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COMPARATIVE ASSESSMENT OF CARBON DIOXIDE EMISSIONS FROM INTERNAL COMBUSTION ENGINES VEHICLES, PLUG-IN HYBRID ELECTRIC VEHICLES, BATTERY ELECTRIC VEHICLES AND FUEL-CELL ELECTRIC VEHICLES OPERATED IN POLAND FROM 2025–2040 – ALL TYPES OF VEHICLES M1 CATEGORY

Summary. This study presents calculations of relative carbon dioxide emissions for different types of passenger cars (internal combustion engine vehicles, plug-in hybrid electric vehicles, battery electric vehicles, and fuel cell electric vehicles). Using a model based on the life cycle assessment methodology, carbon dioxide equivalent emissions were determined for these vehicles, taking into account three scenarios of energy diversification for Poland from 2025 to 2040. Based on the research, it was concluded that the most environmentally friendly vehicles (in terms of carbon dioxide emissions) are fuel cell electric vehicles. The least environmentally friendly vehicles during operation are plug-in hybrid electric vehicles.

1. INTRODUCTION

The increase in the average surface temperature of the Earth by 1°C (as of 2015) compared to the pre-industrial average is attributed to anthropogenic carbon dioxide emissions. The current concentration of this gas in the atmosphere is the highest in the planet's history, exceeding 400 ppm [1]. Transport contributes 14.5% to CO_2 emissions into the atmosphere (road transport accounts for 10.6% of emissions) [1, 2].

To reduce greenhouse gas emissions in accordance with the Intergovernmental Panel on Climate Change (IPCC) methodology in various economic sectors of countries, representatives of UN (United Nations) member states signed a legal act known as the Paris Agreement [2]. This agreement has contributed, among other things, to the promotion and current global trends in the use of hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs) [2]: changes in favor of alternative mobility in legal acts are noticeable in China, the NEV (New Emission Vehicle) credit mandate [3]; in the state of California, the ZEV (Zero Emission Vehicle) program [4]; in India, the FAME (Faster Adoption and Manufacturing of Hybrid and Electric Vehicles) program [5]; in the European Union, the Clean Mobility package [6]; and in the ban on manufacturing of internal combustion engines vehicles (ICEVs) from 2035. However, are HEVs, BEVs, and FCEVs truly environmentally friendly, considering the high energy input required for their production, operation, and disposal?

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According to the studies [7] based on life cycle assessment (LCA), the CO_2 emissions of BEVs depended on the country in which they were operated. In countries where electricity production was largely based on renewable energy (RE) or nuclear energy, the CO_2 emissions of BEVs were lower than those of ICEVs (e.g., in Norway). However, in countries where coal-based energy had a significant share, BEVs emitted more CO_2 than ICEVs (e.g., in China) [7].

In other studies [8], four major passenger car markets (China, USA, India, and Europe) were considered. Different types of powertrains were considered – ICEVs (including HEVs and PHEVs) as well as BEVs and FCEVs. Various types of fuels (gasoline, diesel, natural gas, biofuels, synthetic fuels, and hydrogen) and different shares of RE in electricity generation were also considered. BEVs and FCEVs showed the most potential to achieve greenhouse gas reductions. The CO_2 emissions (LCA) of an average new mid-sized BEV were lower than those of a comparable spark ignition (SI) engine vehicle (66–69% less in Europe, 60–68% less in the USA, 37–45% less in China, and 19–34% less in India). The CO_2 emissions (LCA) of BEVs were lower than those of an FCEV. The carbon footprint of an FCEV was, on average, 26–40% lower than that of an SI engine vehicle. However, with the production of 'green hydrogen,' these emissions could be even 76–80% lower than those of an average ICEV [8].

The authors of the publication [9] conducted an LCA analysis of BEVs and ICEVs. They pointed out that BEVs in regions with a high rate of conventional energy use generate higher CO_2 emissions (compared to ICEVs). BEVs in regions with a higher level of RE use contribute to the reduction of CO_2 emissions.

In [10], a model was developed to determine the total CO_2 emissions during the life cycle of ICEVs, PHEVs, BEVs, and FCEVs. The lowest relative CO_2 emissions were generated by the BEV – Tesla 3SP (approximately 5.96 Mg), assuming it was powered by electricity obtained from RE sources. The least favorable solution was the use of an ICEV – VW Passat 2.0 TSI, which, according to the LCA, emitted approximately 49.6 Mg of CO_2. A slightly lower emission was observed for the Mercedes-Benz C300de (PHEV) – approximately 38.5 Mg. The ICEV – Audi A4 40 g-tron showed relatively low CO_2 emissions (approximately 9.43 Mg). The FCEV – Toyota Mirai, with a value of approximately 19.75 Mg, was in the top 40% of vehicles in terms of CO_2 emissions.

The conclusions from previous studies are confirmed by the carbon footprint (LCA) analysis of BEVs. They performed significantly better than ICEVs in every European country (with varying shares of RE). The average new European BEV had more than three times lower carbon footprint compared to a comparable mass-market new SI engine vehicle purchased in 2022 (up to -69% CO_2 emissions). In the best-case scenario, where the battery production and charging network were based on the 'cleanest' electricity grid, the average BEV had up to a six times lower carbon footprint (-83%). In the worst-case scenario, where the BEV's battery was produced in China, and the BEV was operated in Poland, the BEV was still more environmentally friendly, with a 37% lower carbon footprint compared to ICEV [11].

Studies [12] have confirmed that BEVs, after covering about 200,000 km (LCA), emit less CO_2 in many European countries. The total CO_2 emissions were 30 t in Germany, 26 t in the European Union, 23 t in Austria, 17 t in France, and 16 t in Norway. The comparable CO_2 emissions for an ICEV were 40 t, and for an HEV, 33 t. Unfortunately, a notable exception was the use of BEVs in Poland, where the CO_{2eq} emissions of an average BEV reached as high as 41 t [12].

In [13], the authors examined the CO_{2eq} emissions for passenger cars with different powertrains operated in various countries. Emissions were determined for three vehicle segments: small, compact, and medium, both with conventional and SUV body types. The researchers considered ICEVs (powered by gasoline, diesel, and liquified petroleum gas (LPG)), HEVs (powered by gasoline or LPG), and BEVs. The results confirmed that the operation of BEVs in countries with high and medium CO_2 emissions during electricity generation is less environmentally friendly than the operation of HEVs and ICEVs powered by LPG, as indicated by lower CO2eq emissions in the life cycle assessment (LCA).

According to the literature review, BEVs are not always the most environmentally friendly means of transport. On the other hand, noticeable research results indicate that BEVs emit lower carbon emissions than ICEVs. The discussion on selecting the most environmentally friendly passenger vehicles motivated the authors to establish the study's objective.

The primary objective of the study was to conduct a comparative assessment of carbon dioxide equivalent (CO_{2eq}) emissions from passenger cars, including ICEVs, HEVs, BEVs, and FCEVs, operating in Poland, considering the vehicle's life cycle (LCA) under various energy scenarios.

An additional objective was to determine the percentage differences in CO_{2eq} emissions for passenger cars equipped with different types of powertrains. To achieve the objectives of the study, the following research questions were posed:

1. To what extent does the use of RE contribute to reducing the CO_2 emissions of PHEVs and BEVs?
2. Which of the presented energy diversification scenarios in Poland is the most advantageous for the application of PHEVs and BEVs?

To accomplish the study's objectives and answer the research questions, the publication presents issues related to the vehicle life cycle (Chapter 2), energy acquisition scenarios in Poland (Chapter 3), research methods (Chapter 4), and research results (Chapter 5).

2. VEHICLE LIFE CYCLE ASSESSMENT – CARBON FOOTPRINT

Environmental LCA is a technique used to measure the total environmental impact of a product [14]. This method is useful for determining the carbon footprint of a vehicle in individual phases of its life (manufacturing, operation, recycling) as well as throughout its entire life cycle [14], according to the following relationship [10]:

$$E_{life,tot}=E_{prod,tot}+E_{util,\,tot}-E_{recyc,\,tot} \quad , \tag{1}$$

where:

$E_{prod,tot}$ – production emissions (kg CO_{2eq}, Mg CO_{2eq}), $E_{util,tot}$ – operational emissions (kg CO_{2eq}, Mg CO_{2eq}), $E_{recyc,tot}$ – vehicle recycling (kg CO_{2eq}, Mg CO_{2eq}).

2.1. Vehicle production emissions

The production process involves a deliberate and complex series of actions aimed at manufacturing a motor vehicle. The production process is associated with production-related emissions [15]. The production emissions of a vehicle can be described by the following relationship [10]:

$$E_{prod,tot}=m_{veh,body}\cdot e_{prod,\,body}+C_{bat}\cdot e_{prod,\,bat} \quad , \tag{2}$$

where:

$m_{veh,body}$ – vehicle curb weight (kg), C_{bat} – electrical capacity of the traction battery (kWh) – only for PHEVs, BEVs and FCEVs, $e_{prod,\,body}$ – relative CO_{2eq} emissions for the production of the vehicle body (kg CO_{2eq}/kg): ICEV gasoline, PHEV gasoline – 4.56 kg CO_{2eq}/kg; ICEV diesel, PHEV Diesel – 4.73 kg CO_{2eq}/kg; ICEV CNG, CBG vehicle – 4.16 kg CO_{2eq}/kg; BEV, FCEV – 4.17 kg CO_{2eq}/kg [10, 16], $e_{prod,\,bat}$ – relative carbon dioxide (equivalent) emissions for the production of the vehicle's traction battery (kg CO_{2eq}/kWh): 61.6–106 kg CO_{2eq}/kWh [17].

2.2. Vehicle operational emissions

Another stage following production that contributes to the carbon footprint is the operation of the vehicle. Activities related to operation include the use of the vehicle [10], which is associated with operational emissions [10, 13]:

$$E_{util,tot}=\left(\frac{FC}{100}\cdot e_{prod,\,fuel}+\frac{EC}{100}\cdot e_{prod,elec}\cdot \varepsilon_{char}\right)\cdot d_{tot} \quad , \tag{3}$$

where:

FC – milage fuel consumption (dm^3/100 km), EC – milage energy consumption (kWh/100km), $e_{prod,fuel}$ – relative CO_{2eq} emissions for the production of a specific fuel (kg CO_{2eq}/dm^3) – WtW (Well to Wheel): gasoline(E95) – 2.83 kg CO_{2eq}/dm^3; diesel – 3.18 kg CO_{2eq}/dm^3; CNG – 2.68 kg CO_{2eq}/kg; CBG – 0.749 kg CO_{2eq}/kg; H_2 – 9.13 kg CO_{2eq}/kg [10, 13, 18], $e_{prod,elec}$ – relative CO_{2eq} emissions for the generation of electricity (kg CO_{2eq}/kWh) – WtT (well to tank): conventional electricity (Poland – year 2023) –

0.662 kg CO_{2eq}/kWh, renewable electricity – 0.003–0.068 kg CO_{2eq}/kWh [10], ε_{char}– traction battery charging efficiency (lithium-ion batteries = 94%), d_{tot} – total vehicle mileage (km).

Operational activities also include maintaining the vehicle in good technical condition, such as regular maintenance, inspections, and repairs. The literature [13] includes reports describing that the CO_2 emissions resulting from the use of the vehicle, the frequency of oil changes, and emissions related to the production of engine oil, brake components, or tires are very low compared to those from vehicle use [11, 16].

2.3. Vehicle recycling

Vehicle recycling is associated with the "second life" of automotive parts. Recycling reduces the carbon footprint of a vehicle. It results in the material recovery of the vehicle body and its traction battery [19]:

$$E_{recyc,tot}=m_{veh,body}\cdot e_{recyc,\ body}+C_{bat}\cdot e_{recyc,\ bat}\ , \tag{4}$$

where:

$e_{recyc,\ body}$ – relative CO_{2eq} emissions recovered in the process of body recycling (kg CO_{2eq}/kg), $e_{recyc,\ bat}$ – relative CO_{2eq} recovered in the recycling process of a vehicle traction battery (kg CO_{2eq}/kWh).

3. SCENARIOS OF ENERGY DIVERSIFICATION IN POLAND

In recent years (2018–2023), the relative CO_{2eq} for generating 1 kWh of energy in Poland have decreased (0.809 kg CO_{2eq}/kWh–0.662 kg CO_{2eq}/kWh [20]). Nevertheless, the total electricity consumption has remained almost unchanged (157–156 TWh) [21] (Fig. 1). Energy diversification has contributed to an increase in RE in total energy production (share of RE in 2018: 9%, share of RE in 2023: 25%). The authors of the report [21] predict that the RE market will continue to grow between 2025 and 2040. Various scenarios for the development of the RE market are forecast, including a significant increase in energy obtained from photovoltaic panels, wind power plants, and hydroelectric power plants. According to the first scenario, a slow development of the RE market in Poland is predicted. In 2025, the forecasted share of RE is 27% (only 2% more than in 2023). The goal for 2040 is to achieve a 37% share of RE in the total energy production balance. In 2025, the forecasted relative CO_2 emissions for electricity generation are expected to be 0.696 kg CO_{2eq}/kWh. The goal for 2040 is to reduce this to 0.577 kg CO_{2eq}/kWh.

The second scenario predicts a moderate development of the RE market in Poland. In 2025, the forecasted share of RE is 29% (4% more than in 2023). The goal for 2040 is to achieve a 59% share of RE in the total energy production balance. In 2025, the forecasted relative CO_2 emissions for electricity generation are expected to be 0.648 kg CO_{2eq}/kWh. The goal for 2040 is to reduce this to 0.372 kg CO_{2eq}/kWh.

The last scenario predicts the dynamic growth of the RE market in Poland. In 2025, the forecasted share of RE is 38% (a 13% increase from 2023). The goal for 2040 is to achieve a 73% share of RE in the total energy production balance. In 2025, the forecasted relative CO_2 emissions for electricity generation will be 0.495 kg CO_{2eq}/kWh. The goal for 2040 is to reduce this to 0.300 kg CO_{2eq}/kWh. The CO_{2eq} emission calculations, based on the adopted scenarios, were determined by the authors of the publication.

4. RESEARCH METHODS

The research methodology included a description of the research method used, as well as a detailed account of the technical and operational data of the selected research objects.

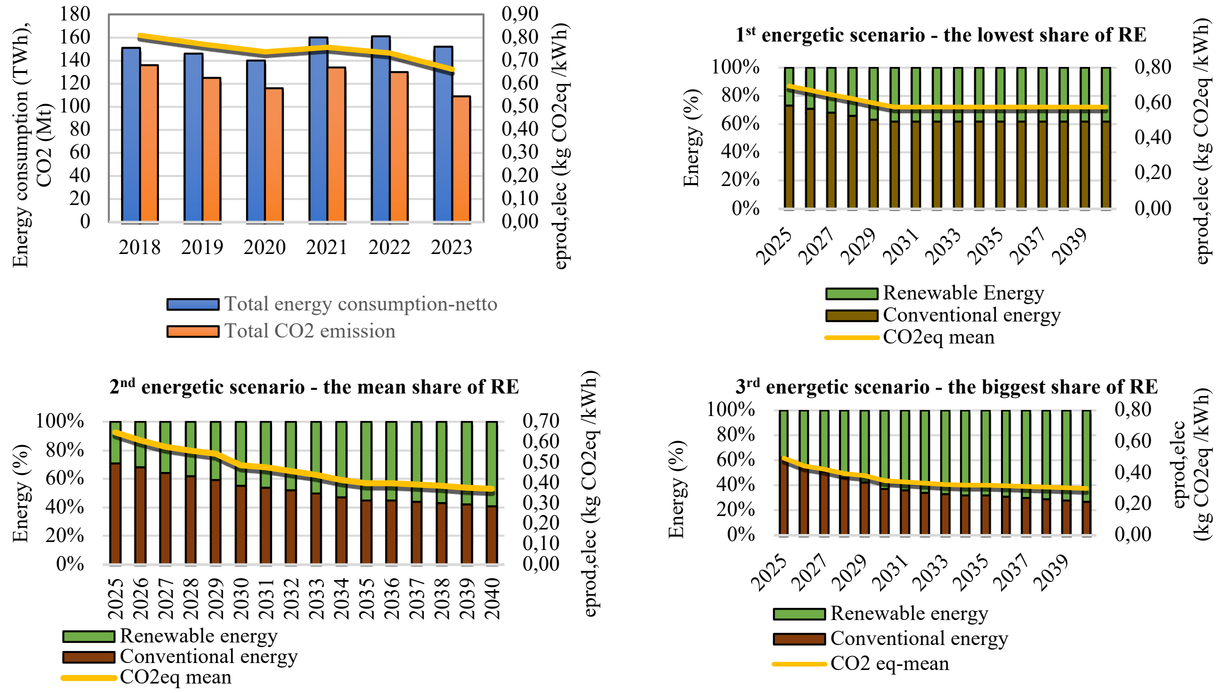

Fig. 1. Energy consumption, total equivalent CO2 emissions in Poland [21, 22], and projected energy scenarios for 2025–2040

4.1. Research method

The LCA research method [14] (Fig. 2) was employed to model the CO_2 emissions of passenger cars. It utilized production, operational, and recycling emissions from Chapter 2, based on selected research objects from Chapter 4.2.

Basic assumptions and limitations of LCA included:

- vehicle WtT (well to tank) CO_{2eq} emissions could differ depending on the location where the fossil fuels are extracted (ICEVs/PHEVs),
- vehicle WtT CO_{2eq} emissions could vary depending on the location from where the fossil fuels are transported (ICEVs/PHEVs),
- vehicle operational CO_{2eq} emissions were not included in the maintenance activities of the vehicle (emissions related to oil changes – ICEVs/PHEVs, production of engine oil – ICEVs/PHEVs, brake components – ICEVs/PHEVs/BEVs/FCEVs, tires – ICEVs/PHEVs/BEVs/FCEVs, etc.)
- operational CO_{2eq} emissions of PHEVs/BEVs/FCEVs were related to the transport of fossil fuels (e.g., coal, extruded oil).

The modeling of relative CO_2 emissions during a vehicle's life cycle consisted of four stages: data identification, determination of the decision variable, definition of constraints, and determination of the criterion function.

Data identification allowed for the identification of significant parameters related to vehicle CO_2 emissions. These included $m_{veh,body}$ (Chapter 4.2), C_{bat} (Chapter 4.2), $e_{prod,bod}$ (Chapter 2.1), $e_{prod,bat}$ (Chapter 2.1), the number of vehicle types S={1,2,3,4}, 1- ICEV, 2- PHEV, 3- BEV, 4- FCEV; the number of vehicles studied n=32; the number of fuel/energy consumption cases for each vehicle m=3; FC (Chapter 4.2), EC (Chapter 4.2), $e_{prod,fuel}$ (Chapter 2.2), $e_{prod,elec}$ (Chapter 2.2, Chapter 3), $e_{recyc,body}$ (Chapter 2.3), $e_{recyc,bat}$ (Chapter 2.3), the operational period of each vehicle equal to 16 years (from 2025 to 2040) in Poland, and the annual mileage of each vehicle at 20,000 km, with d_{tot} = 320,000 km.

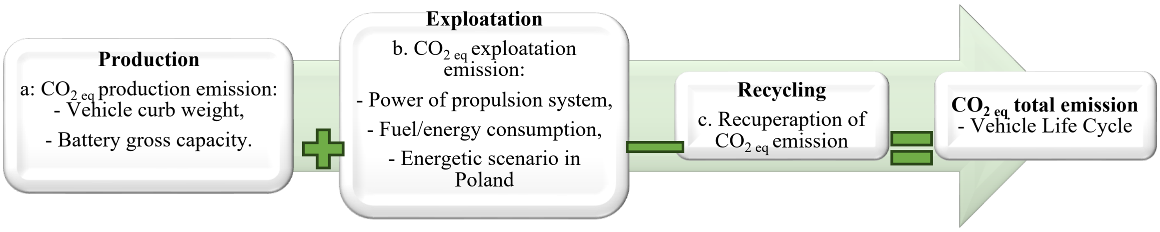

Fig. 2. LCA method

The decision variable was the specified energy scenario implemented in Poland (2025–2040):
Scenario 1: $e_{prod,bat}$ = 106 kg CO_{2eq}/kWh, $e_{recyc,bat}$ = -2.33 kg CO_{2eq}/kg, $e_{recyc,bat}$ = -41.1 kg CO_{2eq}/kWh;
Scenario 2: $e_{prod,bat}$ = 83.5 kg CO_{2eq}/kWh, $e_{recyc,bat}$ = -2.93 kg CO_{2eq}/kg, $e_{recyc,bat}$ = -48.4 kg CO_{2eq}/kWh;
Scenario 3: $e_{prod,bat}$ = 61.6 kg CO_{2eq}/kWh, $e_{recyc,body}$ = -3.52 kg CO_{2eq}/kg, $e_{recyc,bat}$ = -55.7 kg CO_{2eq}/kWh.

The LCA method modeling was characterized by assumptions and constraints, including:

- only selected ICEVs, PHEVs, BEVs, and FCEVs from the M1 category were considered;
- FC and EC values were determined based on user feedback [22] [23];
- parameter ranges: $m_{veh,body}$ (ICEV): 1150–2000 kg, $m_{veh,body}$ (PHEV): 1480–2458 kg, $m_{veh,body}$ (BEV): 1440–2095 kg, $m_{veh,body}$ (FCEV): 1875–1900 kg; P_{ps} (ICEV): 74–228 kW, P_{ps} (PHEV): 104–340 kW, P_{ps} (BEV): 80–239 kW, P_{ps} (FCEV): 130–135 kW; *FC* (ICEV): 2.06–11.97 dm³/100 km, *FC* (PHEV): 0–11.30 dm³/100 km, *EC* (PHEV): 0–39.15 kWh/100 km, *EC* (BEV): 9.40–25.70 kWh/100 km, *FC* (FCEV): 0.72–1.28 kg/100 km.

The criterion function was understood as the sum of relative CO_{2eq} emissions during the entire vehicle life cycle. It allowed for the optimization (minimization) of CO_2 emissions in the context of selecting a specific type of vehicle (based on defined research objects). It was determined by the following relationship:

$$F=\sum_1^S \sum_1^n \sum_1^m \frac{E_{life,tot}}{n} \rightarrow \min. \quad (5)$$

4.2. Research objects

The research objects included passenger cars from leading manufacturers. The group of vehicles consisted of ICEVs (Volkswagen, Volvo, Toyota, BMW, Kia, Mercedes, Hyundai, Mini, and Audi – Table 1), as well as PHEVs (Volkswagen, Volvo, Toyota, BMW, Kia, Mercedes, Hyundai, Mini, Peugeot, and Porsche – Table 2), BEVs (Tesla, Hyundai, Mini, Peugeot, Volkswagen, Nissan, Renault, Kia, Mercedes, and BYD – Table 3), and FCEVs (Toyota, Hyundai – Table 4). ICEV passenger cars (Table 1) were equipped with both spark ignition (SI) and compression ignition (CI) engines. Three vehicles (Volkswagen, Volvo, and Toyota) were equipped with SI engines. The remaining seven ICEVs (BMW, Kia, Hyundai, Mini, Mercedes, and Audi) used CI engines. An interesting solution was represented by the Audi A4 40 g-tron, which could be powered by both compressed natural gas (CNG) and compressed biomass gas (CBG) fuel. It achieved the lowest fuel consumption per distance (3.78–4.09 dm³/100 km).

Nine PHEVs (Volkswagen, BMW, Volvo, Toyota, Kia, Hyundai, Mini, Peugeot, and Porsche) were equipped with a powertrain consisting of an SI engine and electrical machines (EMs; Table 2). In the case of the tenth vehicle, a powertrain was used that operated on the synergy of a CI engine with an EM. The presented values of FC and EC were considered for three driving modes.

The first mode was the electric vehicle (EV) mode. In this mode, each vehicle did not consume fuel but instead consumed the maximum amount of electric energy.

The second mode (ICE+EV) assumed synergy between the internal combustion engine (ICE) and EMs. In this case, the vehicles consumed “average” values of FC as well as “average” values of EC simultaneously.

The third driving mode (ICE) assumed the complete discharge of the traction battery. In this mode, the vehicle consumed the highest amount of FC (which was necessary to overcome rolling resistance as well as to power the generator).

The lowest FC of 1.68 dm^3/100 km was recorded for the Volvo V60 II Recharge 2.0 T8 (in ICE+EV mode), while the highest FC was for the Porsche Cayenne Coupe E-Hybrid, at 11.30 dm^3/100 km (in ICE mode).

BEVs (Table 3) differed in the electric capacity of their traction batteries, which ranged from 40 kWh to 77.4 kWh. The vehicle with the lowest EC was the Tesla Model 3 (9.4–19.2 kWh/100 km).

For all models of vehicles: *FC – EV-min: 0 dm^3/100 km, **EC – ICE-min: 0 dm^3/100 km, P_{ps} – power of propulsion system.

FCEVs (Table 4) were representatives from Toyota and Honda. Both vehicles were equipped with hydrogen fuel cells. The Honda Clarity FCV had the lowest FC (0.72–1.00 kg/100 km).

Table 1

Technical and operational data of selected ICEV passenger cars [23, 24]

	Engine	Vehicle model	P_{ps}	$m_{veh,body}$	FC		
			(kW)	(kg)	(dm^3/100 km)		
					min	median	max
1	SI	VW Passat 2.0 TSI	206	1653	5.19	6.02	7.58
2	SI	Volvo V60 II 2.0	228	2000	7.17	8.23	9.80
3	SI	Toyota XII 1.2T	85	1395	5.10	5.52	6.01
4	CI	BMW 740d xDrive	235	1935	7.56	8.21	11.97
5	CI	Kia Ceed 1.6 CRDi	100	1462	2.06	4.24	7.58
6	CI	Hyu-i i30 1.6 CRDi	128	1509	3.15	6.63	7.52
7	CI	Mini One D	74	1150	4.54	5.19	5.60
8	CI	Mercedes C 300 d	180	1635	4.55	5.16	6.23
9	CI- CNG	Audi A4 40 CNG	125	1665	3.78	3.88	4.09
10	CI- CBG	Audi A4 40 CBG	125	1665	3.78	3.88	4.09

Table 2

Technical and operational data of selected PHEV passenger cars [23, 24]

	Energy source	Vehicle model	P_{ps}	$m_{veh,body}$	C_{bat}	FC		EC	
			(kW)	(kg)	(kWh)	(dm^3/100 km)*		(kWh/100 km)**	
						ICE+EV-96 km	ICE	ICE+EV-96 km	EV
						median	max	median	max
1	SI+EM	VW Passat GTE	160	1730	13.0	4.40	5.64	10.91	11.50
2	SI+EM	BMW 740e i	240	1900	9.2	5.70	7.18	13.02	13.30
3	SI+EM	Volvo V60 II 2.0	287	1989	18.8	1.68	3.80	18.66	20.0
4	SI+EM	Toyota Prius XW50	72+53	1575	1.2	2.30	3.92	14.26	17.40
5	SI+EM	Kia Niro 16 GDi	104	1519	8.9	3.62	5.65	17.86	19.89
6	SI+EM	Hyundai Ioniq	104	1480	8.9	3.56	5.23	14.70	16.78
7	SI+EM	Mini SE ALL 4	162	1790	10.0	5.54	7.24	14.96	25.17
8	SI+EM	Peugeot 3008	221	1918	13.2	4.79	7.24	21.56	28.90
9	SI+EM	Porsche Cayenne	340	2458	14.1	8.07	11.30	28.42	39.15
10	CI+EM	MB C 300 de	225	2060	13.5	3.92	6.42	22.00	26.72

5. RESULTS AND DISCUSSION

According to the adopted research methodology, considering the life cycle of each selected vehicle, the presented energy scenarios, and the technical and operational data of the research objects (ICEVs, PHEVs, BEVs, and FCEVs), the following were determined: the relationships of relative CO_{2eq} for selected vehicles, the relationship of relative CO_{2eq} to the vehicle's weight, and the solution of the criterion function.

5.1. Relative carbon dioxide emissions for selected vehicles

The CO_{2eq} of selected passenger cars varied in each of the presented scenarios (Figs. 3-5, pages 9–11). They were divided into four categories: production, operation, recycling, and total emissions.

Table 3

Technical and operational data of selected BEV passenger cars [23, 24]

	Vehicle model	P_{ps}	$m_{veh,body}$	C_{bat}	EC		
		(kW)	(kg)	(kWh)	(kWh/100 km)		
					min	median	max
1	Tesla Model 3	208	1835	60	9.4	14.4	19.2
2	Hyundai IONIQ 6	239	2095	77.4	11.7	16.9	23.1
3	Mini Electric Cooper SE		1440	32.6	10.9	17.6	22.9
4	Peugeot e-208	100	1530	50	10.8	16.0	22.6
5	Volkswagen ID3.pro	150	1815	62	11.2	15.3	23.2
6	Nissan Leaf II	110	1580	40	11.0	17.1	23.6
7	Renault Zoe ZE50 R110	80	1577	54.7	10.9	17.4	23.6
8	Kia Niro EV	150	1757	68	11.2	16.4	23.6
9	Mercedes EQA 250+	140	2045	73.9	11.4	16.8	23.8
10	BYD Atto 3	150	1825	62	12.3	15.6	25.7

Table 4

Technical and operational data of selected FCEV passenger cars [23,24]

	Fuel cell	Vehicle model	P_{ps}	$m_{veh,body}$	C_{bat}	FC		
			(kW)	(kg)	(kWh)	(kg/100 km)		
						min	median	max
1	H_2	Toyota Mirai	135	1900	2.0	0.74	0.79	1.18
2	H_2	Honda FCV	130	1875	1.7	0.72	0.76	1.00

According to the first energetic scenario (Fig. 3, page 9), the ICEV that emitted the least CO_{2eq} (LCA) was the Audi A4 40 g-tron CBG (12.11–12.35 Mg CO_{2eq}). It was powered by CBG fuel (a non-fossil energy carrier). The smallest carbon footprint from SI engines was left by the Toyota Corolla XII 1.2T VVT-iW (49.30–57.54 Mg CO_{2eq}), while for CI engines, it was the Kia Ceed Sportswagon 2022 1.6 CRDi (24.47–80.64 Mg CO_{2eq}). The largest carbon footprint was attributed to the BMW G11 7 Series 740d xDrive (81.57–126.45 Mg CO_{2eq}).

The PHEV that emitted the least CO_{2eq} (LCA) was the Volkswagen Passat GTE (28.16–66.81 Mg CO_{2eq}). This vehicle was equipped with an SI engine and EMs. The largest carbon footprint was left by the Porsche Cayenne Coupe E-Hybrid (86.27–188.60 Mg CO_{2eq}). This significant carbon footprint was associated with the vehicle's high weight (2458 kg) and the considerable power of its HEV powertrain (340 kW). The BEV that emitted the least CO_{2eq} (LCA) was the Tesla Model 3 (26.45–46.44 Mg CO_{2eq}). The largest carbon footprint was attributed to the BYD Atto 3 (32.48–59.82 Mg CO_{2eq}).

The FCEV that emitted the least CO_{2eq} (LCA) was the Honda Clarity FCV (24.60–32.78 Mg CO_{2eq}).

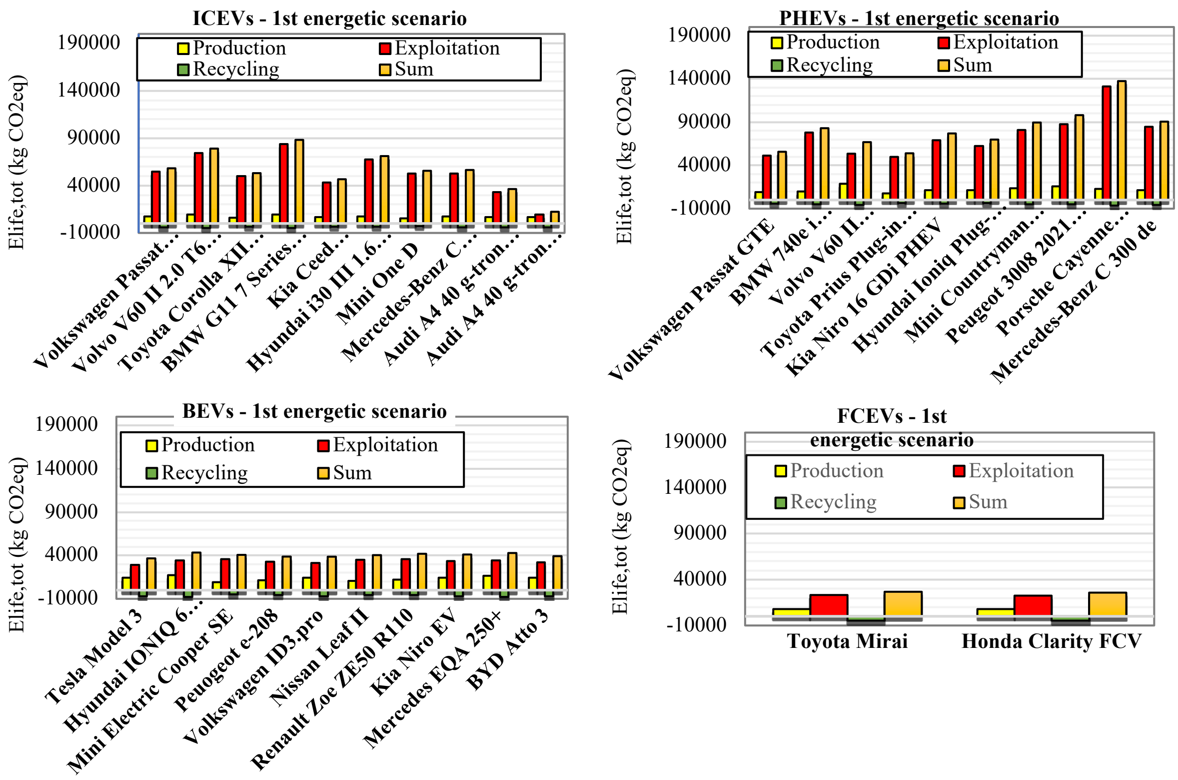

Fig. 3. Elife, tot emission for chosen ICEVs, PHEVs, BEVs, FCEVs (category M1) in Poland – First energetic scenario (2025–2040)

According to the second energetic scenario (Fig. 4, page 10), the ICEV that emitted the least CO_{2eq} (LCA) was the Audi A4 40 g-tron CBG (11.11–11.85 Mg CO_{2eq}). The one with the smallest carbon footprint among those with SI engines was the Toyota Corolla XII 1.2T VVT-iW (48.46–56.70 Mg CO_{2eq}), while the Kia Ceed Sportswagon 2022 1.6 CRDi had the lowest footprint among CI engine vehicles (23.59–79.77 Mg CO_{2eq}). The largest carbon footprint among ICEVs was left by the BMW G11 7 Series 740d xDrive (80.41–125.29 Mg CO_{2eq}).

The PHEV that emitted the least CO_{2eq} (LCA) was, again, the Volkswagen Passat GTE (21.70–60.61 Mg CO_{2eq}). The highest carbon footprint among PHEVs was attributed to the Porsche Cayenne Coupe E-Hybrid (67.23–169.56 Mg CO_{2eq}).

The BEV that emitted the least CO_{2eq} (LCA) was the Tesla Model 3 (19.44–35.14 Mg CO_{2eq}). The largest carbon footprint among BEVs was from the BYD Atto 3 (24.15–45.62 Mg CO_{2eq}). The FCEV that emitted the least CO_{2eq} (LCA) was the Honda Clarity FCV (23.42–31.60 Mg CO_{2eq}).

According to the third energetic scenario (Fig. 5, page 10), the ICEV that emitted the least CO_{2eq} (LCA) was the Audi A4 40 g-tron CBG (10.13–10.87 Mg CO_{2eq}). The one with the smallest carbon footprint among those with SI engines was the Toyota Corolla XII 1.2T VVT-iW (47.64–55.88 Mg CO_{2eq}), while the Kia Ceed Sportswagon 2022 1.6 CRDi had the lowest footprint among CI engine vehicles (22.73–78.90 Mg CO_{2eq}). The largest carbon footprint among ICEVs was left by the BMW G11 7 Series 740d xDrive (79.27–124.15 Mg CO_{2eq}).

The PHEV that emitted the least CO_{2eq} (LCA) was again the Volkswagen Passat GTE (15.77–54.90 Mg CO_{2eq}). The highest carbon footprint among PHEVs was attributed to the Porsche Cayenne Coupe E-Hybrid (49.93–152.26 Mg CO_{2eq}).

The BEV that emitted the least CO_{2eq} (LCA) was the Tesla Model 3 (12.90–24.74 Mg CO_{2eq}). The largest carbon footprint among BEVs was from the BYD Atto 3 (16.41–32.60 Mg CO_{2eq}). The FCEV that emitted the least carbon dioxide (LCA) was the Honda Clarity FCV (22.26–30.44 Mg CO_{2eq}).

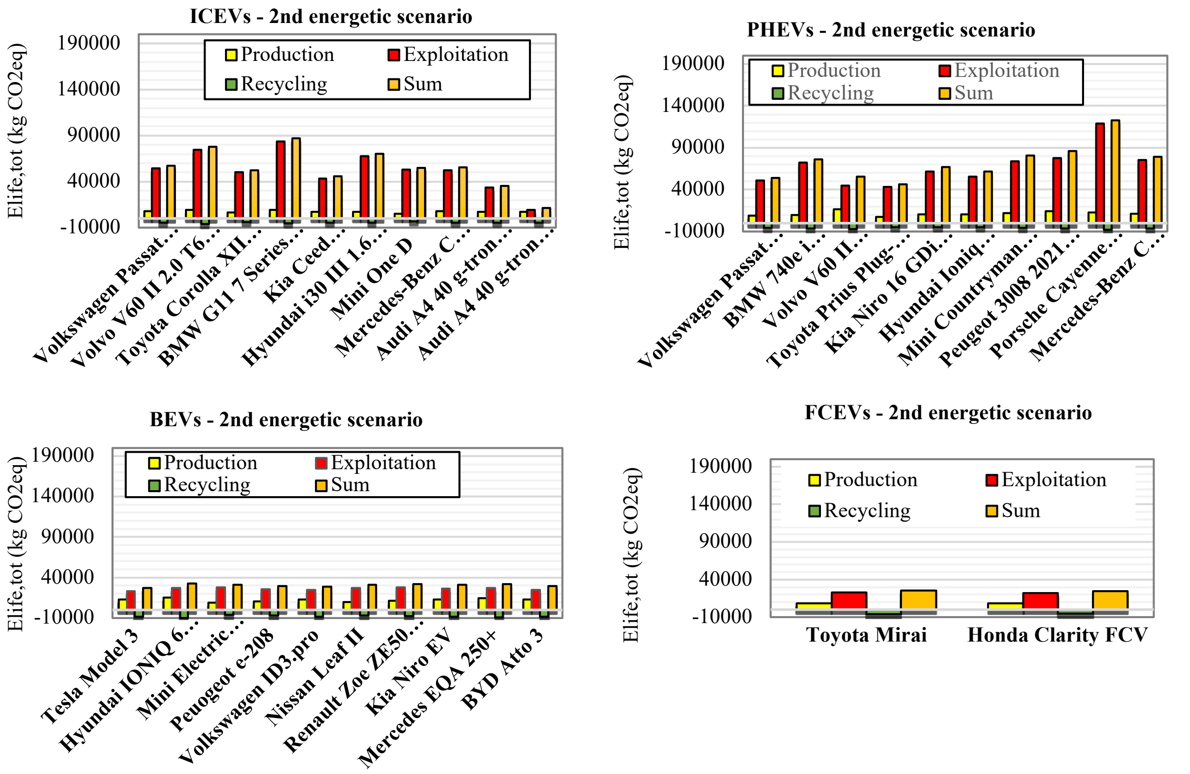

Fig. 4. Elife, tot emission for chosen ICEVs, PHEVs, BEVs, FCEVs (category M1) in Poland – Second energetic scenario (2025–2040)

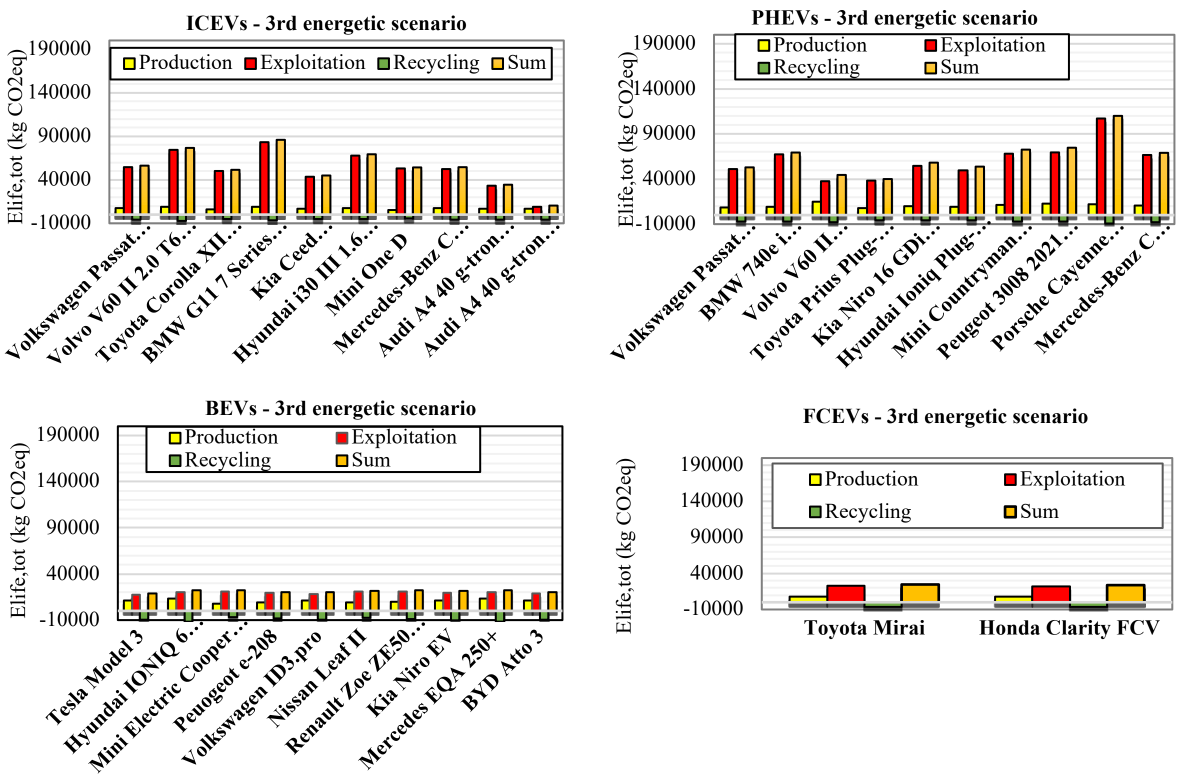

Fig. 5. Elife, tot emission for chosen ICEVs, PHEVs, BEVs, FCEVs (category M1) in Poland – Third energetic scenario (2025–2040)

5.2. Relative carbon dioxide emissions versus vehicle weight

In Fig. 6 (page 11), the characteristics of relative CO_{2eq} were gathered for the presented energy scenarios. Trend lines were fitted to the obtained points, considering the error bars resulting from the varying fuel and energy consumption for each category of vehicle. In every case, an increase in the vehicle's weight was associated with an increase in total relative CO_2 emissions throughout the vehicle's life cycle.

According to the first energetic scenario, the trend line for ICEVs was positioned higher than the trend line for BEVs and FCEVs while being lower than the trend line for PHEVs. The first scenario exhibited the overall highest relative CO_{2eq} emissions during the vehicles' lifetimes. It is worth noting that the emissions from the Audi A4 g-tron powered by CNG or CBG were below the trend line for BEVs.

The second energetic scenario allowed for lower CO_{2eq} emissions than the first. The trend line for ICEVs was again positioned higher than the trend line for BEVs and FCEVs, but it was lower than the trend line for PHEVs. The two lines (ICEVs and PHEVs) converged at a vehicle weight of approximately 1480 kg. This suggests that a PHEV weighing less than 1470 kg should emit less CO_2 than an ICEV.

The third energetic scenario resulted in the lowest CO_{2eq} emissions. The trend line for ICEVs was positioned higher than the trend line for BEVs and FCEVs while being lower than the trend line for PHEVs. The two lines (ICEVs and PHEVs) converged at a vehicle weight of approximately 1640 kg. This suggests that a PHEV weighing less than 1640 kg should emit less CO_2 than an ICEV. The equations describing the trend lines for each energy scenario have been compiled in Table 5 (page 12).

Based on the presented scenarios and estimated trend line equations, the percentage comparison of CO_{2eq} emissions relative to the vehicle's mass during its entire life cycle was determined (Fig. 7, page 13) according to the previously defined energy scenarios. According to the first energetic scenario, the highest relative CO_{2eq} emissions are characteristic of PHEV (114% of ICEV emissions at a mass of 1500 kg; 141% of ICEV emissions at a mass of 2100 kg). BEVs emit 75% of ICEV emissions at a mass of 1500 kg and 59% of ICEV emissions at a mass of 2100 kg. FCEVs are the most environmentally friendly, emitting 37% of ICEV emissions at a mass of 1800 kg and 49% of ICEV emissions at a mass of 2100 kg.

According to the second energetic scenario, the highest relative CO_{2eq} emissions are characteristic of PHEVs (103% of ICEV emissions at a mass of 1500 kg and 127% of ICEV emissions at a mass of 2100 kg). BEVs emit 58% of ICEV emissions at a mass of 1500 kg and 44% of ICEV emissions at a mass of 2100 kg. FCEVs are the most environmentally friendly, emitting 36% of ICEV emissions at a mass of 1800 kg and 47% of ICEV emissions at a mass of 2100 kg.

According to the third energetic scenario, the highest CO_2 emissions are characteristic of PHEVs (101% of ICEV emissions at a mass of 1700 kg and 115% of ICEV emissions at a mass of 2100 kg). For vehicle masses ranging from 1400 to 1500 kg, CO_{2eq} emissions are lower than those of ICEVs (92% and 97%, respectively).

BEV emits 42% of ICEV emissions at a mass of 1500 kg and 31% of ICEV emissions at a mass of 2100 kg. FCEV is the most environmentally friendly, emitting 35% of ICEV emissions at a mass of 1800 kg and 46% of ICEV emissions at a mass of 2100 kg.

5.3. Solution of the criterion function

The results of the criterion function were as follows:

- First energetic scenario: ICEV - 55.69 Mg CO_{2eq}, PHEV - 82.23 Mg CO_{2eq}, BEV - 40.35 Mg CO_{2eq}, FCEV - 33.69 Mg CO_{2eq}
- Second energetic scenario: ICEV - 54.73 Mg CO_{2eq}, PHEV - 73.00 Mg CO_{2eq}, BEV - 30.40 Mg CO_{2eq}, FCEV - 26.43 Mg CO_{2eq}
- Third energetic scenario: ICEV - 53.78 Mg CO_{2eq}, PHEV - 64.53 Mg CO_{2eq}, BEV - 21.23 Mg CO_{2eq}, FCEV - 19.71 Mg CO_{2eq}.

The solution of the criterion function is the FCEVs used according to the third energetic scenario (highest share of RE).

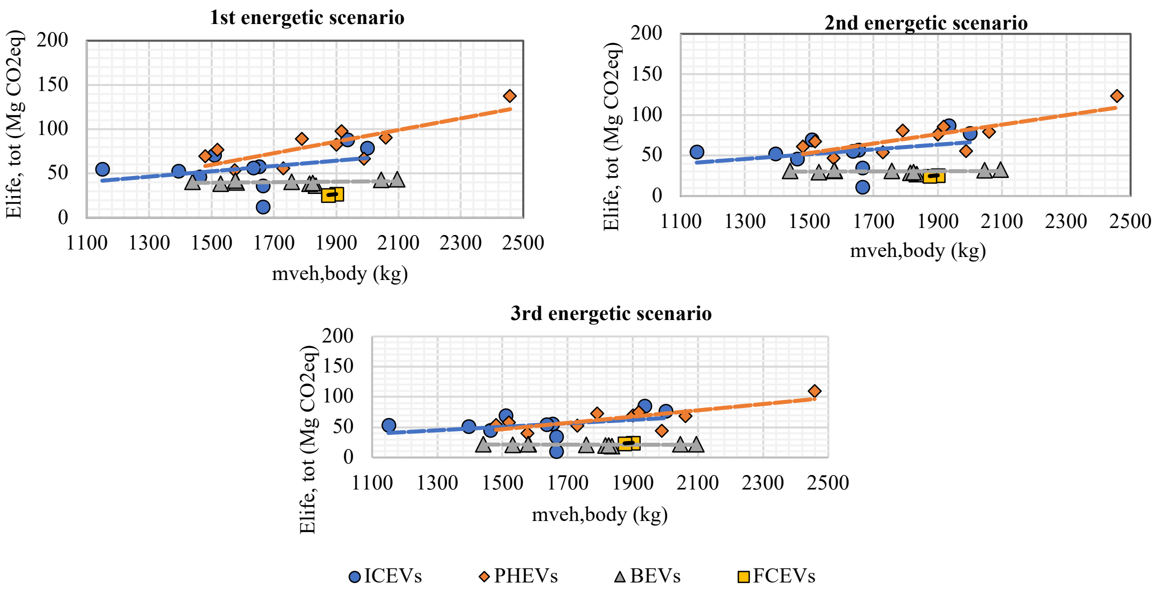

Fig. 6. Elife, tot vs. mveh, body for ICEVs, PHEVs, BEVs, and FCEVs (category M1) in Poland – First, second, and third energetic scenario (2025–2040)

Table 5

Trend line equations

	Vehicle type	$E_{life,tot}$ Equation		
		1st energetic scenario	2nd energetic scenario	3rd energetic scenario
1	ICEVs	$0.0301m_{veh,body} + 7.3764$	$0.0295m_{veh,body} + 7.3764$	$0.0289m_{veh,body} + 7.3764$
2	PHEVs	$0.0656m_{veh,body} - 38.583$	$0.0584m_{veh,body} - 34.657$	$0.052m_{veh,body} - 31.194$
3	BEVs	$0.0029m_{veh,body} + 35.263$	$0.0011m_{veh,body} + 28.429$	$- 0.0007m_{veh,body} + 22.385$
4	FCEVs	$0.0377m_{veh,body} - 44.882$	$0.0367m_{veh,body} - 44.262$	$0.0358m_{veh,body} - 43.655$

6. CONCLUSION AND DIRECTIONS FOR FUTURE RESEARCH

Based on the conducted research (LCA modeling) for 32 selected vehicles (96 cases of fuel/energy consumption) equipped with various drivetrains (ICEVs, PHEVs, BEVs, and FCEVs) and for three energetic scenarios, it was found that the **most environmentally friendly are FCEVs**. **The second-most eco-friendly type is BEVs**. The least eco-friendly vehicles are PHEVs, especially those with a curb weight > 1700 kg (Fig. 7).

When comparing the percentage of relative carbon dioxide emissions:

- First energetic scenario: **PHEVs** from **114% to 141%** of ICEVs, **BEVs** from **75% to 59%** of ICEVs, **FCEVs** from **37%** to **49%** of ICEV;
- Second energetic scenario: **PHEVs** from **103% to 127%** of ICEVs, **BEVs** from **58% to 44%** of ICEVs, **FCEVs** from **36%** to **48%** of ICEV;
- Third energetic scenario: **PHEVs** from **92% to 115%** of ICEVs, **BEVs** from **42% to 30%** of ICEVs, **FCEVs** from **34%** to **47%** of ICEV.

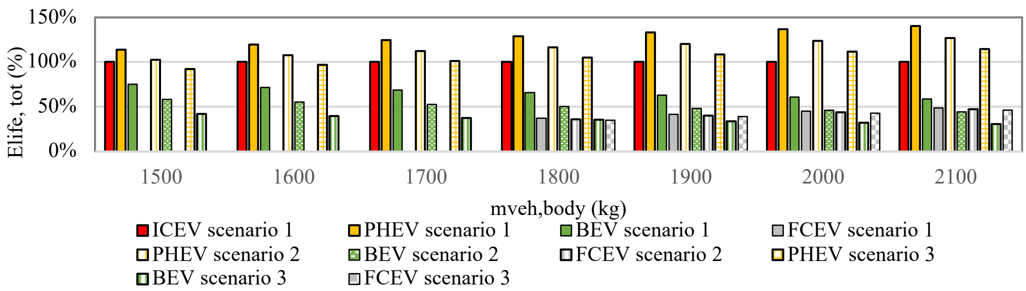

Fig. 7. Elife, tot vs. mveh, body for ICEVs, PHEVs, BEVs, and FCEVs (category M1) in Poland – First, second, and third energetic scenario (2025–2040)

In response to the research questions:

- **The use of RE** significantly contributes to **reducing CO_2** emissions from **BEVs**.
- Assuming the least eco-friendly (i.e., the most emissive and most realistic) first energetic scenario, CO_{2eq} emissions **from BEVs are lower** than those **from ICEVs**.
- A noticeable **lower emission from PHEVs** compared **to ICEVs** can be observed when applying the **third energetic scenario** (with a vehicle weight of <= 1600 kg).
- **The third energetic scenario** is the most advantageous for the use of **PHEVs and BEVs**.

The conclusions confirm the growing ecological trend of electrifying transport and the use of hydrogen for FCEVs. It is also worth noting the potential use of synthetic fuels to power ICEVs (the Audi A4 40 g-tron powered by CBG emitted only 10.13–12.85 Mg CO_{2eq}).

Based on the results, it is important to extend the share of RE in Poland's electricity system. Carbon intensity in 2023 was high in Poland (662 g CO_{2eq}/kWh) in comparison to other countries (Fig. 8).

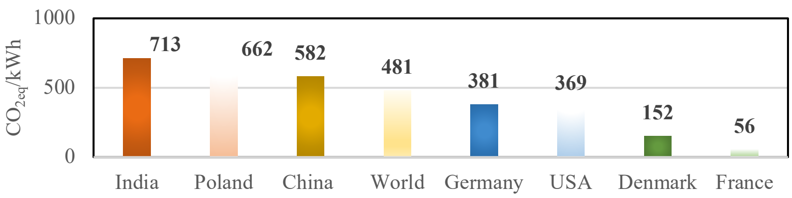

Fig. 8. Carbon intensity of electricity generation for other countries in 2023 [21]

In 2030, the share of conventional energy (CE) generation should not exceed 37% (third energetic scenario – 0.383 CO_{2eq}/kWh). According to the guidelines of the Energy Transformation of the Polish Ministry of Climate and Environment, the share of CE is predicted to be 56% (closest to the second energetic scenario – 0.487 CO_{2eq}/kWh). Apart from increasing energy diversification through the use of biofuels, it is also important to plan and extend the infrastructure of charging station grids and hydrogen refueling stations. Also of considerable importance is the further promotion of programs like "NaszEauto" ("OurEauto") [25].

Given the identified design and operational trends, a proposal for further research could be to compare the relative CO_2 emissions (LCA) of passenger cars and commercial vehicles equipped with ICEVs (powered by synthetic fuels) with those of BEVs and FCEVs. It is also a great opportunity to assess various types of vehicles from the transportation sector (cars, ships, planes, etc.) and their environmental impact.

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