called Vehicle-to-everything (V2X) technology [18, 19]. This article focuses on Vehicle-to-Home (V2H) technology solutions, i.e. bidirectional flow of electric energy from the electric vehicle to the household electrical system to use it for personal purposes [20]. It should be emphasized that the aforementioned solutions do not only concern the discharge of the vehicle, but also effective management of vehicle charging (aka smart charging) [21].

In order to minimize the negative economic effect resulting from increasing electricity prices for households, equipped with PV system and EV, an energy management algorithm was proposed. It allows the user to decide the appropriate energy flow depending on the current technical, meteorological or economic conditions.

The design of the algorithm also considers the current state of the law regarding the billing of end customers for electricity, including prosumers, as presented in [22 - 24]. At the same time, it was ensured that the algorithm could also be suitable in case the end user would use a contract with dynamic energy prices (varying throughout the day), which is planned to be implemented with the next amendment of the Polish Energy Law [25], adapting it to the Directive of the European Parliament of 5 June 2019 on common rules for the internal market for electricity [26].

The article is composed as follows. First, the simulation model of the designed algorithm is presented. It focuses on the description of its basic functions, and then presents the process of creating a dynamic billing system for the purchase and sale of electricity, in which prices vary every hour. The assumptions for the benchmark household are then presented in terms of: its energy demand, the tariff used for electricity billing, the power characteristics of the owned PV system and the EV. Based on adopted assumptions and developed simulation model, the results for the specific examined case were gathered. Based on the results obtained, conclusions were drawn and also described.

Model of energy management algorithm

In order to minimize the electricity fees of a household that has both its own PV and EV installation, an energy management algorithm can be designed to dynamically change the decision depending on the observed environmental conditions. The developed algorithm should be versatile so that many types of household electricity billing methods can be applied to it. So, a mathematical model of energy flows was developed and implemented in the energy management algorithm. A main target of the algorithm is to achieve the lowest possible electricity fee at the end of the single day. The algorithm integrates all elements of household's electrical infrastructure by defining an electricity flow conditions between following elements:
- household's buildings,
- a PV installation,
- an EV equipped with a high-voltage battery,
- a bidirectional wallbox-type charging station.

Figure 1 shows a model diagram of a household alongside the various components of modern distributed generation resources.

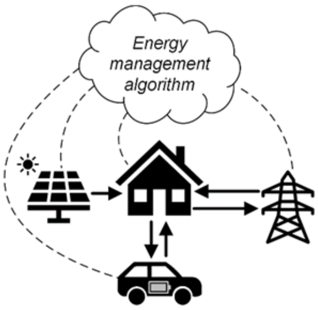

Fig. 1. Diagram of modelled household equipped with PV and EV

Firstly, in the energy management algorithm an electricity balance of the household's buildings at a given hour *t* is calculated according to equation (1).

$$\Delta_t = D_{h,t} - E_{PV,t} \quad (1)$$

where: Δ_t – electricity balance, in kWh, $D_{h,t}$ – household's electricity demand in hour *t*, in kWh, $E_{PV,t}$ – electricity produced by a PV installation in hour *t*, in kWh.

Based on the calculated value Δ_t, it can be determined whether the household covers its demand from the electricity produced by its PV installation (self-consumption). Thus:

$$\begin{cases} \Delta_t > 0\ , D_{h,t}\ not\ covered\ by\ electricity\ from\ PV \\ \Delta_t \leq 0\ , D_{h,t}\ covered\ by\ electricity\ from\ PV \end{cases} \quad (2)$$

After validating whether the household demand is covered, it should be verified whether the electric vehicle can be used in further energy management processes. It should be noted that in this case the electric vehicle is a mobile energy storage. So, in the next step of the algorithm implementation, it is necessary to check if the electric vehicle is present in the household in hour *t*. If it is, then it can be said that the electric vehicle is available. This situation is represented by the variable $EV_{av,t}$, which takes the following values:

$$EV_{av,t} = \begin{cases} 1, & EV\ available\ in\ household \\ 0, & otherwise \end{cases} \quad (3)$$

However, it should be remembered that the use of EV in energy management processes only makes sense if a positive economic effect is reached. This means that before defining the actions that can be taken with an EV, i.e. discharging or charging, it is first necessary to define the economic conditions that will set the boundary conditions.

Three billing methods were developed in the model. First two of them are polish tariff systems named G11 and G12. G11 is a single-zone tariff for households and G12 is a two-zone tariff for households, which means that there are two rate zones in it: daily and nightly. Let S_{EN}^{G11} denote the electricity rate of the G11 tariff, while $S_{EN_D}^{G12}$ and $S_{EN_N}^{G12}$ denote the daytime and nighttime electricity rates of the G12 tariff, respectively. The third of billing systems is developed for paper purposes Dynamic Billing System (DBS). To its develop, historical data of the power exchange prices and volumes of electricity were used. By using historical data, a day-ahead energy price behaviour profile can be created. It should be noted that in the final implementations, the algorithm should use advanced forecasting tools in order to constantly update the profile. The method of calculating the factors, which determine the electricity price profile is described by equation (4), and the values obtained are shown in Table 1.

$$k_t = \frac{S_{EN,t}^{DAH}}{\frac{\sum_{t=1}^{24} S_{EN,t}^{DAH}}{24}} \quad (4)$$

where: $S_{EN,t}^{DAH}$ - electricity price in *t*-hour on the day-ahead market, in PLN/kWh; k_t- electricity price profile factor in *t*-hour.

Table 1. Electricity price profile factors based on historical data from polish power exchange day-ahead market

t	k_t		*t*	k_t	
	Summer day	Winter day		Summer day	Winter day
1	0,85	0,81	**13**	1,12	1,19
2	0,80	0,79	**14**	1,10	1,20
3	0,79	0,77	**15**	1,05	1,11
4	0,79	0,77	**16**	1,05	1,08
5	0,80	0,79	**17**	1,06	1,07
6	0,85	0,85	**18**	1,08	1,11
7	0,98	0,92	**19**	1,07	1,11
8	1,06	1,07	**20**	1,11	1,05
9	1,12	1,16	**21**	1,11	1,01
10	1,13	1,23	**22**	1,00	0,91
11	1,11	1,19	**23**	0,95	0,83
12	1,12	1,20	**24**	0,88	0,78

Thus, the electricity rate in hour *t*, in the DBS billing method is equal to:

$$S_{EN,t}^{DBS} = k_t \cdot S_{avg}^{DAH} \quad (5)$$

where: S_{avg}^{DAH} - buy/sell price of electricity on the day-ahead market in single-price system (for polish power exchange index: TGeBase), in PLN/kWh; $S_{EN,t}^{DBS}$- buy/sell electricity rate in hour *t*, in the DBS method, in PLN/kWh.

In order to evaluate whether the use of electricity stored in an electric vehicle will help to achieve a positive economic effect, certain threshold values of state of charge (SOC) of the battery need to be defined. This is a necessary action to establish the ranges within which an economic criterion will influence whether or not the vehicle will yield energy to the household. It was assumed that the EV battery would be used within 15% - 90% of its net capacity (accessible to the user), due to the optimization of its lifetime. Let SOC_t^{ACT} denote the state of charge of the electric vehicle at beginning of hour *t*. Therefore, if the EV is in a household then:

(6) $$\bigwedge_{\Delta_t \le 0 \wedge EV_{av,t}=1} SOC_t^{ACT} \in \begin{cases} \langle SOC_{MAX}^{C}; 100\%\rangle \\ \langle SOC_{UP}^{C}; SOC_{MAX}^{C}\rangle \\ \langle SOC_{LOW}^{C}; SOC_{UP}^{C}\rangle \\ \langle 0; SOC_{LOW}^{C}\rangle \end{cases}$$

where: SOC_{MAX}^{C} - maximum SOC value, to which EV is charged; SOC_{UP}^{C}- the upper limit of the vehicle's SOC value, which determines the charging method (PV, grid or both); SOC_{LOW}^{C} - the lower limit of the vehicle's SOC value, which determines the charging method (PV, grid or both);

or:

(7) $$\bigwedge_{\Delta_t > 0 \wedge EV_{av,t}=1} SOC_t^{ACT} \in \begin{cases} \langle SOC_{UP}^{D}; 100\%\rangle \\ \langle SOC_{LOW}^{D}; SOC_{UP}^{D}\rangle \\ \langle 0; SOC_{LOW}^{D}\rangle \end{cases}$$

where: SOC_{UP}^{D}- the upper limit of the vehicle's SOC value, which determines the household's source of electricty (EV or grid); SOC_{LOW}^{D} - the lower limit of the vehicle's SOC value, which determines the household's source of electricty (EV or grid);

However, it is important to keep in mind the present constraint, i.e. the maximum charging and discharging power of the EV. Assuming that the vehicle charges at hour *t* with a constant power equal to the maximum power, it is possible to determine the volume of energy that can be maximally delivered to or drawn from the vehicle:

(8) $$E_{EV,t}^{MAX} = P_{EVSE}^{MAX} \cdot t$$

where: $E_{CH,t}^{MAX}$- maximal value of electric energy that can be delivered to or drawn from EV during charging and discharging process in hour *t*, in kWh; P_{EVSE}^{MAX} - maximal charging/discharging power, in kW.

Firstly, the actions of the algorithm during surplus of produced energy from PV plant i.e. $\Delta_t \le 0$ are going to be discussed. Let us start with circumstances where the EV is not in the household i.e. $EV_{av,t}$ =0. At those conditions the surplus electricity produced is sold to the power system.

Then, it is necessary to analyse the volumes of electricity that flow between the different elements that make up the household electricity system (PV, EV, demand). First, the volume of energy that can be sold to the grid is defined. It occurs when the following conditions exist:

(9) $$\begin{cases} \Delta_t \le 0 \\ EV_{av,t} = 1 \wedge SOC_t^{ACT} \in \langle SOC_{MAX}^{C}; 100\%\rangle \\ EV_{av,t} = 0 \end{cases}$$

It is described by equation (10).

(10) $$\bigwedge_{\Delta_t \le 0} E_{SELL,t}^{PS} = |\Delta_t|$$

where: $E_{SELL,t}^{PS}$ - the volume of electricity sold to the power system in hour *t*, in kWh.

The next case deals with the situation where there are surplus PV electricity production i.e. $\Delta_t \le 0$, while the EV is located in the household and its SOC is in the range: $SOC_t^{ACT} \in \langle SOC_{UP}^{C}; SOC_{MAX}^{C}\rangle$. Then the vehicle is charged from the surplus electricity produced by the PV installation:

(11) $$\bigwedge_{\Delta_t \le 0 \wedge EV_{av,t}=1} E_{EV,t}^{DPV} = \begin{cases} |\Delta_t|, if\ |\Delta_t| < E_{EV,t}^{MAX} \\ E_{EV,t}^{MAX}, if\ \ if\ |\Delta_t| \ge E_{EV,t}^{MAX} \end{cases}$$

(12) $$\bigwedge_{SOC_t^{ACT} \in \langle SOC_{UP}^{C}; SOC_{MAX}^{C}\rangle} SOC_{t+1}^{ACT\prime} = SOC_t^{ACT} + \frac{E_{EV,t}^{DPV}}{C_n}$$

(13) $$E_{EV,t+1}^{ACT\prime} = C_n \cdot SOC_{t+1}^{ACT\prime}$$

where: $SOC_{t+1}^{ACT\prime}$ - the state of charge of the electric vehicle at hour *t+1* after charging only from PV surplus; $E_{EV,t+1}^{ACT\prime}$ – electric energy stored in the electric vehicle in the hour *t+1* after charging only from PV surplus, in kWh ; C_n- EV battery capacity, in kWh; $E_{EV,t}^{DPV}$- volume of electric energy delivered to the EV from surplus PV plant generation in hour *t*, in kWh.

Another case analyzed involves a scenario where the EV is located at the household site, the PV system is generating surplus ($\Delta_t \le 0$), but the SOC of the EV is in the range $\langle SOC_{LOW}^{C}; SOC_{UP}^{C}\rangle$. So, the algorithm chooses the charging method for the EV depending on end user's method of billing electricity.

- For tariffs G11 and G12

In the case of tariff billing, the vehicle will be charged using both electricity from surplus PV production ($\Delta_t \le 0$) and energy from the electricity grid.

(14) $$E_{CH,t}^{GRID} = E_{EV,t}^{MAX} - E_{EV,t}^{DPV}$$

(15) $$\bigwedge_{SOC_t^{ACT} \in \langle SOC_{LOW}^{C}; SOC_{UP}^{C}\rangle} SOC_{t+1}^{ACT\prime\prime} = SOC_t^{ACT} + \frac{E_{CH,t}^{GRID}}{C_n} + \frac{E_{EV,t}^{DPV}}{C_n}$$

(16) $$E_{EV,t+1}^{ACT\prime\prime} = C_n \cdot SOC_{t+1}^{ACT\prime\prime}$$

where: $E_{CH,t}^{GRID}$- the volume of electricity drawn from the grid that is used to charge the EV in hour *t*, in kWh; $SOC_{t+1}^{ACT\prime\prime}$- the state of charge of the electric vehicle at hour *t+1* after charging from PV surplus and grid; $E_{EV,t+1}^{ACT\prime\prime}$ - electric energy stored in the electric vehicle in the hour *t+1* after charging from PV surplus and grid, in kWh.

- For DBS

For the DBS method of billing the end user for electricity and noted PV surplus, firstly it is necessary to check the energy price in the day-ahead market in hour *t* i.e. $S_{EN,t}^{DBS}$. Then it should be analysed if there is a reason to charge the vehicle with more energy using grid power or to use only energy from the surplus PV.

(17) $$E_{CH,t}^{DBS} = \begin{cases} E_{EV,t}^{DPV}, & if\ S_{EN,t}^{DBS} > S_{avg}^{DAH} \\ E_{CH,t}^{GRID} + E_{EV,t}^{DPV}, & if\ S_{EN,t}^{DBS} \le S_{avg}^{DAH} \end{cases}$$

(18) $$\bigwedge_{SOC_t^{ACT} \in \langle SOC_{LOW}^{C}; SOC_{UP}^{C}\rangle} SOC_{t+1}^{ACT\prime\prime\prime} = SOC_t^{ACT} + \frac{E_{CH,t}^{DBS}}{C_n}$$

(19) $$E_{EV,t+1}^{ACT\prime\prime\prime} = C_n \cdot SOC_{t+1}^{ACT\prime\prime\prime}$$

where: $E_{CH,t}^{DBS}$ – volume of electric energy that is being delivered to EV in DBS billing method in hour *t*, in kWh; $SOC_{t+1}^{ACT\prime\prime\prime}$- the state of charge of the electric vehicle at hour *t+1* after charging from PV surplus and grid, while end user is using DBS; $E_{EV,t+1}^{ACT\prime\prime\prime}$ - electric energy stored in the electric vehicle in the hour *t+1* after charging from PV surplus and grid, while end user is using DBS, in kWh.

The last case when $\Delta_t \leq 0$ refers to when the SOC of the vehicle is less than the minimum SOC value that determines the way the vehicle is charged. In other words, below the SOC_{LOW}^{C} value, the vehicle is always going to be charged from the grid and from surplus production from PV. Thus, the energy supplied to the vehicle from the grid will be calculated according to equation (14), and the EV charge level and stored energy is:

(20)
$$\bigwedge_{SOC_t^{ACT} \in \langle 0; SOC_{LOW}^{C} \rangle} SOC_{t+1}^{ACT_L} = SOC_t^{ACT} + \frac{E_{CH,t}^{GRID}}{C_n} + \frac{E_{EV,t}^{DPV}}{C_n}$$

(21)
$$E_{EV,t+1}^{ACT_L} = C_n \cdot SOC_{t+1}^{ACT_L}$$

where: $SOC_{t+1}^{ACT_L}$ – the state of charge of the electric vehicle at hour *t+1* after charging from PV surplus and grid, when SOC is lower than the value, which determines the charging method; $E_{EV,t+1}^{ACT_L}$ - electric energy stored in the electric vehicle in the hour *t+1* after charging from PV surplus and grid, when SOC is lower than the value, which determines the charging method.

The second main operation of the algorithm scenario deals with situations where there is an unbalanced demand for electricity in the household i.e. $\Delta_t > 0$. In case the electric vehicle is not in the household i.e. $EV_{av,t}=0$, the demand is covered from the electricity grid. Let $E_{HH,t}^{GRID}$ denote this value. Therefore:

(22)
$$\bigwedge_{\Delta_t>0 \wedge EV_{av,t}=0} E_{HH,t}^{GRID} = |\Delta_t|$$

However, if the EV is located on the household site, it should be considered to use its battery capacity as mobile energy storage to support demand covering. In the first case of such a situation, it has to be assumed that the SOC_t^{ACT} is greater than the threshold value of SOC_{UP}^{D}. Then the EV yields its stored energy to supply the household. Therefore:

(23)
$$\bigwedge_{\Delta_t>0 \wedge EV_{av,t}=1} E_{EV,t}^{DISB} = \begin{cases} |\Delta_t|, if\ |\Delta_t| < E_{EV,t}^{MAX} \\ E_{EV,t}^{MAX}, if \quad if\ |\Delta_t| \geq E_{EV,t}^{MAX} \end{cases}$$

(24)
$$\bigwedge_{SOC_t^{ACT} \in \langle SOC_{UP}^{D}; 100\% \rangle} SOC_{t+1}^{ACT_{D1}} = SOC_t^{ACT} - \frac{E_{EV,t}^{DISB}}{C_n}$$

(25)
$$E_{EV,t+1}^{ACT_{D1}} = C_n \cdot SOC_{t+1}^{ACT_{D1}}$$

where: $SOC_{t+1}^{ACT_{D1}}$ - the state of charge of the electric vehicle at hour *t+1* after discharging its capacity to cover household's demand; $E_{EV,t+1}^{ACT_{D1}}$ – electric energy stored in the electric vehicle in the hour *t+1* after discharging its capacity to cover household's demand, in kWh ; $E_{EV,t}^{DISB}$- volume of electric energy delivered from EV to the household in hour *t*, in kWh.

The next case considered is when the measured SOC_t^{ACT} of EV is within the threshold range $(SOC_{LOW}^{D}; SOC_{UP}^{D}\rangle$ and an unbalanced electricity demand occurs ($\Delta_t > 0$). Then the method of billing the consumer for electricity must be analyzed and actions are taken based on it.

- For tariffs G11 and G12

In the case of tariff billing, EV will not be used in household electricity demand balancing processes. Therefore:

(26)
$$E_{HH,t}^{GRID} = |\Delta_t|$$

(27)
$$\bigwedge_{SOC_t^{ACT} \in (SOC_{LOW}^{D}; SOC_{UP}^{D}\rangle} SOC_{t+1}^{ACT_{DT}} = SOC_t^{ACT}$$

(28)
$$E_{EV,t+1}^{ACT_{DT}} = C_n \cdot SOC_{t+1}^{ACT_{DT}}$$

where: $SOC_{t+1}^{ACT_{DT}}$- the state of charge of the electric vehicle at hour *t+1* during unbalanced demand period, while using tariff billing system; $E_{EV,t+1}^{ACT_{DT}}$ - electric energy stored in the electric vehicle in the hour *t+1* during unbalanced demand period, while using tariff billing system, in kWh.

However, a special case may occur when the EV user wants to recharge the EV to the SOC_{t+1}^{NEW} level. So the increase of the electricity demand by the value of the energy supplied to the vehicle $E_{EV,t}^{XCH}$ has to be taken into account:

(29)
$$\Delta_t^N = \Delta_t + E_{EV,t}^{XCH}$$

(30)
$$\bigwedge_{E_{EV,t}^{XCH} \leq E_{EV,t}^{MAX}} E_{EV,t}^{XCH} = (SOC_{t+1}^{NEW} - SOC_t^{ACT}) \cdot C_n$$

(31)
$$E_{HH,t}^{GRID'} = |\Delta_t^N|$$

(32)
$$E_{EV,t+1}^{ACT_{T'}} = C_n \cdot SOC_{t+1}^{NEW}$$

where: Δ_t^N – unbalanced electricty demand in household, which includes EV chargning in hour *t*, in kWh; $E_{EV,t+1}^{ACT_{T'}}$ – electric energy stored in the electric vehicle in the hour *t+1* after charging its capacity, while household's demand is unbalanced, in kWh; $E_{HH,t}^{GRID'}$ - volume of electric energy, that has to be delivered from the grid to household in hour *t*, in kWh.

- For DBS

In the case of DBS billing, it is possible to use the EV battery capacity to optimize household electricity demand. However, it is necessary to compare the energy purchase price at hour *t* with the average price available in the day-ahead market. If this price is higher than the average, the EV should be discharged. Otherwise, the demand will be covered from the grid or there will be a possibility to charge the EV additionally - analogous to equations (29) - (32). Hence:

(33)
$$E_{DIS,t}^{DBS} = \begin{cases} E_{EV,t}^{DISB}, & if\ S_{EN,t}^{DBS} > S_{avg}^{DAH} \\ E_{HH,t}^{GRID'}, & if\ S_{EN,t}^{DBS} \leq S_{avg}^{DAH} \end{cases}$$

(34)
$$\bigwedge_{SOC_t^{ACT} \in (SOC_{LOW}^{D}; SOC_{UP}^{D}\rangle \wedge E_{DIS,t}^{DBS} = E_{EV,t}^{DISB}} SOC_{t+1}^{ACT_{D2}} = SOC_t^{ACT} - \frac{E_{EV,t}^{DISB}}{C_n}$$

(35)
$$\bigwedge_{SOC_t^{ACT} \in (SOC_{LOW}^{D}; SOC_{UP}^{D}\rangle \wedge E_{DIS,t}^{DBS} = E_{HH,t}^{GRID'}} SOC_{t+1}^{ACT_{D2'}} = \begin{cases} SOC_t^{ACT}, if\ E_{EV,t}^{XCH} = 0 \\ SOC_{t+1}^{NEW}, if\ E_{EV,t}^{XCH} > 0 \end{cases}$$

(36)
$$E_{EV,t+1}^{ACT_{D2}} = \begin{cases} C_n \cdot SOC_{t+1}^{ACT_{D2}}, if\ E_{DIS,t}^{DBS} = E_{EV,t}^{DISB} \\ C_n \cdot SOC_{t+1}^{ACT_{D2'}}, if\ E_{DIS,t}^{DBS} = E_{HH,t}^{GRID'} \end{cases}$$

where: $E_{DIS,t}^{DBS}$ – volume of electric energy that is calculated in DBS billing method, while demand of household is unbalanced in hour *t*, in kWh; $SOC_{t+1}^{ACT_{D2}}$ - the state of charge of the electric vehicle at hour *t+1* after discharging its capacity to cover household's demand in DBS method; $SOC_{t+1}^{ACT_{D2'}}$- the state of charge of the electric vehicle at hour *t+1*, while EV is not used for discharging purposes in DBS method; $E_{EV,t+1}^{ACT_{D2}}$ - electric energy stored in the electric vehicle in the hour *t+1* during unbalanced demand period, while using DBS billing system, in kWh.

The last case relates to a situation, where there is an unbalanced household energy demand and the SOC_t^{ACT} is in the $\langle 0; SOC_{LOW}^{D}\rangle$ range. It can be described analogously to the case characterized by equations (26) - (32). Therefore, further consideration of this case is omitted.

Once all energy flow cases have been characterized and the decisions to be made by the designed algorithm have been defined, the economic aspects must be analyzed. In this model, the primary objective is to minimize the electricity fees, while the end user can use three billing systems. So, based on the electricity input flows, the cash flows have to be defined and calculated. It is assumed that the energy drawn from the grid by the household for tariff billing will be settled using the rates that apply with the respective retailer and Distribution System Operator (DSO). In the case of selling surplus energy from PV installations to the grid, the rate S_{avg}^{DAH} will be applied, which results from the single-price index on the day-ahead market. For the DBS billing method, the sale price is not distinguished from the purchase price of energy at a given hour *t*. For all billing methods, the algorithm is designed to calculate the daily cash flow.

Let $E_{G+,t}$ be the billing volume of energy drawn from the grid consumed by the end user in hour *t*. Its value can be equal to one of the volumes belonging to the set of all electricity flows in which energy is withdrawn from the grid - equation (33). Let $E_{G-,t}$ denote the volume of energy sold to the grid by the final customer in hour *t*, which is needed for settlement. In this case, however, there is only one energy volume in the designed algorithm that fulfills the assumptions. It is described by the equation (34).

Let $E_{G+,t}$ be the billing volume of energy drawn from the grid consumed by the end user in hour *t*. Its value can be equal to one of the volumes belonging to the set of all electricity flows in which energy is withdrawn from the grid - equation (37). Let $E_{G-,t}$ denote the volume of energy sold to the grid by the final customer in hour *t*, which is needed for settlement. In this case, however, there is only one energy volume in the designed algorithm that fulfills the assumptions. It is described by the equation (38).

$$E_{G+,t} = \{E_{CH,t}^{GRID}, E_{HH,t}^{GRID}, E_{HH,t}^{GRID'}\} \tag{37}$$

$$E_{G-,t} = E_{SELL,t}^{PS} \tag{38}$$

Thus, the billing fee for the end user in hour *t* for the G11 tariff $O_{G11,t}$ is described as follows:

$$O_{G11,t} = \begin{cases} E_{G+,t} \cdot S_{EN}^{G11} + O_{DSO,t}, for\ consumption \\ -(E_{G-,t} \cdot S_{avg}^{DAH}), for\ selling\ surplus \end{cases} \tag{39}$$

For the G12 tariff – daily rates:

$$\bigwedge_{t \in T_d} O_{G12,t}^{D} = \begin{cases} E_{G+,t} \cdot S_{EN_D}^{G12} + O_{DSO,t} \\ -(E_{G-,t} \cdot S_{avg}^{DAH}) \end{cases} \tag{40}$$

For the G12 tariff – nightly rates:

$$\bigwedge_{t \in T_n} O_{G12,t}^{N} = \begin{cases} E_{G+,t} \cdot S_{EN_N}^{G12} + O_{DSO,t} \\ -(E_{G-,t} \cdot S_{avg}^{DAH}) \end{cases} \tag{41}$$

For DBS method:

$$O_{DBS,t} = \begin{cases} E_{G+,t} \cdot S_{EN,t}^{DBS} + O_{DSO,t} \\ -(E_{G-,t} \cdot S_{EN,t}^{DBS}) \end{cases} \tag{42}$$

where: $O_{G11,t}$ - the cash balance for the end user settled in the G11 tariff in hour *t*, in PLN; $O_{G12,t}^{D}$ - the cash balance for the end user settled in the G12 tariff in daily hour *t*, in PLN; $O_{G12,t}^{N}$- the cash balance for the end user settled in the G12 tariff in nightly hour *t*, in PLN $O_{DBS,t}$- the cash balance for the end user settled in DBS method in hour *t*, in PLN; O_{DSO}- the fee paid to DSO by end user according to rules described in network code in hour *t*, in PLN; T_d- set of daily hours in the G12 tariff; T_n- set of nightly hours in the G12 tariff.

It is worth mentioning that in case of settlement using the DBS method, distribution fees were assumed as for the G12 tariff (rates depending on day and night hours).

In the case of a conditions, where an electric vehicle is charged from surplus production from a PV plant ($E_{EV,t}^{DPV}$) or is discharged for household needs ($E_{EV,t}^{DISB}$) then the charge for energy drawn/sold is 0 as there is no flow of energy from or to the grid. Based on equations (39) - (42), the 24-hour cash balance for the end user can be calculated:

$$O_{G11}^{24h} = \sum_{t=1}^{24} O_{G11,t} \tag{43}$$

$$O_{G12}^{24h} = \sum_{t=1}^{T_d} O_{G12,t}^{D} + \sum_{t=1}^{T_n} O_{G12,t}^{N} \tag{44}$$

$$O_{DBS}^{24h} = \sum_{t=1}^{24} O_{DBS,t} \tag{45}$$

where: O_{G11}^{24h}- 24-hour cash balance for the end user setteled in G11 tariff, in PLN; O_{G12}^{24h}- 24-hour cash balance for the end user setteled in G12 tariff, in PLN; O_{DBS}^{24h}- 24-hour cash balance for the end user setteled in DBS method, in PLN.

Results

In order to verify correctness of proposed algorithm, simulations were performed for assumed benchmark household. It is assumed that household is located in central Poland - in the Lodzkie voivodeship – and is equipped with all aforementioned necessary elements of energy management infrastructure.

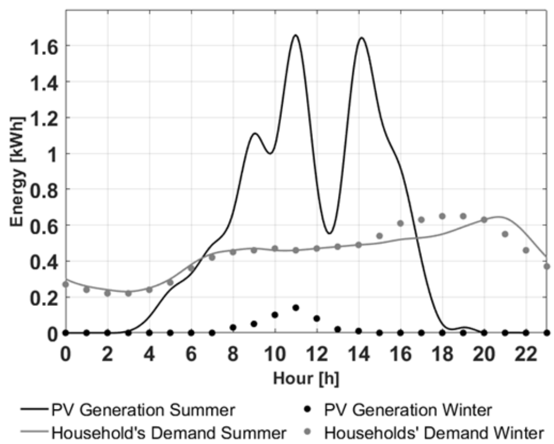

Fig. 2. Household demand and generation profiles from PV installations

The average daily electricity demand of a household was assumed as 10.62 kWh, and its profile was specified using the coefficients established for the use of standard profiles, according to the Distribution Grid Operation and

Maintenance Code [27]. Then, the energy generation profile of the 2,5 kW PV system was determined. For this purpose, the sector software HomerPro [28] was used. Figure 2 shows the profiles of energy demand and energy generation from PV installation during summer and winter days.

Table 3. contains input data implemented in simulation. The necessary price rates were taken from the distribution tariff and the tariff for sale of electricity to household customers, prepared by the local Distribution System Operator (DSO) - PGE Dystrybucja [29] and the retailer of ex-officio - PGE Obrót [30].

Table 3. Input parameters in the simulation model

Parameter	Value	Unit
$SOC_{t,s}^{ACT}$	50	[%]
$SOC_{t,w}^{ACT}$	80	[%]
D_d	10.5	[kWh]
PV installation capacity	2.5	[kW]
SOC_{MAX}^{C}	90	[%]
SOC_{UP}^{C}	70	[%]
SOC_{LOW}^{C}	60	[%]
SOC_{UP}^{D}	80	[%]
SOC_{LOW}^{D}	50	[%]
Net battery capacity	37	[kWh]
Time of EV's departure from the household	5	[–]
Time of EV's arrival to the household	8	[–]
Distance traveled during absence in household	60	[km]
P_{EVSE}^{MAX}	3.6	[kW]
S_{EN}^{G11}	0.4295	[PLN/kWh]
$S_{EN_D}^{G12}$	0,4668	[PLN/kWh]
$S_{EN_N}^{G12}$	0,2935	[PLN/kWh]
Duration of the day tariff	06:00 – 13:00 15:00 – 22:00	[–]
Duration of the night tariff	13:00 – 15:00 22:00 – 06:00	[–]
$S_{EN,t}^{DBS}$ / S_{avg}^{DAH}	0.69	[PLN/kWh]

where: $SOC_{t,s}^{ACT}$ – initial SOC value (at midnight) for a summer day, $SOC_{t,w}^{ACT}$ – initial SOC value (at midnight) for a winter day, D_d – daily electricity demand.

A purpose of assuming two different values of the initial SOC was to demonstrate the impact of the DBS billing system on the algorithm's actions. which are shown in the Table 4:

Table 4. Tags and description of decisions made by the algorithm

A		
Tag	Decision	Meaning in the algorithm
↑$	Sell electricity to the grid	Electricity produced by the PV installation is returned and sold to the grid because the household's demand has been in a given hour covered and the battery's SOC exceeds the maximum allowable level.
↑☀	Charge EV from the PV	No fees because the EV is charged by electricity produced by the PV installation.
↑↓☀ ⚡	Charge EV from the PV and the grid	A fee for electricity drawn by the charging station to charge the EV in a given hour.
↓⚡	Draw from the grid	A fee for electricity equal to household's demand in a given hour.
↑🚘	Draw from the EV	No fees because household's demand is covered by the EV.

where: A – algorithm's decision.

Results for the summer day for all settlement systems are summarised in the Table 5. During the night, when household's demand cannot be covered by the PV, energy is drawn from the grid. In the morning, when there occur a PV surplus and the EV is not available in the household's area, electricity is sold to the grid. When the EV is back and its state of charge $SOC_t^{ACT} \in (SOC_{LOW}^{C}; SOC_{UP}^{C}\rangle$, it is charged simultaneously from the PV installation and the grid. In the afternoon, when there still occurs a PV surplus and the household's demand is covered, the EV is charged solely from the PV installation. In the evening, when the $SOC_t^{ACT} \in (SOC_{UP}^{C}; SOC_{MAX}^{C}\rangle$ and electricity produced by PV is insufficient to cover the household's demand, the EV's battery is discharged. When the household was billed in the DBS system the EV discharging last longer due to the fact that $SOC_t^{ACT} > SOC_{UP}^{C}$. That action allowed to generate savings in a single day settlement regarding DBS system. For input data adopted in this simulation, billing in the G11 tariff became the most beneficial at the end of the day. When comparing the G11 and G12 tariffs, the difference was 0,26 PLN and was mainly due to more electricity consumed from the grid in the daily hours, nearly 8 kWh. In contrast, the difference between the G11 tariff and the DBS method was 3.62 PLN. This indicates an important issue, which is the adjustment of the appropriate billing method depending on the needs of the household. Another problem was also raised which is the effective management of electricity in a household with an EV. It was assumed that a monthly electricity supply of 316 kWh would be needed to cover the demand of the household and 502 kWh of energy to charge the vehicle. So, for example, the monthly electricity charge in the G11 tariff would be about **574,84 PLN**. As a result of the algorithm, this fee could be reduced by **238,8 PLN**.

Next, the simulations for a winter day were performed. The results carried out for a winter day are shown in the Table 6. Electricity produced by the PV installation in winter is lower than the household's demand the whole day through, so there is no possibility to donate PV surplus to cover household's demand. While settlement in the tariff systems, the household draws electricity from the grid every hour of the day. In opposite to the previous case, G12 turned out to be more beneficial than G11 due to consuming higher amount of electricity during the day. As shown in Table 6., actions taken in DBS system are slightly different than in the tariff systems. During the afternoon peak, when electricity rates became higher than daily average, the algorithm decides that electricity, for covering household's demand, will be drawn from the EV. Thanks to that, available energy was managed better than during settlement in the tariff systems. However, looking at the final settlement on that day, G12 tariff system turned out to be the most beneficial billing method.

To compare the profitability of the developed algorithm, simulations were carried out for an assumed household with an electric vehicle but no PV installation. The calculations assume that the EV is used in the same manner every day. The household's demand (for its self-consumption) is also the same every day. The simulation results for the summer month have shown that the savings can be up to 34 PLN for G11 tariff and 43 PLN for G12 tariff. For the same assumptions simulations were performed for the winter month. The simulation results showed that by implementing an appropriate infrastructure and management algorithm it is possible to generate savings of 26 PLN in G11 tariff and 50 PLN in G12 tariff.

Table 5. Results for the summer day

		Tariff systems					DBS			
t [h]	Δ_t [kWh]	A	Δ_G [kWh]	SOC_t^{ACT} [%]	$O_{G11.t}$ [PLN]	$O_{G12.t}^{D/N}$ [PLN]	A	Δ_G [kWh]	SOC_t^{ACT} [%]	$O_{DBS.t}$ [PLN]
0	0.3	↓⚡	0.3	50	0.25	0.16	↓⚡	0.3	50	0.24
1	0.26	↓⚡	0.26	50	0.22	0.14	↓⚡	0.26	50	0.21
2	0.24	↓⚡	0.24	50	0.21	0.13	↓⚡	0.24	50	0.2
3	0.22	↓⚡	0.22	50	0.2	0.13	↓⚡	0.22	50	0.18
4	0.16	↓⚡	0.16	50	0.16	0.11	↓⚡	0.16	50	0.15
5	0.06	↓⚡	0.06	42	0.09	0.07	↓⚡	0.06	42	0.09
6	0.05	↓⚡	0.05	33	0.08	0.09	↓⚡	0.05	33	0.1
7	-0.05	↑$	-0.05	24	-0.04	-0.04	↑$	-0.05	24	-0.04
8	-0.21	↑↓☀⚡	3.39	35	2.29	2.54	↑↓☀⚡	3.39	35	3.6
9	-0.64	↑↓☀⚡	2.96	47	2.01	2.22	↑↓☀⚡	2.96	47	3.18
10	-0.58	↑↓☀⚡	3.02	59	2.05	2.27	↑↓☀⚡	3.02	59	3.21
11	-1.2	↑↓☀⚡	2.4	72	1.64	1.81	↑↓☀⚡	2.4	72	2.56
12	-0.37	↑☀	0	73	–	–	↑☀	0	73	–
13	-0.21	↑☀	0	74	–	–	↑☀	0	74	–
14	-1.13	↑☀	0	78	–	–	↑☀	0	78	–
15	-0.73	↑☀	0	80	–	–	↑☀	0	80	–
16	-0.4	↑☀	0	82	–	–	↑☀	0	82	–
17	0.12	↑🚗	0	82	–	–	↑🚗	0	82	–
18	0.5	↑🚗	0	81	–	–	↑🚗	0	81	–
19	0.56	↑🚗	0	80	–	–	↑🚗	0	80	–
20	0.63	↓⚡	0.63	80	0.47	0.51	↑🚗	0	79	–
21	0.64	↓⚡	0.64	80	0.47	0.52	↑🚗	0	78	–
22	0.55	↓⚡	0.55	80	0.41	0.24	↓⚡	0.55	78	0.45
23	0.42	↓⚡	0.42	80	0.33	0.2	↓⚡	0.42	78	0.33
S [PLN]					**10.84**	**11.1**				**14.46**

where: S – sum, in PLN; Δ_G – electricity exchanged between the grid and household, in kWh;

Table 6. Results for the winter day

		Tariff systems					DBS			
t [h]	Δ_t [kWh]	A	Δ_G [kWh]	SOC_t^{ACT} [%]	$O_{G11.t}$ [PLN]	$O_{G12.t}^{D/N}$ [PLN]	A	Δ_G [kWh]	SOC_t^{ACT} [%]	$O_{DBS.t}$ [PLN]
0	0.27	↓⚡	0.27	80	0.23	0.15	↓⚡	0.27	80	0.22
1	0.24	↓⚡	0.24	80	0.21	0.13	↓⚡	0.24	80	0.2
2	0.22	↓⚡	0.22	80	0.2	0.13	↓⚡	0.22	80	0.18
3	0.22	↓⚡	0.22	80	0.2	0.13	↓⚡	0.22	80	0.18
4	0.24	↓⚡	0.24	80	0.21	0.13	↓⚡	0.24	80	0.2
5	0.28	↓⚡	0.28	72	0.23	0.15	↓⚡	0.28	72	0.23
6	0.36	↓⚡	0.36	63	0.29	0.31	↓⚡	0.36	63	0.38
7	0.42	↓⚡	0.42	54	0.33	0.36	↓⚡	0.42	54	0.47
8	0.42	↓⚡	0.42	54	0.33	0.36	↑🚗	0	53	–
9	0.41	↓⚡	0.41	54	0.32	0.35	↑🚗	0	52	–
10	0.37	↓⚡	0.37	54	0.29	0.32	↑🚗	0	51	–
11	0.32	↓⚡	0.32	54	0.26	0.28	↑🚗	0	51	–
12	0.39	↓⚡	0.39	54	0.31	0.34	↑🚗	0	50	–
13	0.46	↓⚡	0.46	54	0.35	0.21	↓⚡	0.46	50	0.46
14	0.48	↓⚡	0.48	54	0.37	0.22	↓⚡	0.48	50	0.45
15	0.54	↓⚡	0.54	54	0.41	0.45	↓⚡	0.54	50	0.6
16	0.61	↓⚡	0.61	54	0.45	0.5	↓⚡	0.61	50	0.66
17	0.63	↓⚡	0.63	54	0.47	0.51	↓⚡	0.63	50	0.71
18	0.65	↓⚡	0.65	54	0.48	0.53	↓⚡	0.65	50	0.73
19	0.65	↓⚡	0.65	54	0.48	0.53	↓⚡	0.65	50	0.7
20	0.63	↓⚡	0.63	54	0.47	0.51	↓⚡	0.63	50	0.66
21	0.55	↓⚡	0.55	54	0.41	0.45	↓⚡	0.55	50	0.54
22	0.46	↓⚡	0.46	54	0.35	0.21	↓⚡	0.46	50	0.34
23	0.37	↓⚡	0.37	54	0.29	0.18	↓⚡	0.37	50	0.28
S [PLN]					**7.94**	**7.44**				**8.19**

Conclusions

The aim of this paper was to design a household energy management algorithm that considered the integration of both PV installation and EV. By using it, the end user, actually a prosumer, can demonstrate savings in electricity bills. It was indicated that a key aspect of optimal demand balancing is a correctly designed algorithm that defines an electricity flow in a whole V2H infrastructure. It should be understood that the strategy has to be correctly adapted to the electricity's demand and its distribution over time.

One of the elements in the V2H infrastructure was an electric vehicle that, from the point of view of conducted considerations - was mobile energy storage. Including electric vehicles in the electricity billings may be cost-effective, provided that users will use the EV's battery in an appropriate and recommended manner. The authors mean that the V2H concept has also disadvantages such as an accelerated battery's aging process that results from increased frequency of charging and discharging cycles. That aspect has also a further negative impact on the secondary automotive market.

None of the technologies that interfere with an operability of an electricity grid can be deployed in a large scale without an appropriate legal policy. Concerning polish regulations, the most significant barrier to the wide V2H deployment is a lack of acknowledging an EV's battery as an "energy storage". As a result, there is no possibility to integrate such type of energy storage with the electricity grid using a bidirectional charging station.

To cap it all, regardless pros and cons of the V2H technology, this concept is a muse of the future, due to bringing invaluable advantages to the national electricity system, which are securing electricity supplies on a domestic level and ensuring the stability of the electricity network.

***Authors**: inż. Aleksander Lula, Politechnika Warszawska, Plac Politechniki 1, 00-661 Warszawa , E-mail: aleksander.lula.stud@pw.edu.pl; mgr inż. Krzysztof Zagrajek, Politechnika Warszawska, Instytut Elektroenergetyki, Zakład Trakcji i Gospodarki Elektroenergetycznej, ul. Koszykowa 75, 00-662 Warszawa, E-mail: krzysztof.zagrajek@pw.edu.pl.*

REFERENCES

[1] Rokicki T., Bórawski P. et al., Differentiation and Changes of Household Electricity Prices in EU Countries, Energies, 14(2021), no. 21, 6894.
[2] Li R., Leung G.C.K., The relationship between energy prices, economic growth and renewable energy consumption: Evidence from Europe, Energy Reports, 7 (2021), 1712-1719.
[3] Pietzcker R., Osorio S., Rodrigues R., Tightening EU ETS targets in line with the European Green Deal: Impacts on the decarbonization of the EU power sector, *Applied Energy*, 293 (2021), 116914.
[4] Żuk P., Żuk P., Increasing Energy Prices as a Stimulus for Entrepreneurship in Renewable Energies: Ownership Structure, Company Size and Energy Policy in Companies in Poland, *Energies*, 14(2021), no. 18, 5885.
[5] Abdel-Hadi A., Salem A. R. et al., Study of Energy Saving Analysis for Different Industries, *Journal of Energy Resources Technology*, 143 (2021), no.5, 052101.
[6] Zdonek I., Tokarski S., Mularczyk A., Turek M., Evaluation of the Program Subsidizing Prosumer Photovoltaic Sources in Poland, *Energies*, 15(2022), no. 3, 846.
[7] Szeląg-Sikora A., Sikora J. et al., Solar Power: Stellar Profit or Astronomic Cost? A Case Study of Photovoltaic Installations under Poland's National Prosumer Policy in 2016–2020, *Energies*, 14(2021), no. 14, 4233.
[8] Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources
[9] Tang Y., Cockerill T.T., Pimm A.J., Yuan X., Environmental and economic impact of household energy systems with storage in the UK, *Energy and Buildings*, 250(2021), 111304.
[10] Zou T., Lou L. et al., Study on operating conditions of household vanadium redox flow battery energy storage system, *Journal of Energy Storage*, 46 (2022), 103859.
[11] Zagrajek K., A Survey Data Approach for Determining the Probability Values of Vehicle-to-Grid Service Provision, *Energies*, 14 (2021), no. 21, 7270.
[12] Ma Y., Houghtion T., Cruden A., Infield D., Modeling the Benefits of Vehicle-to-Grid Technology to a Power System, *IEEE Transactions on Power Systems*, 27 (2012), no. 2, 1012 – 1020.
[13] Contestabile M., Alajaji M., Almubarak B., Will current electric vehicle policy lead to cost-effective electrification of pas-senger car transport?, *Energy Policy*, 110 (2017), 20–30.
[14] Morfeldt J., Davidsson Kuland S., Johansson D., Carbon footprint impacts of banning cars with internal combustion engines, *Transportation Research Part D: Transport and Environment*, 95 (2021), 102807.
[15] Siskos P., Capros P., De Vita A., CO_2 and energy efficiency car standards in the EU in the context of a decarbonisation strategy: A model-based policy assessment, *Energy Policy*,84 (2015), 22–34.
[16] Thiel C., Nijs W. et al., The impact of the EU car CO_2 regulation on the energy system and the role of electro-mobility to achieve transport decarbonization, *Energy Policy*, 96 (2016), 153–166.
[17] Curry C., Lithium-ion battery costs and market, *Bloomberg New Energy Finance*, 5 (2017), 4-6.
[18] Kester J., Noel L., Zarazua de Rubens G., Sovacool K. B., Promoting Vehicle to Grid (V2G) in the Nordic region: Expert advice on policy mechanisms for accelerated diffusion, *Energy Policy*, 116 (2018), 422–432.
[19] Zhou Y., Cao S., Hensenb J.L.M., Lundc P. D., Energy integration and interaction between buildings and vehicles: A state-of-the-art review, *Renewable and Sustainable Energy Reviews*, 114 (2019), 109337.
[20] Liu C., Chau K.T., Wu D., Gao, S., Opportunities and Challenges of Vehicle-to-Home, Vehicle-to-Vehicle, and Vehicle-to-Grid Technologies, Proceedings IEEE, 101 (2013), 2409–2427.
[21] Sijm J., Gockel P.et al., The supply of flexibility for the power system in the Netherlands, 2015-2050 Report of phase 2 of the FLEXNET project, 2017, available online (accessed: 04.03.2022): https://www.tno.nl/media/12356/e17044-flexnet-the-supply-of-flexibility-for-the-power-system-in-the-netherlands-2015-2050-phase-2.pdf
[22] Polish Act on Energy Law, April 10th 1997, (Dz. U. 1997, no. 54 Item 348), [***in Polish***], available online (accessed: 04.03.2022): http://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU19970540348/U/D19970348Lj.pdf.
[23] Polish Act on Renewable Energy Sources, February 20th 2015, (Dz. U. 2015, Item 478), [***in Polish***], available online (accessed : 04.03.2022): https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20150000478/U/D20150478Lj.pdf
[24] The Regulation of the Minister of Energy of 6 March 2019 on the detailed rules for shaping and calculating tariffs and settlements in electricity trade (Dz. U. 2019, Item 503) [***in Polish***], available online (accessed: 04.03.2022): http://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20190000503/O/D20190503.pdf
[25] Project of the Amendment to Polish Energy Law (UC74), [***in Polish***], available online (accessed: 04.03.2022): https://legislacja.rcl.gov.pl/projekt/12347450/katalog/12792158.
[26] Directive 2019/944 of 5 June 2019 on Common Rules for the Internal Market for Electricity, European Parliament: Brussels, Belgium, 2019.
[27] Distribution Grid Operation and Maintenance Code for PGE, available online (accessed: 09.04.2022): https://pgedystrybucja.pl/content/download/9118/file/iriesd_pge-dystrybucja-sa_tekstjednolityobowiazujacy_od_17_02_2022_.pdf
[28] *Homer Pro software*, available online (accessed: 04.03.2022): *https://www.homerenergy.com/products/pro/index.html*
[29] Distribution tariff of PGE Dystrybucja S.A., available online (accessed: 09.04.2022): https://pgedystrybucja.pl/content/download/12183/file/taryfa-2022.pdf
[30] PGE Electricity Sales Tariff , available online (accessed: 09.04.2022): https://www.gkpge.pl/content/download/49134/file/taryfa_dla-energii_elektrycznej_dla_odbircow-_z-grup_taryfowyc_g.pdf