DOI:10.34918/87427

Julia JANOSZKA[1], Rafał SETLAK[2]

7. COMPARISON OF ENERGY CONSUMPTION AND CO2 EMISSIONS IN THE LIFE CYCLE OF SELECTED ELECTRIC AND COMBUSTION VEHICLES

7.1. Identification of the problem

Electric cars can play a dual role in future. Firstly, they will traditionally be used to move goods and people, and secondly they could be used to store energy for balancing in renewable energy.

In both cases, it is important to know the full carbon footprint of electric vehicles relative to combustion vehicles. It is straightforward to compare the carbon footprint for the use phase of electric vehicles and combustion vehicles that run on a specific driving cycle. However, comparing the energy consumption and associated CO2 emissions during the production phase of vehicles and, in particular, during the manufacture of the materials from which the vehicles are built, is not straightforward. This article has been written with this in mind. It is an attempt to calculate the energy consumption and CO2 emissions over the life cycle of selected electric and combustion vehicles. Such calculations can be done with available data by students or renewable energy engineers. This is a good basis for a public discussion about the benefits of electric vehicles because publications available to non-engineers are often based on the feelings of the authors rather than on numerical data. The target audience for our article should therefore be students, engineers or readers interested in motoring who want to see how to estimate the energy consumption for the production of objects (in this case, a combustion car and an electric car) and how to calculate the CO2 emissions associated with it. We show in the article that it is not necessary to have dedicated computing programs or large

[1] Politechnika Śląska, Faculty of Electrical Engineering, e-mail: julijan438@student.polsl.pl.
[2] Silesian University of Technology, Faculty of Electrical Engineering, Department of Electrical Engineering and Computer Science, e-mail: rafal.setlak@polsl.pl.

computer processing power for this purpose. This simplified approach is quick and gives a good idea of energy levels and CO2 emissions. More complex models taking into account, for example, the exact place of production of each component from which the car is later built is possible, but was not considered here. Nor was the level of recycling of the material from which a given part is built considered separately for each part. Instead, it was considered on a general level, as an average share of recycling of a given material in the whole group in the automotive industry.

7.2. The lca method used

We have carried out life cycle analysis for many pairs of vehicles, but in this chapter we present only two types of one car model. One is a car with a combustion engine and the other is an electric vehicle. We chose Peugeot vehicles, model 208 because these vehicles are very popular in the EU, they occupy the top sales positions in the year 2021 in the EU market and most importantly they are twin vehicles. The aim of the calculations within the framework of the article is to compare how much energy is used to produce the component materials from which both vehicles are built, how much energy is used in the automotive industry to produce a combustion vehicle and its electric counterpart (also its batteries), how much energy is not used due to recycling, and later how much energy the analysed two types of cars consume during operation over a similar distance. At each stage, we additionally calculated the accompanying CO2 emissions.

Figure 7.1 shows the main stages of our analysis. For the analysis results to be reliably compared, it is necessary to select vehicles with similar performance. This means that the combustion engine (from the manufacturer's offer) must be powerful enough to achieve similar acceleration as the EV. In the case of the Peugeot 208, the acceleration time to 100km/h for the internal combustion vehicle with a 1.2 PureTech 96 kW engine and EAT8 gearbox is 8.7 seconds, while for the 100 kW electric version this time is 8.1 seconds. The combustion vehicle should also have an automatic transmission configured (for the 208 model this is the AISIN EAT8 transmission).

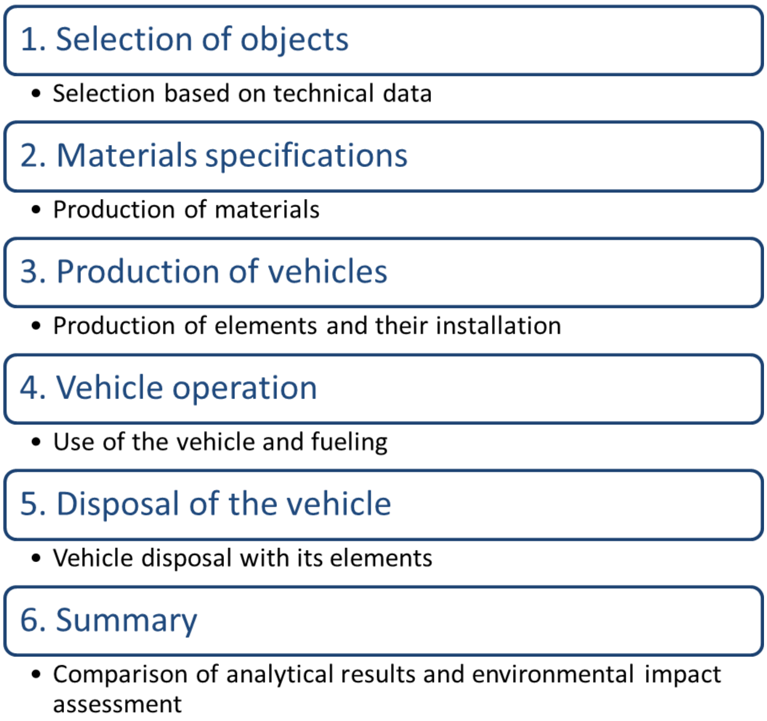

Fig. 7.1. Block diagram of the LCA analysis performed
Rys. 7.1. Schemat blokowy przeprowadzonej analizy LCA

The first step of the analysis is to determine which major groups of materials both cars are composed of. In our case, we assumed that we take into account the most important materials that both cars are composed of:

- Metals (steel, cast iron),
- Non-ferrous metals (copper, aluminium),
- Plastic group
- Rubber
- Glass
- Oil

Then, using literature data, we assumed the expected percentages of each material group in the mass of each car[3]. At this stage, a rather common mistake may be made if it is forgotten that an electric car should be analysed as two objects: separately the battery (the mass of the battery) and the rest of the vehicle (the mass of the rest of the vehicle after deducting the mass of the battery from its own mass)[4].

---

[3] https://autokult.pl/4985,materialy-konstrukcyjne-w-nowoczesnych-pojazdach-samochodowych-cz-1; https://autokult.pl/4757,materialy-konstrukcyjne-w-nowoczesnych-pojazdach-samochodowych-cz-2.

[4] https://www.joanneum.at/life/aktuelles/news/news-detail/expert-notification-on-estimating-ghg-emissions-and-primary-energy-of-vehicles-tested-in-green-ncap-lca-methodology-and-data.

For our two analysed vehicles, we assumed that the contribution of the main material groups to their total mass (for the electric vehicle, the total mass is minus the mass of the entire battery bank) is as shown in Figure 7.2.

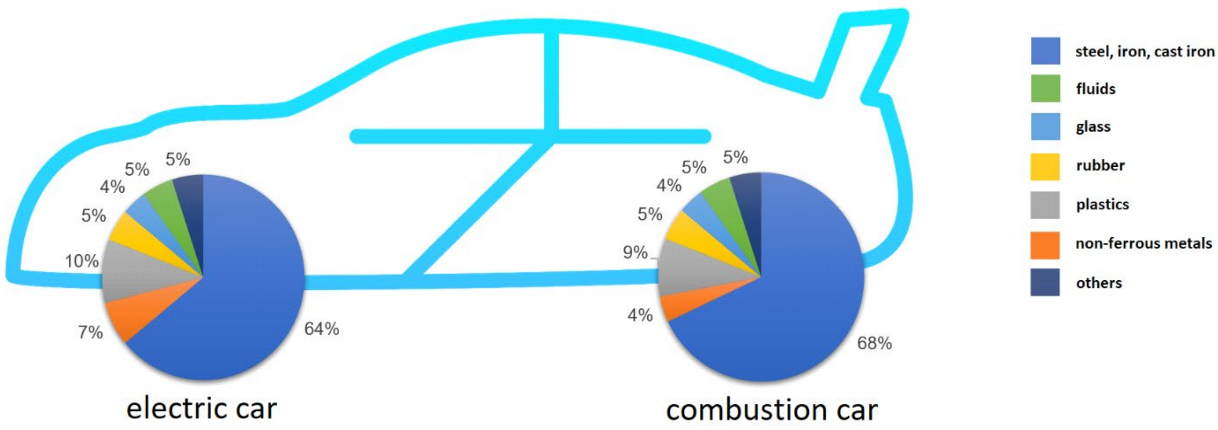

Fig. 7.2. Percentage of the main material groups in the total mass of the analysed vehicles
Rys. 7.2. Procentowy udział głównych grup materiałów w masie całkowitej analizowanych pojazdów

Then, based on data from the literature, we considered the amount of energy that is consumed in industry to produce materials from a given material group.

For example:

- arc furnaces to melt 1000 kg of steel consume on average 405–475 kWh[5],
- the production process of 1 kg of aluminium consumes from 53 kWh to 64 kWh of energy[6],
- the production process of 1 kg of copper consumes from 3889 kWh to 5556 kWh[7],
- the production process of 1 kg of elements from the plastic group consumes about 20–25 kWh/kg[8].
- the production process of one car tyre consumes between 259 kWh and 316 kWh[9].
- the production process for 1 kg of glass consumes 5–7 kWh[10].

For some material groups the exact calculation of their mass in a specific car is difficult (e.g. the proportion of steel by grade) but some materials are easy to estimate.

[5] Zdonek B, Szypuła I.: Instytut Metalurgii Żelaza im. St. Staszica „Zmniejszanie emisji co2 w procesie elektrostalowniczym poprzez stosowanie alternatywnych materiałów nawęglających we wsadzie" – prace inż. 1, 2010.
[6] https://energyeducation.ca/encyclopedia/Aluminum.
[7] Leksykon naukowo-techniczny z suplementem. Warszawa: WNT, 1989. ISBN 83-204-0967-5.
[8] https://learn.openenergymonitor.org/sustainable-energy/energy/industry-plastic?fbclid=IwAR2-AAuYRML-hMnUw644U7-6_aYuji_DzQ5RYVEP327JFF3NrS-9fDLcMAA.
[9] Piotrowska K, Kruszelnicka W, Bałdowska-Witos P, Kasner R, Rudnicki J, Tomporowski A, Flizikowski J, Opielak M.: "Assessment of the Environmental Impact of a Car Tire throughout Its Lifecycle Using the LCA Method" 2019 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6947500/.
[10] https://www.sciencedirect.com/science/article/abs/pii/0166309781900614.

For glass, for example, the total mass of glazing is the same in both types of vehicle. The components of this mass are shown in Table 7.1 (the mass of mirrors and the glass roof window are not included).

Table 7.1

Mass of glass in Peugeot 208

No.	Type of car windows	Number of car windows	Mass of a single car window
	-	-	kg
1.	Front	1	11,0
2.	Rear	1	4,3
3.	Front door	2	3,5
4.	Front bodywork	2	0,6
5.	Rear door large glass	2	2,6
6.	Rear door small window	2	1,3

Table 7.2

Results of the calculation of the energy consumption of the vehicle material groups – Peugeot 208 electric car

Peugeot e-208 Mass: 1105 kg (without battery)				
No.	Name of the material groups in the construction of the vehicle	Percentage share	Mass	Energy required to produce the material
	-	%	kg	kWh
1.	Steel, cast iron	68,0	787	21 249
2.	Non-ferrous metals	4,7	55	4 254
3.	Plastics	9,1	105	848
4.	Rubber	5,2	60	1 471
5.	Glass	3,2	37	308
6.	Liquids	5,1	60	b.d
7.	Other	4,7	54	b.d

Source: Zdonek B, Szypuła I.: Instytut Metalurgii Żelaza im. St. Staszica „Zmniejszanie emisji co2 w procesie elektrostalowniczym poprzez stosowanie alternatywnych materiałów nawęglających we wsadzie" – prace inż. 1, 2010; https://energyeducation.ca/encyclopedia/Aluminum; Leksykon naukowo-techniczny z suplementem. Warszawa: WNT, 1989. ISBN 83-204-0967-5. https://learn.openenergymonitor.org/sustainable-energy/energy/industry-plastic?fbclid=IwAR2-AAuYRML-hMnUw644U7-6_aYuji_DzQ5RYVEP327JFF3NrS-9fDLcMAA; Piotrowska K., Kruszelnicka W., Bałdowska-Witos P., Kasner R., Rudnicki J., Tomporowski A., Flizikowski J., Opielak M.: "Assessment of the Environmental Impact of a Car Tire throughout Its Lifecycle Using the LCA Method" 2019 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6947500/; https://www.sciencedirect.com/science/article/abs/pii/0166309781900614.

Table 7.3

Results of the calculation of the energy consumption of the vehicle material groups Peugeot 208 internal combustion car

Peugeot 208 Mass: 1158 kg				
No.	Name of the material groups in the construction of the vehicle	Percentage share	Mass	Energy required to produce the material
	-	%	kg	kWh
1.	Steel, cast iron	64,6	714	19 272
2.	Non-ferrous metals	6,7	74	5 763
3.	Plastics	9,5	105	848
4.	Rubber	5,5	60	1 471
5.	Glass	3,4	37	308
6.	Liquids	5,1	56	b.d
7.	Other	5,3	58	b.d

Different energy intensity values for the production of batteries for electric cars are available in the literature data. The cells of the Peugeot 208 electric vehicle are manufactured in the PRC by CAyTL.

The results of the LCA analyses of EV battery banks vary in the range of assumptions made, methodology and input data. The Li-Ion cells themselves (different cathode materials) adopted in the analyses are also different. The production of cathode materials and aluminium is the dominant contributor to CO2 emissions so producing Li-Ion batteries for an electric vehicle can result in emissions in the range of 56–494 kg of CO2 per 1 kWh of energy.

Table 7.4 shows publications in the literature (not older than 5 years) that describe the results of LCA analyses of CO2 emissions from battery production for electric vehicles.

Table 7.4

Results of LCA analyses of CO2 emissions related to the production of batteries for EVs

No.	Publication	Emissions from the production of battery
	-	kg CO2 e/ kWh
1.	Maarten Messagie, Vrije Universiteit Brussel, Transport & Environment	56
2.	Han Hao, Zhexuan Mu, Shuhua Jiang, Zongwei Liu, & Fuquan Zhao, Tsinghua University	96–127

continue table 7.4

3.	Mia Romare & Lisbeth Dahllöf, IVL Swedish Environmental Research Institute	150–200
4.	Wolfram P & Wiedmann T, Applied Energy	106
5.	Hanjiro Ambrose & Alissa Kendall, Transport and Environment	148–254 (without recycling) 194–494 (with recycling)
6.	Jennifer Dunn, Linda Gaines, Jarod Kelly, & Kevin Gallagher, Argonne National Laboratory	30–50
7.	Linda Ager-Wick Ellingsen, Bhawna Singh, & Anders Strømman, Environmental Research Letters	157 (Europe – use phase)
8.	Hyung Chul Kim, Timothy Wallington, Renata Arsenault, Chulheung Bae, Suckwon Ahn, & Jaeran Lee, Environmental Science & Technology	140
9.	Jens Peters, Manuel Baumann, Benedikt Zimmermann, Jessica Braun, & Marcel Weil, Renewable and Sustainable Energy Reviews	110
10.	Rachael Nealer, David Reichmuth, & Don Anair, Union of Concerned Scientists	73

Source: Kiełtyka A., Przemysł pojazdów EV w Polsce, praca inżynierska, Wydział Elektryczny Politechnika Śląska, Gliwice 2022; https://www.transportenvironment.org/publications/electric-vehicle-life-cycle-analysis-and-raw-material-availability; http://www.mdpi.com/2071-1050/9/4/504; http://www.sciencedirect.com/science/article/pii/S0306261917312539; Wolfram P, Wiedmann T.: Electrifying Australian transport: Hybrid life cycle analysis of a transition to electric light-duty vehicles and renewable electricity, Applied Energy, 2017, http://www.ivl.se/download/18.5922281715bdaebede9559/1496046218976/C243+The+life+cycle+energy+consumption+and+CO2+emissions+from+lithium+ion+batteries+.pdf; Ambrose H, Kendall A.: Effects of battery chemistry and performance on the life cycle greenhouse gas intensity of electric mobility, Transportation Research Part D: Transport and Environment, 2016, http://www.sciencedirect.com/science/article/pii/ S1361920915300390; http://www.anl.gov/energy-systems/publication/life-cycle-analysis-summary-automotivelithium-ion-battery-production-and; http://iopscience.iop.org/article/10.1088/1748-9326/11/5/054010; http://pubs.acs.org/doi/abs/10.1021/acs.est.6b00830; http://www.ucsusa.org/clean-vehicles/electric-vehicles/life-cycle-ev-emissions#.WWamKdNuJTY

The analytical results shown in Table 7.4 fall within a very wide range of values from 56 to 494 kg CO2 e/ kWh. It is therefore important to state the assumptions and boundary conditions used in the publications indicated in Table 7.4:

- It was assumed that a vehicle with a mass of 1200 kg and a 30 kWh battery travels 200,000 km in Europe. The actual electricity consumption of the vehicle analysed is 0,2 kWh/km. The result of the analyses: even in the EU countries with the highest CO2 emissions, EVs emit more than 25% less greenhouse gases into the atmosphere than diesel vehicles. The comparison of life cycle CO2 emissions of EVs after taking into account the energy mix in the energy system of the respective country (year 2017) is: Germany 119 g CO2/kWh, Italy 99 g CO2/kWh, Belgium 77 g CO2/kWh, Sweden 41 g CO2/kWh.

- The energy mix of China has been taken into account and cars with 20-30kWh batteries are operated in the USA. CO2 emissions associated with the production of components for the car have been taken into account. Batteries made in the US produce 65% less CO2 emissions than in the PRC.
- Results are shown for the ten most popular EVs in 2016 (including Tesla S 86 kWh, Nissan Leaf 23.8 kWh). It was assumed that EV car assembly consumes 350–650 kWh and battery production in the PRC. CO2 emissions were determined using a bottom-up analysis. The emissions of the elements used in the battery were calculated. Conclusions: energy for battery production accounts for at least 50% of the car's life cycle emissions.
- For an EV with a 42 kWh battery, it was assumed that it travels 150,000 km in its cycle and that the energy consumption during driving is 15 kWh/100km. The determined CO2 emissions were 351 g CO2/kWh. According to the authors, the production of a lithium-ion battery in the PRC can contribute to the emission of 317 g CO2/kWh battery.
- The research was conducted for EVs: Kia Soul 27 kWh, Fiat 500e 24 kWh, Honda FIT 20 kWh. The vehicle batteries analysed were manufactured taking into account the energy mix in the PRC.
- It uses a bottom-up analysis using the energy mix in the US for battery production.
- The authors modelled four vehicle sizes: small (17.7 kWh), medium (24.4 kWh), large (42.1 kWh) and luxury (59.9 kWh). The segments differed by the weight of the car and the maximum battery capacity that could be fitted to the car. The reports covered cars with 180,000 km mileage, would be used in Europe, where an average energy mix of 521 g CO2/kWh was assumed for the use phase.
- The study was based on data from a Ford Focus EV. The assessment was based on a compilation of materials and primary data from the battery industry. Conclusion: electric car production produces 39% more greenhouse gases than a comparable petrol or diesel car.
- The article provides an overview of LCA studies on lithium-ion batteries with a focus on the battery production process. Available studies in 2016 are summarised, followed by a comparison with actual data from industry and research institutions. Based on the results of the analysed studies, average values of the environmental impact of battery production are calculated.
- The report presents comprehensive results comparing global warming emissions from electric cars with their gasoline and diesel counterparts in the US.

Finally, for the purposes of our calculations, after a review of the literature data, we assumed an energy consumption for the production of Li-Ion cells for the Peugeot EV 208 vehicle of 47 kWh/kg, which for the entire vehicle battery gives a value of 16.5 MWh.

In the next calculation step, it was necessary to determine the CO2 emissions from the production of materials from a given material group. For this purpose, we assumed the simplification that all components of the car came from three locations: France and Slovakia and the Li-Ion cells that make up the battery of the electric vehicle were produced in the PRC. When calculating CO2 emissions, we used the annualised emissions of energy carriers in the energy mixes of the countries where the materials are produced. In this way, we determined the emissivity of the materials (CO2/kg) used to build the cars. In Table 7.5, we have shown the results of calculating CO2 emissions from the production of the main material groups. The simplifying assumption made is: production of materials and assembly of vehicles takes place in the EU (Slovakia and France) and the CATL battery is produced in PRC.

Table 7.5

Results of the calculation of CO2 emissions from the production of the main material groups of the electric and combustion vehicle

No.	Name of the material groups in the construction of the vehicle	CO2 emission – electric Peugeot e-208	CO2 emission – combustion Peugeot 208
	-	kg	kg
1.	Steel, cast iron	1041	1147
2.	Non-ferrous metals	331	230
3.	Plastics	46	46
4.	Rubber	79	79
5.	Glass	17	17
6.	Liquids	b.d	b.d
7.	Other	b.d	b.d

Source: Peters J., Baumann M., Zimmermann B., Braun J., Weil M.: The environmental impact of Li-Ion batteries and the role of key parameters – A review, Renewable and Sustainable Energy Reviews, 2017 http://www.sciencedirect.com/science/article/ pii/S1364032116304713

The final step in the LCA analysis related to the production phase is the consideration of energy consumption and CO2 emissions during the final assembly of the vehicles. Based on the literature, the final assembly process of a car on a production line consumes about 1.5 MWh of energy[11]. We assumed that 50% of this energy value comes from renewable energy sources. The assembly process includes the shaping of steel and aluminium components, welding and sealing of metal parts of the car, bolting of

[11] https://alebank.pl/fabryki-aut-coraz-bardziej-zielone/?id=16653&catid=361.

components, painting, assembly of components, quality testing. There are several activities in the assembly process that are different for both types of vehicles. In spite of the obvious differences in the construction of the propulsion systems, the assembly of the powertrain of both vehicles is very similar. The internal combustion engine or electric motor is connected to the body in the so-called "wedding" process, which consists in lifting the pre-assembled unit: the engine and its accessories, transmission, half-shaft by the wheels together with the suspension and steering systems to the top, where the unit is bolted to the body. The energy consumption for this process can be assumed to be the same. In electric cars, a battery is additionally mounted, but this is done in a similar way to "wedding" and the energy for this process is the same as the assembly of additional assemblies (e.g. exhaust system or radiators) in the case of a combustion engine. It was therefore assumed that the process of assembling the aforementioned non-standard components in an electric car consumes the same amount of electric energy as in a combustion car. The summary results of energy consumption and related CO2 emissions are shown in Fig. 3.

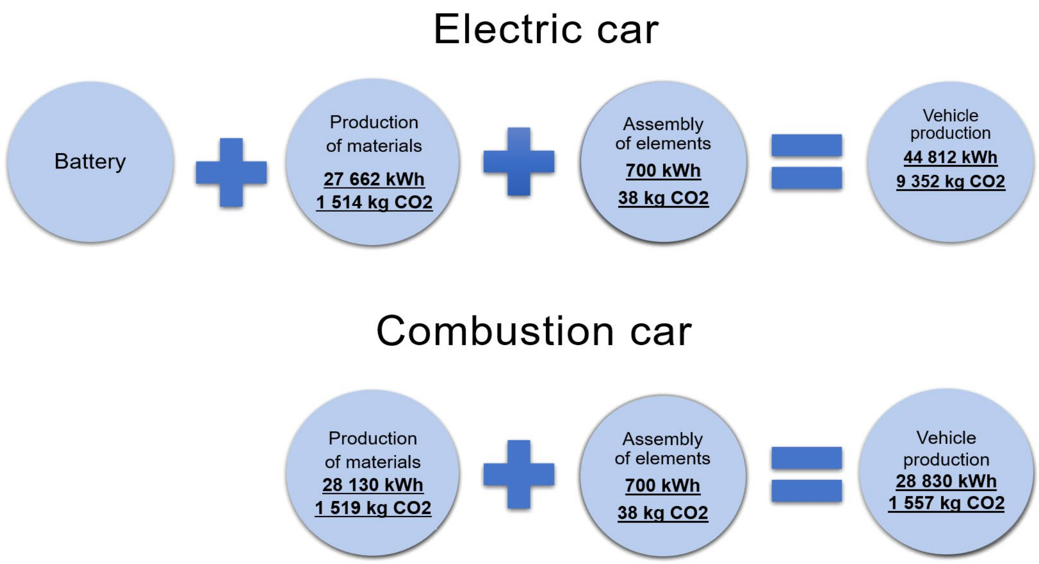

Fig. 7.3. Energy consumption and CO2 emissions - material production and car assembly phase
Rys. 7.3. Zużycie energii i emisja CO2 - produkcja materiałów i faza montażu samochodu

Another area of calculation was the operation of both vehicles. In the analysis, we made the obvious assumption that both vehicles are driven in the same driving cycles. For the calculation of CO2 emissions, the source and method of obtaining energy to power the vehicles is crucial here. The calculations took into account:

- the actual energy consumption of both vehicles,
- the efficiency of the energy system and batteries,
- the efficiency of the oil extraction process and of its transport to the filling station.

It has been calculated that for an electric car, when the above factors are taken into account, for every 10kWh of energy consumption, the CO2 emission is 8.8 kg, while for an internal combustion car, every 10kWh of energy consumption is associated with the emission of 12.2 kg of CO2. The energy consumption and CO2 emissions during operation for up to 200,000 km are shown in Figures 4 and 5. Disposal for both vehicles will consume a similar amount of energy and the difference will occur when disposing of the batteries, which has been taken into account in the calculations.

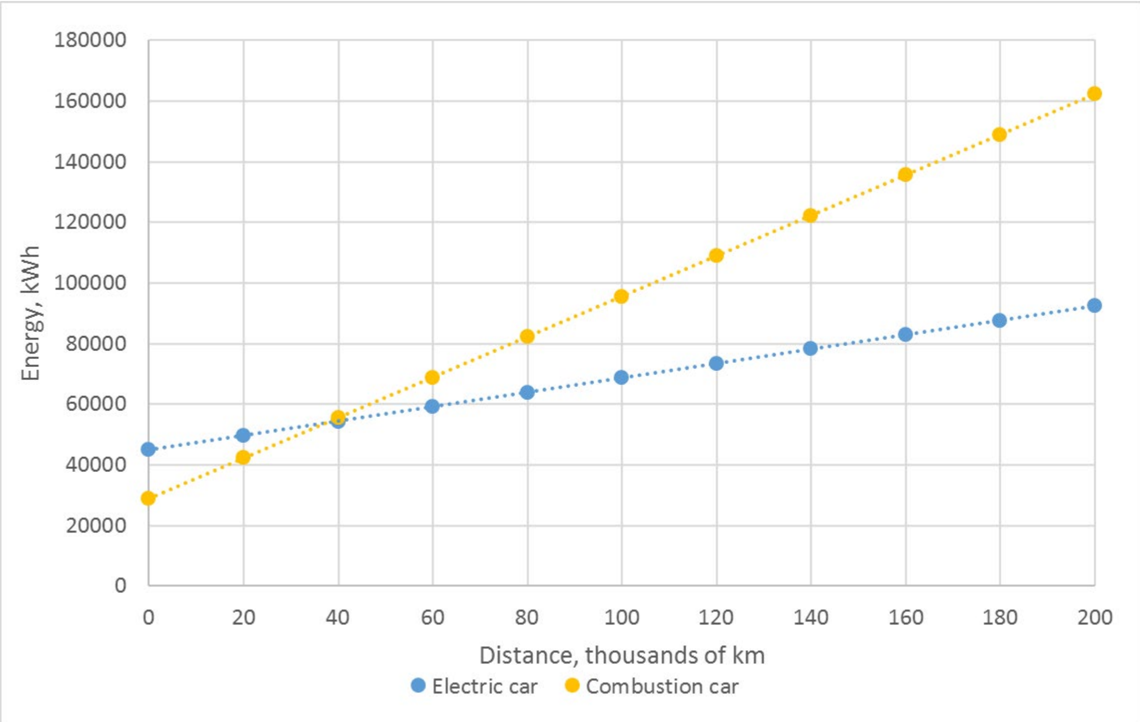

Fig. 7.4. Energy consumption – car use in Poland
Rys. 7.4. Zużycie energii – użytkowanie samochodów w Polsce

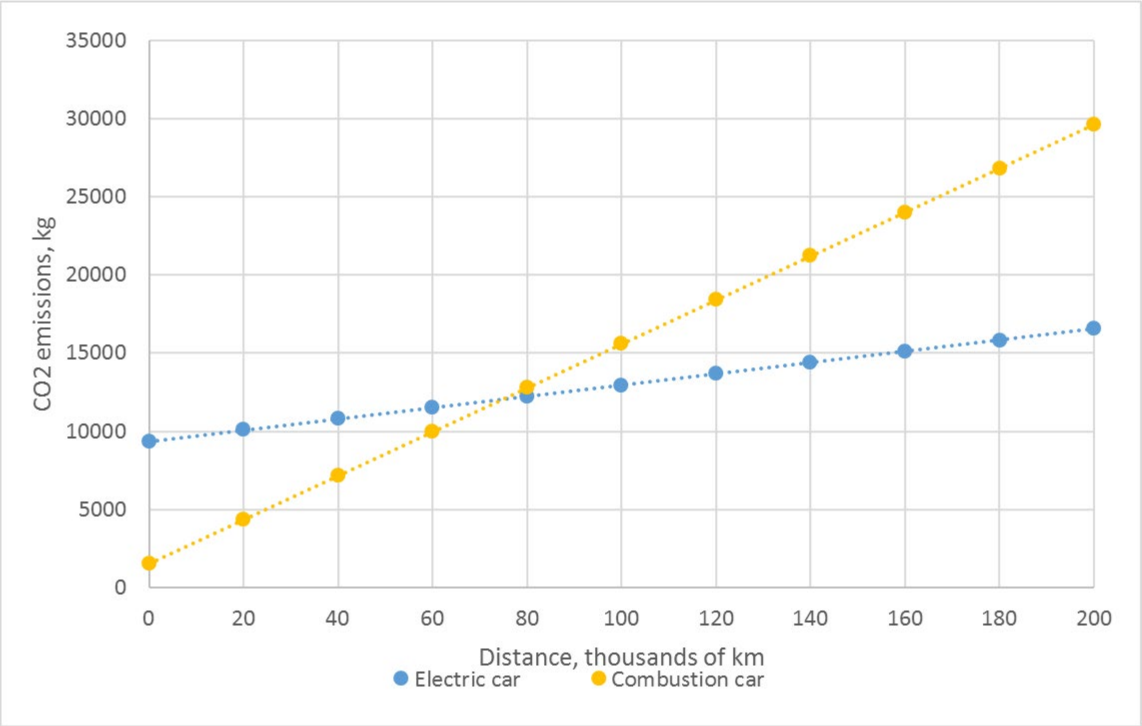

Fig. 7.5. CO_2 emissions – car use in Poland
Rys. 7.5. Emisja CO_2 – użytkowanie samochodów w Polsce

7.3. Key conclusions

Our analysis showed that:

- the energy input to produce an electric car about 1.6 higher than its combustion counterpart,
- battery production accounts for a significant proportion of the energy consumption during vehicle manufacture, so it is beneficial to transfer the production of cells in PRCs to countries with emission factors of the energy mix below 200 g/kWh,
- our analysis did not include processes of capacity recovery in batteries (e.g. after reaching SOH=80%), which will significantly reduce energy consumption Such services will probably appear for Li-Ion cells in a few years (analogically to commonly used such methods for lead-acid cells),
- the current crisis in the EU car market will probably accelerate the trend to establish factories for refurbishing used cars and selling them back to the market. This will reduce the negative impact of motoring on the environment,

- in the case of the energy mix in Poland, the advantage of the EV in terms of CO2 emissions will occur after 120 000 km. In other EU countries it will happen much sooner (e.g. in Germany after 80,000 km, in France after 60,000 km),
- the calculations did not take into account that the vehicles are assembled in factories with zero grid energy consumption (e.g. balancing by PV)-this will significantly improve the carbon balance of production.