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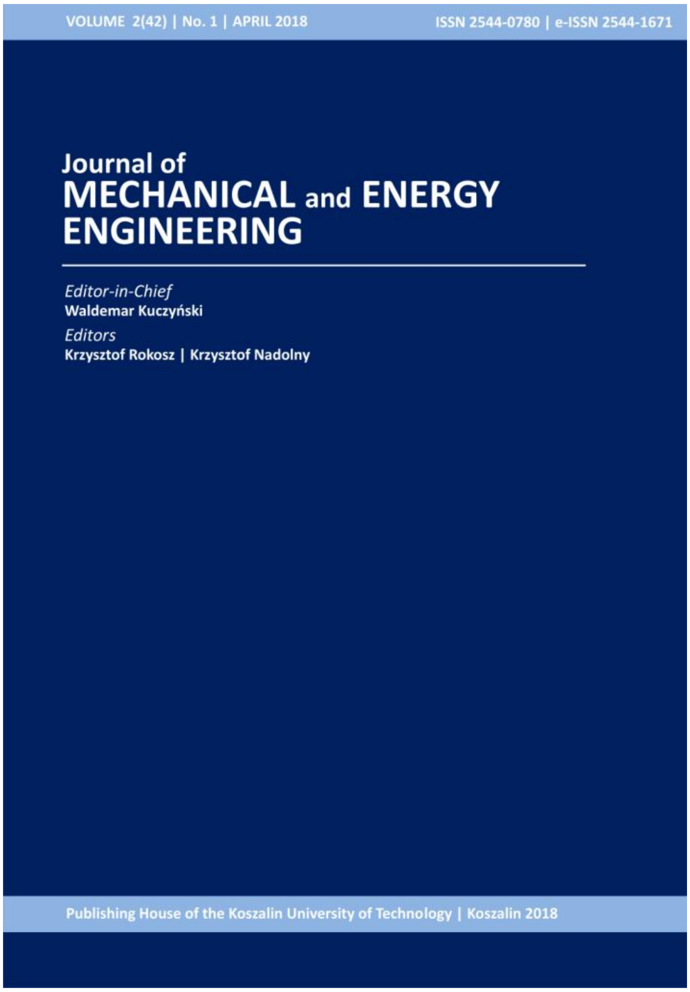

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ELECTROMOBILITY AS ONE OF THE WAYS TO A LOW EMISSION TRANSPORT SYSTEM

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Abstract: The transport sector in Poland heavily pollutes the environment, and together with individual heating systems, it contributes to bad air quality in Polish cities. One of solutions to this problem, among others, is electric transport. It should lead to reduced emissions, but 80% of electricity in Poland is generated from coal and lignite, the “dirty” fuels. This paper is meant to compare the emission of pollutants from power plants per kilometre covered by electric vehicles and by conventional cars. For this purpose, statistical data was used. Additional information concerning possible electromobility evolution, other low emission transport solutions, Polish energy mix evolution, external costs of electricity and differences between EURO limits and real driving emission are also included.

Keywords: electric vehicles, fuels, emission of pollutants in exhaust gases

1. INTRODUCTION

The combustion of fossil fuels is always accompanied by the emission of flue gases. Some of them are responsible for the green-house effect (CO_2, CH_4) and other are considered as pollutants. Every living organism emits green-house gases, therefore their harmfulness is not unequivocal. For many countries, an increase in the year-average temperature would mean a longer growing season, a shorter heating season and better conditions for tourism.

2. AIR QUALITY IN POLAND

Harmful effects of the emission of pollutants, however, are unquestionable. In 2013, the poor quality of air in Polish cities caused around 50,000 of premature deaths [1]. Sulphur dioxide (SO_2) and nitrogen oxides (NO_x) cause immunological problems, headaches and poison surface waters. “Thick” particulates (PM10) cause respiratory problems, and “thin” particulates (PM2.5) together with carbon monoxide (CO) enter the blood circulation system and cause cardiac and nervous system problems [2].

A year-average concentration of pollutants in major Polish cities, along with the WHO recommendations, are presented in Table 1. They are divided into 3 groups depending on their origin (the most severely polluting sectors: energy, transport and households) as shown in Table 2. According to Table 1, only the NO_2 level is acceptable.

It should also be emphasized that the concentration of pollutants strongly depends on a measurement point. In other words, for NO_x those concentrations are halved in suburbs and doubled in city centre traffic [2].

Tab. 1. Year-average concentrations of pollutants in major Polish cities along with WHO recommendations

Pollutant	Median for 19 major Polish agglomerations [3], μg/m^3	WHO recommendations [1], μg/m^3
PM2,5	23.0	10
PM10	32.5	20
SO_2	24.8	20
NO_2	22.0	40
CO	404	-

Tab. 2. Origin of pollutants in Poland [4]

Pollutant	Energy	Transport by roads	Households
PM2,5	10.0 %	13.5 %	49.7 %
PM10	9.3 %	9.0 %	48.5 %
SO_2	47.4 %	0.2 %	32.4 %
NO_2	30.0 %	30.5 %	11.6 %
CO	1.7 %	20.8 %	62.2 %

In February 2017, 4 out of 5 most polluted cities in the world were Polish cities (i.e. Wroclaw, Beijing, Poznan, Katowice, Krakow) [5]. According to the Polish Chief Inspectorate for Environmental Protection on February 15th at 7a.m. the concentration of the PM2.5 particulate reached 352.6 $\mu g/m^3$ (Air Quality Index AQI=402) [6]. The statement on health effects for this situation are as follows "serious aggravation of heart or lung disease and premature mortality in persons with cardiopulmonary disease and the elderly; serious risk of respiratory effects in general population. Everyone should avoid any outdoor exertion; people with respiratory or heart disease, the elderly and children should remain indoors" [7].

3. POLISH POWER PLANTS

Currently, most of the Polish power plants are coal or lignite fired; cf. – Figure 1. 75% are over 25 years old and 62% over 30 [9]. Over the years, they have been modernized to lower the emission of pollutants. At this point, there are 2 European Directives that concern the emission of pollutants from power plants: the Industrial Emission Directive (IED) and the Integrated Pollution Prevention and Control (IPPC) Directive.

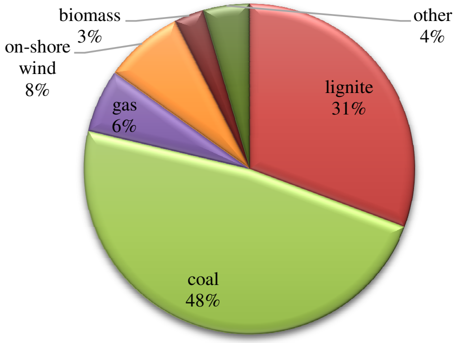

Fig. 1. Polish energy mix 2017 [8]

In 2015, Polish power plants [10]:

- operated with an average efficiency of 40% brut,
- produced 147 TWh brut of electrical energy,
- consumed 12 TWh for auxiliary needs.

Losses in transmission and distribution grids accounted for another 10 TWh, thus the power generation efficiency "at the socket" was around 34% [10].

While comparing electrical energy with crude oil derivatives, it is vital to take into account the emission of pollutants at power plants. It depends on the type of fuel they use.

In the order from the most to the least polluting fuels used to produce electricity, there are the following: coal and lignite, crude oil derivatives, natural gas and neutral to environment renewables and nuclear [11]. In the case of lignite and coal, a significant reduction in the emission of pollutants can be obtained by using the state-of-the-art technology like a fluidized bed boiler. Another solution for emission reduction is gasification. 1 ton of coal can be transformed into 350 m^3 of coke gas and 650 kg of coke [12].

4. EMISSSIONS FROM CARS AND POWER PLANTS

In 2015, there were over 20 mln cars registered in Poland: 11 mln running on gasoline, 6 mln diesels, 3 mln LPG and 500 electric cars. The average age of the car in Poland was around 17 years (the European average is 10 years) [9,13]. Therefore, most of the cars in Poland are subjected to old pollutants emission standards (EURO3/4).

Data concerning emissivity during electricity generation for each type of fuel was taken from the Polish National Centre for Emissions Management [14]. Limiting values for the EURO standards were assumed for a car below 1305 kg of mass, therefore in the calculations it was assumed that the electric car consumes 1 kWh of energy per 6 km of distance covered [15,16]. Such values are correct for small electric cars like Ford Focus (161 km / 23k Wh) or Chevrolet Spark (132 km / 19k Wh) [17]. The results normalized to 1 km of distance covered are shown in Table 3.

Tab. 3. Emission of pollutants per 1 km for different EURO standards (gasoline/diesel) and electric cars in Polish conditions

Source	CO, g/km	HC, g/km	NO_x, g/km	Particulate, g/km	SO_2, g/km
EURO3	2.30/ 0.64	0.20/ 0.06	0.15/ 0.50	-/0.05	-
EURO4	1.00/ 0.50	0.10/ 0.05	0.08/ 0.25	-/-	-
EURO5	1.00/ 0.50	0.10/ 0.05	0.06/ 0.18	0.005	-
EURO6	1.00/ 0.50	0.10/ 0.09	0.06/ 0.08	0.005	-
EV PL	0.04	<0.02 [4]	0.16	0.01	0.25

In the case of power plants, the emission of CO and HC, in other words the incomplete combustion, is much lower than for cars. Higher NO_x emission is mainly due to a higher temperature inside the combustion chamber. The particulates emitted from cars include mainly soot (unburned carbon), the ones from power plants however, come from ash that can account even for 10% of solid fuel mass that enters the combustion chamber. Moreover, contrary to liquid and gaseous fuels, solid fuels contain sulphur. Therefore, cars do not emit any SO_2.

CO_2 emission is proportional to fuel consumption. With the previous assumption on energy consumption by the electrical car of 1 kWh per 6 km of the distance covered, CO_2 emission equals 160 g/km. It is an equivalent of 6 l/100km for internal combustion engines.

5. REAL CAR EMISSION

Due to an enormous number of cars, it is practically impossible to continuously control emission from all of them. In power plants, there is usually one common chimney for multiple units, therefore, there are less than 100 points of measurements. Thus, in the case of power plants, there are real values and in the case of cars there are only estimations based on sample tests. Such an approach may cause pathologies, for instance the design and optimization of the flue gas cleaning system for laboratory conditions instead of the real-driving conditions. This approach also neglects the decay of the car technical condition during its lifetime operation.

It is not a surprise that many researchers claim that the emission obtained during the EURO tests is underestimated comparing to real-driving tests, especially the NO_x emission [18,19,20]. In order to notice that the city driving conditions are far from optimal, one should compare the fuel consumption of the conventional engine with its hybrid equivalent. In the case of Toyota Yaris 2016 [21]:

- 1.33 Dual VVT-i (99HP) – 6.2 l/100km,
- 1.5 Hybrid (100HP) – 3.1 l/100km,
- fuel consumption drops twice.

According to the research conducted at the Poznan University of Technology in 2012, for EURO4 and EURO5 standard cars driving in the city:

- CO emission limit is met after a few minutes of drive,
- HC emission limit is met after 2km (EURO4) or 10km (EURO5) of drive,
- NO_x emission limit is never met,
- The total emission of pollutants is 3 times higher than according to the EURO standards [18].

6. TRANFORMATION OF POLISH ENERGY MIX – 2035 HORIZON

New standards for industrial emission, the so-called BAT (best available technology) conclusions; CO_2 emission fees; depletion of mines; a poor technical condition and low efficiency will result in closing of power plants with the total power of 20 GW between 2017 and 2035 (16 GW hard coal and lignite fired) [8]. LCOE (Lifetime Cost Of Operation) for every conventional energy source will grow, while for wind (both on- and off-shore), PV and nuclear it will fall as shown in Figure 2.

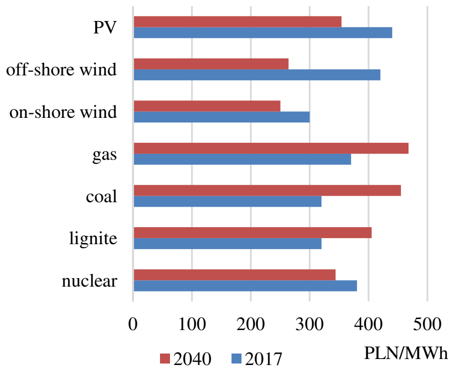

Fig. 2. Current and projected LCOE for different power technologies [8]

To cover the future increase in electricity demand and to fill the gap that will be left after power plants to be closed, Poland has to build new ones. According to [8] there are two scenarios: nuclear (base) and non-nuclear (alternative); cf. Table 4. As a result, more than a half of the electricity will still come from fossil fuels; cf. Figures 3 and 4. In the non-nuclear option, the nuclear share will be covered by gas and off-shore wind. Another positive result, for both scenarios, will be a 50% reduction in CO2 emission per MWh; see Figure 5.

Tab. 4. Forecast for new power investments in Poland in MW of electrical power (starting point: 1/1/2017) [8]

Technology	Base scenario	Alternative scenario
Nuclear	3200	0
Lignite	496	496
Coal	5910	5910
Gas	10193	11693
Pv	3200	4100
On-shore wind	4950	4850
Off-shore wind	3645	6745
Other RSE	3580	5234
Total	35174	39028

We can already identify some of the power plants included in the forecast:

- Turow – 496 MWe lignite (expected commissioning 1/04/2020)
- Kozienice – 1,075 MWe coal (put into service 19/12/2017)
- Jaworzno – 910 MWe coal (expected commissioning 1/11/2019)
- Opole – 2x900 MWe coal (expected commissioning 1/06 and 1/10/2019)
- Ostroleka – 1,000 MWe coal (expected to be the very last coal fired power plant in Poland)
- Wloclawek – 463 MWe gas (put into service 1/06/2017)
- Plock – 596 MWe gas (undergoing final pre-commissioning tests)
- Stalowa Wola – 449 MWe gas (expected commissioning 1/1/2020)
- Zeran – 497 MWe gas
- Lagisza – 417 MWe gas
- Dolna Odra – 2x500 MWe gas

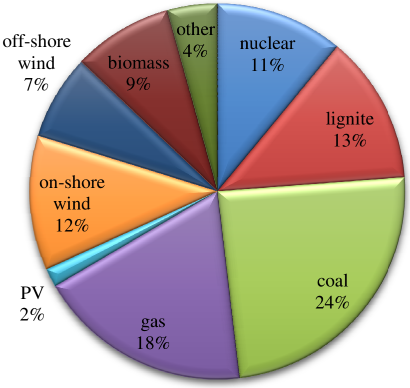

Fig. 3. Polish energy mix in 2035 (base scenario) [8]

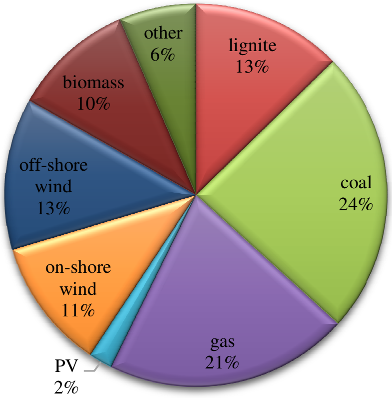

Fig. 4. Polish energy mix in 2035 (alternative scenario) [8]

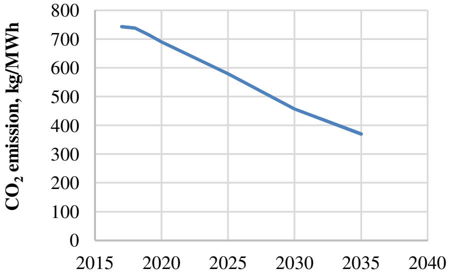

Fig. 5. Projected reduction of CO_2 emission in Polish power sector [8]

Apart from cutting CO_2 emission per MWh in half, change of energy mix and introduction of the BAT conclusions [22] will bring:

- 75% reduction in NOx emission per MWh,
- 85% reduction in SO2 emission per MWh,
- 75% reduction in particulate emission per MWh.

Under the assumptions that the average electric car consumes 20kWh per 100km, covers 20,000 km per year and the charging efficiency equals 0.9, the projected 1 mln electric cars will require 4.5 TWh per year. With 0.75 transmission and distribution grid efficiency, it will translate into 750 MWe unit working at full power for 8,000h a year.

7. PEST ANALYSIS OF ELECTROMOBILITY

PEST (political, economic, social, technical) analysis aims to identify the key factors influencing the development of electromobility.

Political:

- quantitative goal (1mln of electrical cars in 2025 [23]),
- governmental fleet (50% in 2025 [23]) and public transport (1000 electric buses in 40 cities in 2025 [23]) sets an example,
- standardization of plugs,
- development of charging infrastructure (charger at every governmental building [23]),
- 97% of crude oil in Poland comes from Russia [23], therefore electromobility increases the energy independence,
- car and car battery supplier is the same company, proper legislation should solve this problem as it did with electricity (third party access),
- ban of ICE (internal combustion engines) – UK, France, China and India consider introducing the law that will forbid to sale the ICE cars after 2040.

Economic:

- high battery cost,
- low operation cost,

- support programmes (0% excise for electrical cars),
- additional taxes for liquid fuels,
- new high-tech industry,
- lower charging fee at night.

Social:
- fashion,
- air quality,
- fast, easy and available charging,
- free parking, bus lanes and unlimited access to city centre,
- no noise.

Technical:
- emission limits,
- simpler and more robust design (electric engine, no transmission, no spark plugs, no clutch, no gear-box, no oil change),
- maximum torque within a wide range of rotational speed,
- range and charging time,
- 4 wheel drive.

The survey conducted by the Innogy Polska company complies with this list [24]. According to the Polish entrepreneurs, the three main issues concerning electric cars are as follow:
- limited access to charging points,
- limited range,
- high price.

Another survey by Instytut Jagiellonski asked Polish drivers about electric cars [25]. Most drivers stated that electric cars are for the future, they are cheaper in operation and more reliable.

8. ELECTRIC VEHICLES

According to the Polish Electromobility Plan [23], in 2040 there will be 2 bln cars in the world, 500 mln of them will be electric and the annual production capacity of EV will reach 40 mln. It complies with the IEA estimation that 1 “giga-factory” can supply half a million of electric cars [26] and with the statement of Tesla founder Elon Musk that the EV revolution requires 100 “giga-factories” [27]. With the estimated cost of each factory of 10 bln$, the total cost of the EV revolution requires 1 trillion $.

The performance of electric vehicles is improving each year. Between 2008 and 2015, the cost of the battery fell by 75% (from 1000$ per kWh to 250) while its energy density grew 4 times (from 75Wh per litre to 300). Between 2020 and 2022, those values should reach 100$/kWh and 400 Wh/l, respectively [26].

In the near future, the fastest sports cars will be electric. The recently announced Tesla Roadster 2.0 and Rimac C_Two will beat the 2 s barrier in 0-100 km/h acceleration.

According to the manufacturer’s data [28], Tesla Roadster 2.0 will reach 100km/h speed within 1.9 s and complete the ¼ mile drag race within 8.8 s. It will also exceed 400 km/h top speed and 1000 km range.

1914 HP Rimac C_Two will accelerate to 100km/h in 1.85s with top speed 412km/h and 625 km range [29].

Other sports cars manufacturers like Porshe, Aston Martin and Pagani have also announced their own electric vehicles.

At the end of 2017, Tesla announced its first electric truck. According to the manufacturer’s data [28], Tesla Semi will have 800km range (1 MWh battery), 100 km/h top speed and aerodynamics better than Bugatti Chiron. Moreover, while fully loaded (the total mass of 40 tons), it will reach its top speed within 20 s and can sustain it even climbing up a 5% elevation hill.

It can also be charged up to 80% within half an hour. Taking into account the capacity of its battery it requires 1.6 MW charging power, an equivalent of 4,000 households [30].

According to the estimation made by the Rohlig Suus Logistic Company [31], although Tesla Semi is significantly more expensive, it returns 2 times faster owing to 62% less fuel costs. Moreover, within a few years, Tesla Semi may become a fully autonomous truck.

One of the biggest truck manufacturer, Scania, has just announced its testing program for autonomous convoys on Finnish highways [32]. In this solution, only the first truck is fully supervised by a driver and the rest of the trucks just follow the leader. Initially, the drivers will be present, but they will focus on administrative work and engage only in the case of emergency. This is the first such initiative in Europe, but not in the world. Autonomous trucks already operate in Singapore. If the Finnish tests prove to be successful, they will cover Sweden, as well.

Public transport is already electrified to a high degree – trams, suburban and long distance trains, metro and trolley-buses. The only non-electrified public transport vehicles are buses. With modern battery capacities they can run all day on a single charging. Moreover, charging during the night pause can last longer, thus fast, high-power chargers are not required.

The last, but not the least important are light electric vehicles like bikes, scooters and other 2 wheelers. Most cars have 5 seats, but for most of the time they are occupied only by one person. It is a tremendous waste of energy and space. Small electric vehicles occupies a fraction of space required for cars and it consumes very little energy (1 kWh per 100 km for a typical e-bike).

9. OTHER LOW EMISSION SOLUTIONS

As previously mentioned, electric cars are not compatible with the fuel infrastructure dedicated for conventional cars. Yet, electric vehicles are not the only way to lower the overall emission and improve air quality in the cities.

The first possibility is bio-fuels. In the case of transport, alcohols, bio-gas and oils can be utilized. They emit flue gases during combustion, but we have control over impurities during the production process and they are CO_2 neutral (plants absorb CO_2 when they grow). Moreover, they are fully compatible with the current fuel distribution infrastructure and they are already in use (10% share target according to the EU 2020 climate & energy package).

The second option is hybrids. As mentioned before, direct drive in internal combustion engine cars is a source of huge inefficiency. Working in optimal conditions does not only reduce the fuel consumption but it also increases the performance of the flue gas cleaning system. There is a subcategory known as plug-in hybrids that can be charged from the grid, thus for short distance travels no fuel will be consumed.

The third option is to utilize natural gas as a fuel for vehicles. Natural gas is a very pure fuel, thus it does not emit pollutants during the combustion. Transition from gasoline to gas requires minor modifications of the fuel injection system and high pressure tank. Natural gas is widely available owing to the developed transmission and distribution grid.

The last option is to produce synthetic gasoline, synthetic diesel of hydrogen. The process requires a significant energy input, higher than the caloric value of the fuel produced. Therefore, the energy source for the process should be sustainable. The perfect solution is using nuclear energy that cannot be mobilized to produce synthetic fuels by the means of splitting the water. Such a process requires high temperature (1000°C) and the VHTR (very high temperature reactor) technology is not yet available.

Hydrogen is considered to be the purest fuel, because the only product of its combustion is water in vapour state. On the other hand it does not occur in nature, and it has to be produced. Fuel cells that run on hydrogen are very efficient (over 70%), because they are not limited by the first law of thermodynamics.

The key problem with hydrogen is that it is the smallest atom occurring in nature and it can penetrate though every tank. Moreover, it cannot be liquefied at room temperature so in order to obtain a reasonable range it requires very high pressure (200+ bars). Another solution is to bind hydrogen in metal hydrides, but the costs of such tanks are comparable with the cost of batteries for electric vehicles. Additionally, high pressure refuelling requires a significant amount of energy and large compressors at every station.

10. OTHER ASPECTS OF ELECTROMOBILITY

The analysis presented in this paper regards the electric (and other low emission) cars as an alternative for current internal combustion engines widely used in the transport sector. In fact, electromobility can revolutionize the entire transport sector, as the Internet did with communication.

It proves that this young industry is growing very rapidly. Despite the well-established position of a few leading companies, there is still plenty of room to start-up a brand new Polish brand with an export potential. In the case of electric buses, there is already a Polish brand: Solaris, with an international recognition [33].

There are a few differences between liquid fuels and batteries. The total mass of the vehicle is constant, whether it is fully charged or the opposite. Currently 1 km of range requires about 1 kg of battery [34]. Charging, even the fastest one, is still taking much longer than the refuelling. Additionally, there is a lack of experience in long-time operation of currently used batteries and their performance under extremely low temperatures that can occur in Poland.

One of the probable strategies is to use batteries with depreciated capacity as stationary power banks in order to lower the power demand of the charging infrastructure. At some point in the future, it will be profitable to recycle lithium from spent batteries as it was in the case of aluminium.

Using a combination of electric vehicles, internet, big data and machine learning, it is possible to obtain brand new and innovative solutions. One of them is known as car-sharing. A typical car stays immobile for over 90% of time and it is a huge waste of resources. If people resign from an exclusive ownership of a vehicle, this ratio could improve significantly. According to the estimations, car-sharing can reduce the number of vehicles by a factor of 7 to 12 [35]. And if we take the driver out the equation (fully autonomous cars), the price of a taxi ride should fall to the price of a bus ticket.

Batteries installed in electric cars can serve as power banks for solar roofs and other renewable sources of energy. In the future, a large number of such installations will be considered as a virtual power plant.

11. CONCLUSIONS

Currently in Polish conditions, it is not unequivocal whether electric cars supplied with electricity generated from coal are more environmentally friendly than conventional internal combustion engines that cannot meet the prescribed pollutant emission limits.

Of course, for the general population, it is not about the absolute value of emission, but the concentration in populated areas. Power plants are fully transparent in this matter and exhaust at a certain height in rural areas. Cars, however, do this in populated city centres without any effective supervision.

There is a famous study known as ExternE that covers the external costs of different energy technologies. Values recalculated for 1 km of distance covered are presented in Figure 6.

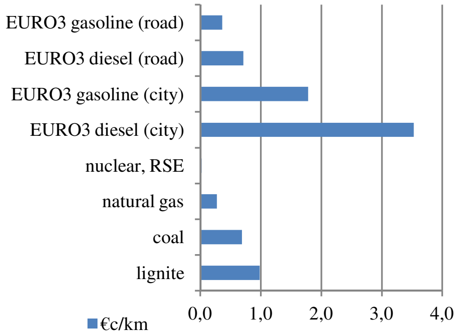

Fig. 6. External costs of vehicle operation [11]

The external costs of energy cover damage to the environment and negative effects on human health. These are stranded costs covered not by the facilities that emit pollutants but by society. According to the data presented in Figure 6, in order to cover for the external costs, the market price of electricity should increase by 0.25 PLN per kWh (the current price is below 0.20) and diesel price should reach 8 PLN per litre (the current price is about 4.50).

Although the Ministry of the Environment charges fees for the emission of pollutants, they are far lower than the actual external costs: NO_x 0.53 PLN/kg (2.9 €/kg), PM2.5 0.35 PLN/kg (19.5 €/kg), lead 43.61 PLN/kg (1600 €/kg) [11,36,37].

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36. Regulation of the [Polish] Council of Ministers of 12 October 2015 on fees for using the environment (in Polish)
37. Notice of the [Polish] Minister of Environment of 29 June 2016 on fees for using the environment in 2017 (in Polish)

Biographical notes

Waldemar Kuczynski is a graduate of the Koszalin University of Technology, Poland. Since 1999, he has been working as the Chair of Thermal Engineering and Refrigerating Engineering. In the year 2002, he was awarded the title of master of science in the field of machine construction and operation in the specialty of thermal engineering. In the years 2002 – 2007, he was a Ph.D. student at the Faculty of Mechanical Engineering of the Koszalin University of Technology. In the year 2008, under a project of the State Committee for Scientific Research, he defended his doctoral thesis entitled “Boiling Testing in Refrigerant Flow under the Conditions of Periodically Generated Disturbances" and in the year 2014 D.Sc. degree in Machinery Construction and Operation from Koszalin University of Technology. Since September 2008 he has been the head of the laboratory of the Chair of Thermal Engineering and Refrigerating Engineering and from 2016 he is also Deputy Dean of the Faculty of Mechanical Engineering of Koszalin University of Technology. He has authored and co-authored more than 100 articles and co-authored nine research projects (and the director of three). His chief interests focus on the issues of wave phenomena and instability during the condensation and boiling of refrigerants in conventional channels and in minichannels.

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