The impact of electric vehicles on the outlook of future energy system

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Abstract: Active promotion of electric vehicles (EVs) and technology of fast EV charging in the medium term may cause significant peak loads on the energy system, what necessitates making strategic decisions related to the development of generating capacities, distribution networks with EV charging infrastructure, and priorities in the development of battery electric vehicles and vehicles with electrochemical generators. The paper analyses one of the most significant aspects of joint development of electric transport system and energy system in the conditions of substantial growth of energy consumption by EVs. The assessments of per-unit-costs of operation and depreciation of EV power unit were made, taking into consideration the expenses of electric power supply. The calculations show that the choice of electricity buffering method for EV fast charging depends on the character of electricity infrastructure in the region where the electric transport is operating. In the conditions of high density of electricity network and a large number of EVs, the stationary storage facilities or the technology of distributed energy storage in EV batteries – vehicle-to-grid (V2G) technology may be used for buffering. In the conditions of low density and low capacity of electricity networks, the most economical solution could be usage of EVs with traction power units based on the combination of air–aluminum electrochemical generator and a buffer battery of small capacity.

1. Introduction

Current trends in motor transport evolution indicate the inevitability of transition to electric vehicles (EVs). It is forecasted that by the year 2030 their number will reach 150 million units (10% of the total number of motor vehicles), and by the year 2060 – 1.2 billion units (60%). Significant growth of EV fleet may have substantial impact on the power supply system, especially taking into consideration the development of quick charging technologies which imply usage of charging terminals with capacity up to 350 kW. In case of estimated increase of EV fleet, their electricity consumption can reach 12% in overall power balance by the year 2030, and 32% by the year 2050 [1]. It should be noted that the increase of EV number may lead not only to growth of overall energy consumption, but also to significant increase of peak electricity consumption, for example in the morning or evening hours.

One of the possible solutions to the problem of growth of peak electricity consumption may be participation of EV fleet in the regulation of power grid regimes based on the use of informational possibilities of smart grids. Another, even more radical, option of smoothing the peaks of consumption loads is the V2G concept, enabling usage of EV batteries for regulation of power grid regimes.
An alternative solution to the problem of covering peak loads on the power system caused by EVs is to install stationary electrochemical storage facilities. Another option of reducing peak loads is to use EVs with electrochemical generators on hydrogen or aluminum [2-4]. The intermediate energy carrier can be produced outside large cities, thus avoiding extra loads on the municipal grids. When using aluminum or hydrogen, EV charging procedure is shortened to 5 -10 min., i.e. it becomes comparable with the duration of fueling of a conventional vehicle. In this case no significant changes of the grid infrastructure are required.

The purpose of this work is to assess of economic efficiency of the listed above options for reducing peak loads on the power system taking into consideration the differences in the procedures of recharging battery electric vehicles (BEVs) and vehicles with traction power units based on electrochemical generators.

2. Problem formulation

This work contains the comparison of expenses for electric energy (energy carrier) and depreciation of the power unit of electric vehicle. It is assumed that other expenses connected with ownership of electric vehicles belonging to one class are approximately the same.

Two types of electric vehicles are being considered:
- electric vehicles with lithium-ion batteries;
- electric vehicles with combined power units based on air-aluminum electrochemical generators and lithium-ion batteries.

It is assumed that BEVs will employ the fast charging option at public charging stations of capacity up to 350 kW. The peak loads on electric grid created by the charging stations are compensated by storage facilities also connected to the grid and located in the same cluster with the particular fast charging station. Two sub-options of energy storage are analyzed. In one case, the electric energy for rapid charging of electric vehicles is accumulated by stationary storage facilities which capacities are specially reserved for these purposes. In the other case, the capacities of EV batteries are employed which are not used at the current time, but are connected to the charging terminal by a bidirectional inverter. The batteries of such group of EVs are provided by their owners to the power system as components of the distributed energy storage system.

The electric vehicle on aluminum fuel is using only the electrochemical generator as the power unit, and the battery is used only as the source of power for acceleration and for recovery of braking energy. Replacement of anodes and electrolyte is performed at special recharging points.

Figure 1. Scheme of V2G technology implementation.
3. Methods

3.1. Expenses related to operation of a battery electric vehicle with buffering of electric energy through V2G

A special feature of this scheme is the usage of EV batteries for two purposes: for EV traction and for buffering of electric energy (figure 1) required for charging of other EVs.

In case of using the charging stations for BEVs with the possibility of using smart grid and V2G for leveling peak loads, the cost of electricity will be the sum of the expenses for purchasing electricity considering the costs of use of storage facilities, and depreciation of the EV battery:

\[
C_{100,year} = \left( \frac{C_{el,year}}{L_{year}} + \frac{C_{V2G,year}}{L_{year}} + \frac{C_{bat,EV,year}}{L_{year}} \right) \cdot 100 ,
\]

where \( C_{el,year} \) - yearly cost of electricity for EV charging, $/year; \( C_{V2G,year} \) - expenses for V2G-regulation, $/year; \( C_{bat,EV,year} \) - EV battery wear when used for EV traction, $/year; \( L_{year} \) - EV yearly kilometrage, km/year; 100 – coefficient for normalizing the expenses per 100 km.

\[
C_{el,year} = \frac{W_{el,year} \cdot C_{el}}{\eta} ,
\]

where \( C_{el} \) - weighted average price of electricity, $/kWh, \( W_{el,year} \) - yearly consumption of electricity for EV running, kWh/year, \( \eta \) - energy efficiency of the storage facility.

Yearly electricity consumption is determined by the specific electricity consumption and kilometrage:

\[
W_{el,year} = \frac{L_{year} \cdot \nu}{100} ,
\]

where \( L_{year} \) - EV yearly kilometrage, km, \( \nu \) - EV specific electricity consumption, kWh/100 km, 100 – coefficient for normalizing the expenses per 100 km.

Expenses for V2G regulation are determined by specific cost of EV batteries, their lifetime number of cycles and depth of discharge. In order to calculate the expenses for V2G regulation, additional expenses for V2G system are estimated which are connected with battery deterioration during leveling of peak consumption \( C_{bat,year} \), $/year, expenses for EV charging equipment and other infrastructure \( C_{inf,year} \), $/year.

\[
C_{V2G,year} = C_{bat,year} + C_{inf,year} ,
\]

Yearly expenses associated with EV battery deterioration resulting from participation in V2G \( C_{bat,year} \), are calculated as:

\[
C_{bat,year} = \frac{C_{bat,EV} \cdot N_{cycle} \cdot DoD}{W_{el,year}} ,
\]

where \( C_{bat,EV} \) - specific cost of battery, $/kWh; \( N_{cycle} \) - battery lifetime number of cycles, \( DoD \) - specific depth of discharge of the battery.

Expenses for V2G infrastructure per one serviced electric vehicle are determined by: its useful capacity \( P_{V2G} \), kW, and service life, \( T_{inf} \). Assuming that one EV takes part in not more than one V2G regulation cycle per day, specific expenses for V2G infrastructure are:
\[
C_{\text{year}}^{\text{inf}} = \frac{C_{\text{inf},V2G}^{V2G}}{T_{\text{inf},V2G}^{V2G} \cdot P_{V2G}^{V2G} \cdot 365 \cdot \lambda_{V2G}^{V2G}} W_{\text{el}}^{\text{year}},
\]  

where \( C_{\text{inf},V2G}^{V2G} \) - cost of V2G infrastructure per one EV, $; \( P_{V2G}^{V2G} \) - useful capacity, kW; \( T_{\text{inf},V2G}^{V2G} \) - infrastructure service life, years, 365 – number of regulation cycles in a year assuming that one EV takes part in one V2G regulation cycle per day, days/year, \( \lambda_{V2G}^{V2G} \) - the ratio of output energy per cycle of V2G- regulation to battery power, kWh/(kW·cycle).

Expenses associated with EV battery deterioration resulting from EV travel are calculated as follows:

\[
C_{\text{bat,EV}}^{\text{year}} = \frac{C_{\text{bat,EV}}^{\text{bat}} \cdot W_{\text{bat}}^{\text{bat}}}{T_{\text{bat}}} ,
\]

where \( C_{\text{bat,EV}}^{\text{bat}} \) - specific cost of EV battery, $/kWh, \( W_{\text{bat}}^{\text{bat}} \) - EV battery capacity, kWh, \( T_{\text{bat}} \) – battery service life, years.

\[
T_{\text{bat}} = \frac{N_{\text{cycle}}}{365},
\]

where \( N_{\text{cycle}} \) - battery lifetime number of cycles, 365 – number of battery operating cycles per year, cycles/year.

3.2. Expenses for BEV kilometrage with buffering of electric energy in stationary storage facilities

In this scheme, buffering of electric energy is implemented by stationary storage facilities located in the energy system (figure 2), necessary for recharging of other electric vehicles.

When stationary storage facilities in the system are used for leveling peak loads caused by fast charging of electric vehicles, the cost of electricity will be the sum of expenses for purchase of electricity, expenses for usage of storage facilities, and depreciation cost of the battery normalized to the run of 100 km. The calculation procedure is generally similar to V2G, but instead of the expenses for EV battery depreciation, the expenses for stationary storage facilities depreciation are taken into account.

![Figure 2. Scheme of EV charging using stationary storage facilities.](image-url)
3.3. Expenses for running of an electric vehicle with air-aluminum electrochemical generator

Cruising range of the electric vehicle on aluminum fuel [2, 3, 5] is not less than 350 km without recharging of the electrochemical generator. This is possible due to separation of the energy source and the power source – figure 3. Substantial quantity of stored energy is provided by the air–aluminum electrochemical generator (AA ECG), while the peak power necessary during speed-up and the recuperation of braking energy is provided by the rechargeable battery.

![Figure 3](image.png)

**Figure 3.** Combined traction power unit based on air–aluminum electrochemical generator [2].

Traction power units of such type, recharging procedure and associated equipment are described in detail in the monograph [2].

AA ECG, rechargeable battery and inverter system comprise the integrated power unit (IPU) of an electric vehicle. AA ECG anodes and electrolyte are replaced as needed. The procedure of replacement of AA ECG is comparatively simple, and the replacement station is not much more complicated than a tire shop.

AA ECG anodes are made of aluminum with alloying additives – indium and tin. Cost of the anode alloy may be reduced if the closed fuel cycle is arranged. The exhausted electrolyte containing products of electrochemical reaction – Al hydroxide – is sent to alumina–aluminum enterprise for restoration of original aluminum. If the closed cycle of energy carrier is organized, the overall cost of AA ECG recharging is low, allowing the EVs on aluminum fuel to compete successfully with battery EVs and hydrogen EVs. More detailed economic calculations and description of the closed fuel cycle are given in [3, 5, 6].

Expenses associated with consumption of aluminum, electricity, IPU depreciation are calculated by the formula:

\[
C_{100\text{km,AA}} = \left( \frac{C_{\text{fuel,AA,year}}}{L_{\text{year}}} + \frac{C_{\text{AA,year}}}{L_{\text{year}}} \right) \cdot 100, \tag{9}
\]

where \(C_{\text{fuel,AA,year}}\) - yearly cost of aluminum for the EV, $/year; \(C_{\text{AA,year}}\) - normalized expenses for EV IPU, $/year, 100 – coefficient for normalizing the expenses per 100 km.

\(C_{\text{fuel,AA,year}}\) is calculated basing on the cost of anode alloy being the consumable component in AA ECG \(C_{\text{AL}}\), $/kWh, and yearly energy expenditures:

\[
C_{\text{fuel,year}} = C_{\text{AL}} \cdot W_{\text{el,year}}, \tag{10}
\]
Annual electricity consumption is calculated in accordance with (3).

\[ C_{\text{AA}}^{\text{year}} = \frac{C_{\text{bat}} + C_{\text{AA}}}{T_{\text{AA}}} \]  

(11)

where \( C_{\text{bat}} \) - cost of rechargeable battery being the component of IPU, $, \( C_{\text{AA}} \) - cost of AA ECG, $, \( T_{\text{AA}} \) - IPU service life which is determined by the service life of rechargeable battery, years.

Cost of rechargeable battery being the component of IPU:

\[ C_{\text{bat}} = C_{\text{bat}}^{\text{EV}} A_{\text{EV}} P_{\text{EV}}^{\text{EV}} \]  

(12)

where \( P_{\text{EV}} \) - capacity of EV power unit, kW, \( \lambda_{\text{EV}} \) - ratio of useful energy during one cycle of battery discharge to EV maximum power, kWh/kW.

Cost of AA ECG being the component of IPU:

\[ C_{\text{AA}} = C_{\text{AA}}^{\text{kWh}} W_{\text{AA}} \]  

(13)

where \( C_{\text{AA}}^{\text{kWh}} \) - specific cost of AA ECG, $/kWh, \( W_{\text{AA}} \) - energy intensity of AA ECG, kWh.

\[ W_{\text{AA}} = \frac{L_{\text{day}} \cdot v}{100} \]  

(14)

where \( L_{\text{day}} \) - EV maximum run until replacement of AA ECG anodes, km, \( v \) - EV specific electricity consumption, kWh/100 km, 100 – coefficient for normalizing the expenses per 100 km.

### 3.4. Adjustment of cost indicators for inflation

The above calculations may be adjusted for the time-related devaluation of money by applying \( CRF \) (capital return factor) - %/year, represented by the formula [8]:

\[ CRF = \frac{d}{1 - (1 + d)^{-T}} \]  

(15)

where \( d \) – weighted average cost of capital, percent per year; \( T \) – service life of the device, years.

### 4. Assumptions

Assumptions for calculations are given in table 1.

Table 1. Assumptions for calculations.

| Parameter | Designation | UOM       | Value     | Reasoning |
|-----------|-------------|-----------|-----------|-----------|
| **General data** |            |           |           |           |
| Discount factor | \( d \) | 10%       | [8]       |           |
| Cost of electricity | \( C_{\text{el}} \) | $/kWh | 0.1       | [10]      |
| Energy efficiency of the storage system | \( \eta \) | 73%       | [11]      |           |
| Battery depth of discharge | \( DoD \) | 0.8       |           |           |
| **Data related to V2G system** |            |           |           |           |
| Specific cost of EV battery participating in V2G regulation. Current / prospective value | \( C_{\text{bat,EV}} \) | $/kWh | 485 / 128 | [1]       |
| Parameter                                      | Designation | UOM    | Value  | Reasoning |
|-----------------------------------------------|-------------|--------|--------|-----------|
| Battery resource                              | $N_{cycle}$ | cycles | 4 000  | [12]      |
| Battery power                                 | $P^{EV}$   | kW     | 70     | [12]      |
| Ratio of battery energy to battery power when participating in V2G regulation | $\lambda_{\text{V2G}}$ | kWh / (kW·cycle) | 1.5 | [12] |
| Cost of electric grid infrastructure for V2G regulation. Capacity of EV inverter: 15 kW. | $C_{\text{inf}^{\text{V2G}}}$ | $$/ EV$ | 1 900 | [11] |
| Infrastructure service life                   | $T_{\text{inf}^{\text{V2G}}}$ | years | 30     | [3]       |
| **Stationary storage facility**               |             |        |        |           |
| Lifetime number of cycles                     | $N_{cycle}$ | cycles | 4 000  | [14]      |
| Battery cost                                  | $C_{\text{bat,ESS}}$ | $$/kWh$ | 1 200  | [14]      |
| Cost of infrastructure                        | $C_{\text{inf,r.ESS}}$ | $$/kW$ | 125    | [14]      |
| Operating costs                               | $C_{\text{year,ESS}}$ | $$/kW·year$ | 10 | [14] |
| Ratio of power and capacity of the storage facility | $\lambda_{\text{ESS}}$ | kWh / (kW·cycle) | 0.5 | [12] |
| Infrastructure useful life                    | $T_{\text{ESS}}$ | years | 30     |           |
| **Electric vehicle**                          |             |        |        |           |
| Energy consumption for running of the electric vehicle | $v$ | kW·h/100 km | 20 | [2] |
| Maximum run before recharging                 | $L_{\text{day}}$ | km    | 350    |           |
| Ratio of power and capacity of EV battery on the run | $\lambda_{\text{EV}}$ | kW / kWh | 0.25 | [12] |
| **Air–aluminum electrochemical generator**    |             |        |        |           |
| Specific cost of the generator                | $C_{AA}$   | $$/kWh$ | 77     | [6]       |
| Specific cost of anode plates                 | $C_{al}$   | $$/kWh$ | 1.0    | [6]       |

5. Results
The dependence of expenses on energy and depreciation of EV power unit on kilometrage is shown in figures 4 and 5.
Figure 4. Dependence of expenses on energy and depreciation of EV power unit on kilometrage. Cost of EV battery – 485 $/kWh.

Figure 5. Dependence of expenses on energy and depreciation of EV power unit on kilometrage. Cost of EV battery – 128 $/kWh (minimum value forecasted for the year 2025).
6. Conclusion

1. The most economical option for providing fast charging of electric transport is the buffering of electricity in the batteries of electric vehicles. This option is feasible when sufficiently large number of electric vehicles is present within a limited area. However, permanent connection of idle electric vehicles to the grid must be provided in this case, which is not always possible.

2. Usage of high-capacity stationary storage facilities allows avoiding permanent connection of EVs to the charging terminal. High-capacity stationary storage facilities support the operation of fast charging terminals. At the same time they solve the problem of integration and stabilization of energy streams coming from distributed energy sources, in particular, from energy generators using renewable energy sources.

3. The competitiveness of electric vehicles employing electrochemical generators will largely depend on the dynamics of decrease of batteries cost. Aluminum as energy carrier may be produced at a sufficient distance from large cities, using cheap electricity produced by high-capacity regional power plants. The energy carrier is transported to the places of consumption, and the products of electrochemical reaction are returned to the production cycle for metal recovery. In this case the refueling infrastructure is similar to the existing system of petrol refueling stations, but simpler, cheaper and more eco-friendly.

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