International Journal of
Sustainable Energy Planning and Management

Comparative economic analysis for different types of electric vehicles

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ABSTRACT

This study is dedicated to comparing the levelized operating costs of various types of power units and energy carriers for electric vehicles: battery systems, hydrogen-air fuel cells, and aluminum-air electrochemical generators. The operating cost considers the power unit itself, energy carrier, and associated charging infrastructure. Each electric vehicle type was calculated in two versions: a passenger electric car and a light duty commercial truck. It is shown that the most cost effective power unit is an aluminum-air generator. Its levelized operating cost is 1.5–2 times lower toward a battery system and 3–4 times lower toward fuel cells. The advantage of aluminum as energy carrier is the low cost and simple design of the corresponding power unit and charging infrastructure compared to those for battery and hydrogen power units. Aluminum recycling is key to its efficient use, this concept may become competitive in the aluminum-producing countries.

Keywords:

Aluminum-air electrochemical generator;
Fuel cells;
Battery electric vehicle;
Cost efficiency;

URL:https://doi.org/10.5278/ijsepm.3831

1. Introduction

The global trend to decrease the use of fossil fuels is caused by environmental, economic, and political reasons [1, 2]. This is true both for large stationary power plants and small mobile power units, particularly for city transportation. In this regard, large scale introduction of hybrid vehicles and BEVs is very promising [3, 4].

In 2017, the global fleet of electric vehicles of all types exceeded 3 million units. By 2030–2050, some countries are planning to stop production of new passenger ICE-cars and restrict the operation of existing ones [5].

Currently, the most common type of autonomous electric transport are Li-ion BEVs. In the developed countries, BEV technology receives strong support from governments and industry, with significant investment into research and development related to EVs and charging stations [1, 6]. At present the following challenges are still limiting mass introduction of BEVs:

- Higher cost and lower autonomy of BEVs compared to ICE cars
- Long charging time when using domestic electric grids
- Insufficiently developed fast-charging infrastructure [3]

To date, the range of the most advanced BEVs (Tesla X, Audi e-Tron, Jaguar I-Pace, Porsche Taycan) is up to 500 km [7]. This is acceptable for daily city use, but not yet adequate for long-distance freight transport [8].

XFC terminals have been designed and are in service. A 400 kW XFC can charge EV batteries to 80% capacity in 10 minutes [9]. However, creating an extensive network of high capacity fast charging terminals, similar to

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Abbreviations

BEV – battery electric vehicle
ICE – internal combustion engine
EV – electric vehicle
XFC – extra fast charge
FCEV – fuel cell electric vehicle
AAEV – aluminum-air electric vehicle
AA ECG – aluminum-air electrochemical generator
EY – electrolysis

the network of modern petrol refuelling stations, is a challenge [4]. It requires additional power plants, upgrades to the existing electric power lines and accelerated construction of stationary energy storage facilities and high power charging terminals [5].

For a large localized fleet of EVs, V2G technology may be advantageous [9–11]. Adaptation of power grids to the demands of a large fleet of BEVs requires substantial investment and time.

FCEVs are manufactured on a substantially smaller scale [12]. Examples include Hyundai Tucson (273 units in 2013–2015), Toyota Mirai (700 units in 2015), and Honda FCX (2,455 units in the USA in 2017) [12–15]. The global fleet of FCEVs in 2015 was approximately 11,300 units, with the expected growth up to 520,000 units by 2020. It is expected that by 2050 the annual sales of FCEVs will reach 35 million units, or approximately 17% of the market [13, 16].

The advantages of hydrogen EVs over BEVs are shorter charging time, comparable to the charging time of ICE cars, and higher specific energy. Taking into account onboard hydrogen storage system, specific energy of fuel cell based power units is 2–3 times that of Li-ion batteries [17], providing FCEVs with a longer range. Thus, Toyota's Project Portal hydrogen-powered truck has an estimated range of 320 km with a gross combined weight capacity of 36 tonnes [18]. For comparison, Iveco Daily Electric BEV with the cargo capacity of 1.1 tonnes has the range of 240 km [19]. Furthermore, hydrogen EVs do not require large scale upgrades to the electric grid, which is another significant advantage over BEVs. The disadvantages of hydrogen transport include safety concerns [6, 20], complex and expensive charging infrastructure, and relatively high cost of fuel cells [12].

In the short to medium term BEVs will be the preferred option for short-range operation, mostly in the cities, defined by the availability of developed electric distribution networks. FCEVs will remain more suitable for long distance operations due to their higher travel range compared to an average Li-ion battery vehicle and their charging infrastructure not tied to electric power hubs [12].

In contrast to BEVs and hydrogen EVs, the development of electric vehicles with metal-air power sources, in particular AA ECGs, has attracted considerably less attention, although some research and development in this field have occurred over the past thirty years [21–24]. AA ECGs are simpler, cheaper, and safer than both Li-ion batteries and hydrogen fuel cells. The specific energy of AA ECGs is approaching that of hydrogen power units. Unlike BEVs, the charging infrastructure for AAEVs does not require expensive upgrades to power grids and is simpler and safer than for FCEVs.

Cost estimates and technical characteristics of existing AA ECGs indicate that their use in transportation may be feasible. Crucially, the products of electrochemical oxidation of aluminum must be returned to the aluminum production cycle [22]. Recycling of spent aluminum significantly reduces the cost of the energy carrier.

The main technical challenges associated with development and deployment of EVs have been already solved. The market share and applications for each type of EVs will be determined by the associated costs and merits of each technology. Therefore, a comparative economic analysis of various types of EVs is needed.

A number of studies provided economic assessment of electric transport, mainly for BEV and FCEV [25–28]. The common conclusion is that in most cases the operation of battery vehicles is cheaper than of hydrogen vehicles. This is mainly due to lower cost of Li-ion batteries compared to hydrogen fuel cells, 250–320 USD/kWh vs. 2,500–5,000 USD/kW [29, 30].

The construction and operating costs of charging stations and related infrastructure networks greatly affect the cost of the provided energy carrier [2–6, 20, 31]. Thus, the average cost of fast charging station is 286–360 thousand USD [31], raising the price of electricity for BEVs from ~0.1 USD/kWh to 0.34–0.58 USD/kWh at the BEV charging station [3, 31]. The cost of hydrogen charging stations may reach 2,406–2,920 thousand USD [6], raising the cost of hydrogen from ~0.09 USD/kWh [14] to 0.28–0.43 USD/kWh at the charging pump [6].

There have been much fewer reports on AA ECGs as mobile power units. Typically they focus on technical problems rather than on economic factors [21, 22, 24]. The authors are not aware of any studies that compare the economic efficiency of BEVs, FCEVs, and AAEVs utilizing a single calculation algorithm and taking into account the cost of the associated charging infrastructure.

The aim of the present study is to fill this gap and provide a direct comparison of the levelized costs of the power units of BEVs, FCEVs, and AAEVs, including the costs of the power unit itself, the energy carrier, and the cost of the associated charging infrastructure. The calculations for each type of EV are done separately for two types of vehicles: i) a C+ class passenger car; and ii) a light duty commercial truck with the total weight of 3,500 kg. The proposed model assumes that the electric vehicles have otherwise identical configuration (body, transmission, controllers, inverters, and electric motors) irrespective of the type of the power source. And therefore, the total prices and operational expenses of different types of electric vehicles were taken equal and excluded from the comparative analysis.

2. Calculation methods

The equation for the levelized costs of electric vehicle ownership is split into several components, which are given with explanations along the section.

2.1 Calculation of the cost of electric vehicle power unit

The energy W (kWh), required to drive an EV over the range L (km) may be calculated as:

$$W = L \cdot q / 100, \tag{1}$$

where q is the specific energy consumption of the EV, kWh/100 km [32].

The cost C, USD, of the power unit for BEV is determined by the cost of the battery assembly:

$$C = \frac{W}{DoD}\left(100\,\% + k_b\right) C_{cap}{}^{bat}, \tag{2}$$

where

k_b is the cost factor of the balancing device of the battery, % of battery cost;

DoD is the battery's permissible depth of discharge, %;

$C_{cap}{}^{bat}$ is the specific cost of the battery, USD/kWh [33].

The cost of the power source for FCEV is determined by the costs of the fuel cell, the Li-ion buffer battery, and the hydrogen tank, USD:

$$C = W_{add} C_{cap}{}^{bat}\left(1 + \frac{k_b}{100\,\%}\right) + N_h C_{cap}{}^{fc} + W C_{cap}{}^{\tan k}, \tag{3}$$

where

W_{add} is the capacity of Li-ion buffer battery, kWh;

$C_{cap}{}^{fc}$ is the specific cost of the fuel cell battery, USD/kW [29, 30];

$C_{cap}{}^{tank}$ is the specific cost of the FCEV fuel tank, USD/kWh;

N_h is the power of the fuel cell, kW:

$$N_h = \frac{W \cdot v}{L}, \tag{4}$$

where

v is the average speed of EV, km/h.

The cost of the AA ECG power unit is determined by the cost of AA ECG itself and the buffer battery, USD:

$$C = W_{add} C_{cap}{}^{bat}\left(1 + \frac{k_b}{100\%}\right) + W C_{cap}{}^{alfc}, \tag{5}$$

where

$C_{cap}{}^{alfc}$ is the specific cost of AA ECG, USD/kWh [22].

2.2. Calculation of the cost of energy carrier and charging infrastructure

Annual operating costs of a charging station of any type C_{opex}, USD/year, are:

$$C_{opex} = C_{power} + C_e + C_{wage} + C_{O\&M} + C_{other}, \tag{6}$$

where

C_{power} is the cost of the electric power delivered to the consumers, USD/year;

C_e is the cost of electricity required to operate the station, USD/year;

C_{wage} is the labor costs (wages and payroll taxes), USD/year;

$C_{O\&M}$ is the equipment maintenance and repair cost, USD/year (assumed 3% of the capital costs);

C_{other} is the miscellaneous and contingencies costs, USD/year (assumed 10% of operating costs).

XFC stations for BEVs operate without permanent on-site personnel. The charging stations for FCEVs and AA ECGs require 2 attendants per shift.

The cost of electricity supplied from the XFC, USD/kWh, comprises:

$$c_t = c_e + \frac{\mathrm{Pr}of + C_{opex} + C_{cap} \cdot CRF}{n_{ev} \cdot 365 \cdot W}, \tag{7}$$

where

c_e is the cost of the energy carrier, USD/kWh;

$Prof$ is the network operator's profit (assumed $Prof = 0.081 C_{opex}$, USD/year);

C_{cap} is the cost of EV charging station, USD;
n_{ev} is a number of EVs charged per day;
CRF is a capital return factor:

$$CRF = \frac{d}{1-(1+d)^{-n}}, \tag{8}$$

where
d is the cost of capital (dimensionless value) [34];
n is the charging station's operational life span, years.

2.3. Charging from electric grid

Taking into account the losses in the charger and on-board power unit, the cost of electricity for BEV supplied from XFC, USD/kWh, is:

$$c_e = \frac{e_p \cdot 100\%}{\eta_{el}}, \tag{9}$$

where
e_p is a cost of medium voltage electricity, USD/kWh;
η_{el} is the efficiency of the charger and BEV battery, %.

2.4. Hydrogen energy carrier

Three versions of hydrogen charging stations are considered. In versions 1 and 2, hydrogen is transported to the charging station by truck from a large scale production site in either compressed (1) or liquefied (2) state. In version 2, hydrogen is liquefied during the production phase and then transported to the charging station in cryogenic form. Before use, liquid hydrogen is converted to the gaseous state. In version 3, hydrogen is produced at the charging station by means of water EY.

In versions 1 and 2, hydrogen is produced via the methane steam reforming method, with the cost $H_{prod.centr}$. In version 3 the cost of hydrogen production, $H_{prod.decentr}$, USD/kg, is determined by the process-specific consumption of electricity and its cost:

$$H_{prod.decentr} = e \cdot B_h, \tag{10}$$

where
e is a cost of low voltage electricity, USD/kWh;
B_h is a specific electricity consumption for EY hydrogen production, kWh/kg.

In versions 1 and 3 hydrogen must be compressed to 700 bar. The cost of compression operation, H_{compr}, USD/kg, is determined by the process-specific consumption of electricity and its cost:

$$H_{compr} = e \cdot B_{compr}, \tag{11}$$

where B_{compr} is a specific electricity consumption for hydrogen compression, kWh/kg.

The cost of liquefying hydrogen, H_{liq}, USD/kg, is determined by the consumption of electricity and its cost:

$$H_{liq} = e \cdot B_{liq}, \tag{12}$$

where B_{liq} is a specific electricity consumption for hydrogen liquefying, kWh/kg.

The transportation costs of hydrogen from the production site to the charging station in compressed and liquefied states, $H_{trans\ compr}$ and $H_{trans\ liq}$ in versions 1 and 2, respectively, are available in ref. [6].

Taking into account the fuel cell efficiency, the cost of hydrogen received from the charging station, USD/kWh, is:

$$c_h = \frac{\left(H_{prod.centr/decentr} + H_{compr/liq} + H_{trans\ compr/liq}\right) \cdot 100\%}{Q_{H2}\, \eta_h}, \tag{13}$$

where
Q_{H2} is hydrogen lower heating value, kWh/kg;
η_h is the efficiency of the fuel cell, %.

2.5. Aluminum energy carrier

Efficient use of aluminum energy carrier requires the infrastructure enabling manufacturing of anodes for AA ECG, delivery of the anodes to the charging stations, and return of the aluminum hydroxide collected from the AAEVs to the aluminum plant for recycling. Sedimentation of hydroxide from the spent electrolyte is a well-developed technology [35]. In the present model it is assumed that sedimentation is performed at the AA ECG charging station [21]. To provide the required efficiency of aluminum oxidation reaction, high-purity metal should be used – not lower than A995 grade.

Dedicated companies – operators of the aluminum energy carrier cycle – can be involved in the implementation of this concept. A plant for the aluminium production/refining and AA ECG anodes manufacture should be managed by that company. It will also include stations for anodes and electrolyte replacement. The operator company will administrate a full aluminium energy carrier cycle, organize and settle logistic flows, anodes manufacture and replacement processes, receiving income from the acquisition of new anodes and electrolyte by the AAEV owner. Thus, the owner of AAEV will own the EV itself and the AA ECG installed on it (capital expenditure). At each visit to charging station, he will pay for the anodes and electrolyte replacement in AA ECG (operational expenditure) – similar to gasoline refueling of ICE car.

The cost of aluminum energy carrier consists of several components: i) the cost of manufacturing A95 technical grade aluminum from alumina [21, 36] (or the cost of refining aluminium to A995 grade, depending on process); ii) the cost of manufacturing aluminum anodes; iii) the cost of aluminum hydroxide (the product of the electrochemical oxidation of Al); iv) the cost of transportation and logistics services for the delivery of the anodes and aluminum hydroxide for recycling between the aluminum plant and the AA ECG charging stations. The profit of the operator of the charging infrastructure and the cost of recycled aluminum, obtained from the returned hydroxide are also taken into account.

The cost of aluminum anodes, C_{al}, USD/kg, is:

$$C_{al} = \left(1 - \frac{k_{rec}}{100\,\%}\right)\left(c_{alu\min a} m_{alu\min a} + e_{al} m_{el} + C_{other}\right) \times \left(1 + \frac{k_{ref}}{100\,\%}\right) + \frac{k_{rec}}{100\,\%}\left(e_{al} m_{el} + C_{other}\right) + C_{prod} + C_{trans}\,, \quad (14)$$

where

k_{rec} is the fraction of the aluminum hydroxide recovered for recycling, %;

$c_{alumina}$ is the price of alumina, USD/kg;

$m_{alumina}$ is the specific consumption of alumina for aluminum production, kg/kg of aluminum;

e_{al} is the cost of electricity for the aluminum plant, USD/kWh;

m_{el} is the specific electricity consumption for production of aluminum, kWh/kg;

C_{other} is the miscellaneous and contingencies costs, USD/kg;

k_{ref} is the cost factor of aluminum refining, % of the cost of primary technical-grade A95 aluminum;

C_{prod} is the cost of manufacturing anodes from refined aluminum, USD/kg;

C_{trans} is the transportation costs, USD/kg.

The cost of aluminum anodes per kWh of generated power is then:

$$c_e = \frac{C_{al} \cdot 100\ \%}{Q_{al} \cdot \eta_{al}}, \quad (15)$$

where

Q_{al} is the specific energy of aluminum, kWh/kg;

η_{al} is the efficiency of AA ECG power unit, %.

Regular replacement of aluminum anodes in normal AA ECG operation cycle should not be confused with the disposal of batteries and fuel cells at the end of their lifetime – it is a replacement of the exhausted energy carrier, which is essentially an equivalent to the recharge procedure.

2.6. Calculation of the vehicle travel cost

For a passenger electric car, the total costs of operating the EV's power unit, per 100 km of travel, $C_{100\ km}$, USD/100 km, is:

$$C_{100\,km} = c_t \cdot q + \frac{C \cdot CRF}{L_{year}{}^{car}} \cdot 100\,km, \quad (16)$$

where

c_t is the cost of the energy carrier, USD/kWh;

q is the EV specific energy consumption, kWh/100 km;

$L_{year}{}^{car}$ is the annual travel range of a passenger EV.

For a light duty commercial truck, the corresponding cost per tonne-kilometer, USD/tonne-km, is:

$$C_{tonne-km} = \left(c_t \cdot q + \frac{C \cdot CRF}{L_{year}{}^{van}}\right) m^{-1}, \quad (17)$$

where

$L_{year}{}^{van}$ is the annual travel range of a light duty commercial electric truck, thousands km/year [8];

m is the load capacity of the electric truck, tonnes.

For comparison with BEV, the load capacities of FCEV and AAEV are adjusted according to the weight difference between the Li-ion battery and the hydrogen-air fuel cell or aluminum-air electrochemical generator.

2.7. Data sources for calculation

Table 1 contains the main data sources for the calculation of life cycle cost of BEVs, FCEVs and AAEVs.

3. Results

In the following subsections the results of calculations are summarized in three figures and one table, the greenhouse gases emission rate compared between three EV concepts in focus and some forecasts are given concerning EV transport industry.

3.1. Calculation results

Table 2 and Figure 1 show the calculated energy carrier cost structure for EVs, assuming the 20 year operating life span of the charging station. Figure 2 shows the calculated levelized costs of the energy carrier and the power unit for passenger cars (USD/100 km) and Figure 3 shows the same for light duty commercial trucks (USD/tonne-km) with different power sources.

Table 1: Basic input values

Parameter	Unit	Value	Symbol	Reference
Specific energy consumption for the EV travel	kWh/100 km	18	q	[32]
Battery's permissible depth of discharge	%	80	DoD	[33]
Specific cost of the Li-ion battery	USD/kWh	197–300	C_{cap}^{bat}	[33, 44]
Specific cost of the fuel cell	USD/kW	50–4,000	$C_{cap.}^{fc}$	[29, 30, 37]
Specific cost of FCEV hydrogen tank	USD/kWh	33	C_{cap}^{tank}	[13]
Specific cost of the AA ECG	USD/kWh	77	C_{cap}^{alfc}	[22]
Life span of the charging stations	years	20	n	[6]
Number of serviced EVs per day	units/day	38	n_{ev}	[3]
Efficiency of the charger and BEV power unit	%	80	η_{el}	[29]
Cost of large-scale hydrogen production by steam methane reforming method	USD/kg	3	$H_{prod.centr}$	[13, 38]
Cost of low voltage electricity	USD/kWh	0.1	e	[1]
Specific energy consumption for hydrogen production by electrolytic method	kWh/kg	60	B_h	[6]
Specific electricity consumption for hydrogen compression	kWh/kg	3	B_{compr}	[39]
Specific electricity consumption for hydrogen liquefaction	kWh/kg	7	B_{liq}	[39]
Efficiency of the fuel cell unit	%	43	η_h	[13]
Price of alumina	USD/kg	0.3	$c_{alumina}$	[36]
Specific consumption of alumina for aluminum production	kg/kg of Al	2	$m_{alumina}$	[36]
Cost of electricity for the aluminum plant	USD/kWh	0.034	e_{al}	[36]
Specific energy consumption for aluminum production	kWh/kg	16	m_{el}	[36]
Efficiency of AA ECG power unit	%	42	η_{al}	[22]
Annual kilometrage of passenger EV	thous. km/year	15	L_{year}^{car}	[5]
Annual kilometrage of a light duty commercial electric truck	thous. km/year	100	L_{year}^{van}	[8]
Load capacity of a light duty commercial battery truck	kg	950	m_e	[19]
Power capacity of the BEV's battery	kWh/kg	0.15	M_{bat}	[12]
Power efficiency of the fuel cell	%	43	η_h	[13]
Power capacity of the FCEV power unit	kWh/kg	0.4	M_{FC}	[40]
Power capacity of AA ECG power unit	kWh/kg	0.3	M_{alfc}	[22]

Table 2: Energy carrier cost structure, USD/kWh

		FCEV			
Parameter	**BEV**	**Compressed hydrogen**	**Liquefied hydrogen**	**EY hydrogen**	**AAEV**
Energy carrier production	0.024	0.210	0.210	0.420	0.497
Hydrogen compressing/liquefying operation	—	0.028	0.042	0.028	—
Energy carrier transportation	0.012	0.141	0.127	—	0.037
Recharging operation	0.264	0.847	0.950	1.053	0.115
TOTAL:	0.299	1.226	1.329	1.502	0.650

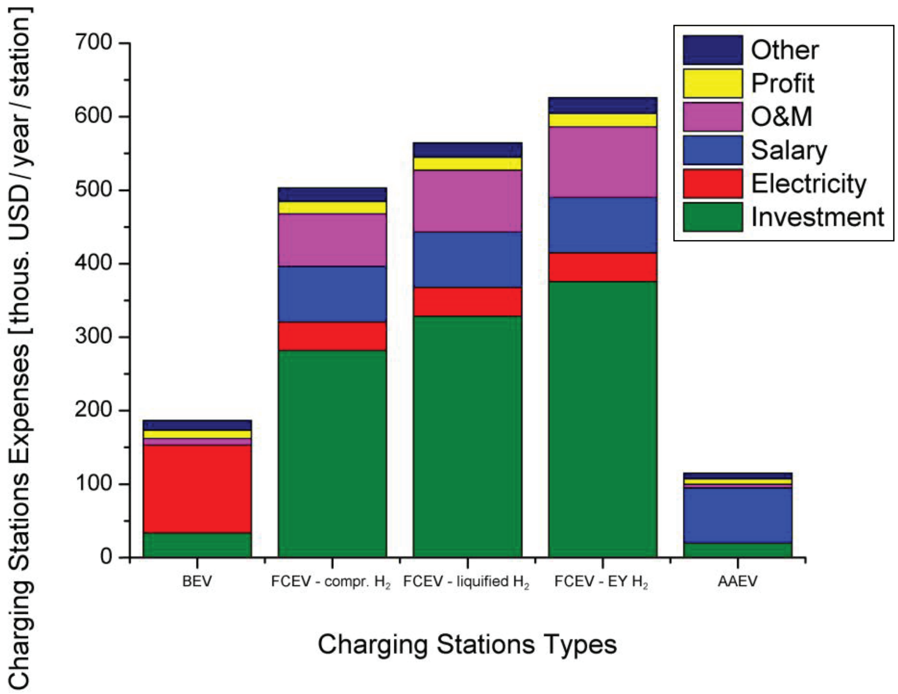

Figure 1: Cost structure of EV charging stations

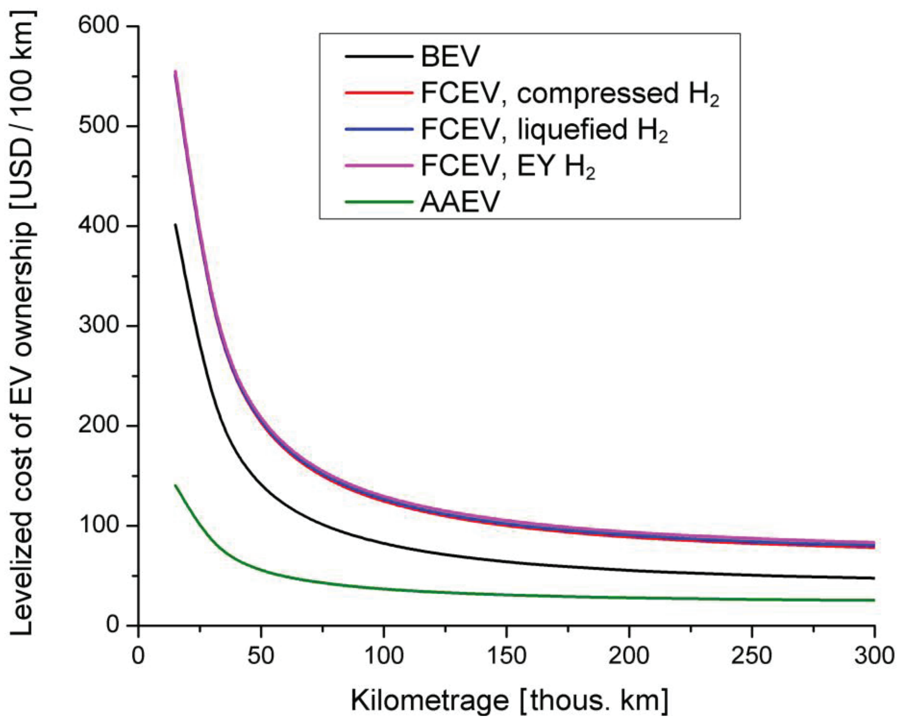

Figure 2: Levelized costs of EV energy carrier and the power unit ownership, passenger cars, USD/100 km

The calculations assume the lifetime range of 300,000 km for passenger electric cars [41] and 500,000 km for electric trucks [42]. Modern Li-ion batteries can operate for at least 3–15 thousand cycles [33]. The operating time of fuel cells and AA ECGs should reach 10–15 thousand hours [43], thus ensuring the specified lifetime EV range without the power unit replacement.

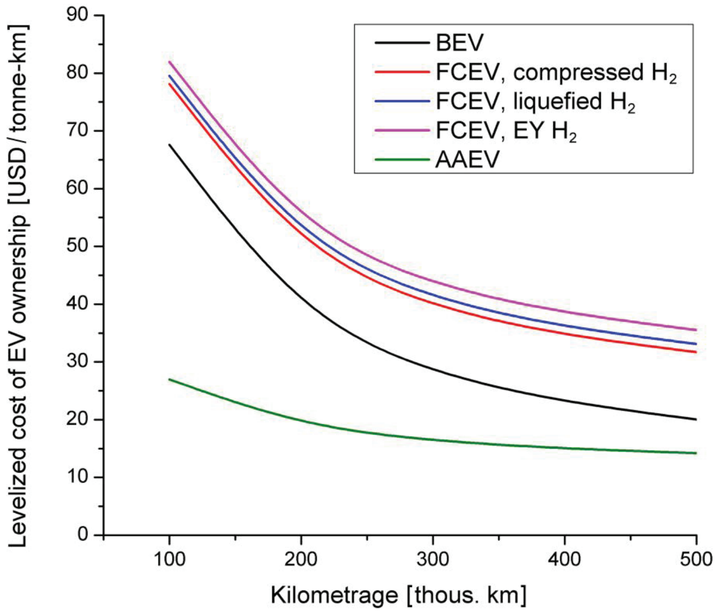

Figure 3: Levelized costs of EV energy carrier and. the power unit ownership, light duty commercial trucks, USD/tonne-km

Figures 1 and 2 show that Al-air electrochemical generator is the most cost-efficient power unit for EVs. For passenger EVs, the total operating cost of AA ECG is 2 times lower than for Li-ion batteries and 3 times lower compared to fuel cells. The trends for commercial trucks are similar. It is also worth noting that AA ECGs have smaller weight per kWh than Li-ion battery, thus increasing the actual load capacity of the vehicle and hence lowering the cost per tonne-km.

3.2. Comparison of greenhouse gas emissions

Greenhouse gas emissions associated with the production, operation and disposal of BEV are estimated at 30-140 g CO_2 eq./km [44, 45], while for FCEV that would be 60-150 g CO_2 eq./km [46]. A smaller value corresponds to the use of renewable sources to generate electricity (for hydrogen production), a larger value involves the use of coal.

Greenhouse gas emissions in the cycle of aluminum production, attributed to the mass of output product, 10 t CO_2 eq./t Al [47]. Given the average anode consumption of 0.053 kg/km, greenhouse gas emissions will amount to 530 g CO_2 eq./km. In addition, it is necessary to take into account emissions associated with the production and disposal of electric vehicle itself – at least 40 g CO_2 eq./km [46], same value for every EV type. Also, the operation of AAEV requires sodium hydroxide as electrolyte, the specific emission for which in electromembrane production process is 1 t CO_2 eq./t NaOH, operational consumption – 0.1 kg NaOH/km, then greenhouse gas emissions attributed to the EV range would be 100 g CO_2 eq./km. Thus, total emissions associated with AAEV operation can be estimated at 670 g CO_2 eq./km, which is higher compared to BEV or FCEV.

3.3. Future trends

In fuel cell development, reducing the costs and replacing platinum in the catalysts, increased efficiency, weight reduction, and increase of the operating life span of fuel cells beyond 15,000 h [43] are anticipated.

The global fleet of EVs is already over 3 million in 2018 and on pace to reach 7 million by 2020 [48]. If the share of FCEVs reaches 25% of the total fleet by the year 2050, the total carbon emissions from transportation may decrease by 10% [13].

The cost of BEVs ownership has a potential for decreasing with the implementation of Smart Charging concepts, which propose to transfer from thoughtless charging upon depletion of the battery towards charging at certain moments when the electricity demand is lowered so the price is reduced [49].

The results of this study suggest that currently, AA ECG is the most cost effective power source technology for EVs. However, in the long term, as major innovations in battery technology result in reduced battery cost, increased life span, and enhancement of charging infrastructure, BEVs may replace AAEV as the most cost-effective EVs.

4. Discussion

Today, battery electric vehicles are the most attractive type of private and urban commercial EVs. This technology can compete with traditional ICE cars. Relatively low cost of electricity has a positive effect on the efficiency of battery-powered electric vehicles. The main disadvantages of BEV are the long charging time from the conventional low power/low voltage grids, as well as the high cost of mass construction of extra fast charging stations and corresponding high power low/medium voltage grids.

Optimistic forecasts suggest that hydrogen-powered electric vehicles may occupy a sizable niche in environmentally friendly transportation segment. Hydrogen FCEVs have a large range, comparable with that of diesel cars, and high charging speed. So far, wide implementation of hydrogen FCEVs is limited by high cost of hydrogen fuel cells and high cost of charging stations. A safety concern is another factor that hampers the widespread introduction of hydrogen FCEVs.

AAEVs will require the development of their own unique charging infrastructure. Electric vehicles with AA ECG have the advantage of a cheap power source with a simple and safe charging process. Convenient and simple distribution and storage of the energy carrier is another important advantage. EV with AA ECG are most attractive for regions with low density of high-power distribution electric grids. This type of EV can be used both in the cities and for long distance transportation since their charging stations are simple and do not require high power electric supply.

Calculations confirm that AAEVs can become the most economical electric transport, even though aluminum itself is the most expensive energy carrier (0.497 USD/kWh vs. 0.024 USD/kWh for electricity and 0.21-0.42 USD/kWh for hydrogen). The key aspects that make AAEVs preferable is the low specific cost of AA ECG (Table 1) and simple, inexpensive charging stations (Table 2). The costly and highly sophisticated charging infrastructure required for hydrogen powered FCEVs is their weakest point.

The levelized cost of powering a passenger AAEV over 150,000 km range is ~30 USD per 100 km, less than half of that of BEV and over 3 times lower than that of FCEV. Over 300,000 km range, the levelized cost of powering a passenger AAEV drops to 25 USD per 100 km. Those of BEV and FCEV show a similar reduction. The levelized cost of powering a light duty commercial truck with AA ECG power unit over 300,000 km range is 16 USD per tonne-km, 1.75 times lower than that of BEV and 2.5 times lower than that of FCEV. When levelized over 500,000 km range, this cost drops to 14 USD per tonne-km, nearly 1.5 times lower than for BEV and ~2.5 times lower than for FCEV.

Since all three concepts considered have their advantages in various conditions, it would be efficient to provide their concurrent operation in a global scale.

Funding: This research was funded by the Russian Academy of Sciences.

Acknowledgments

This paper belongs to an IJSEPM special issue on *Sustainable Development using Renewable Energy Systems*[50]. The study was carried out within the Russian Academy of Sciences General committee program "The Mainstays of Breakthrough Technologies in the Interest of National Security".

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