

Article

Sustainability Investigation of Vehicles' CO₂ Emission in Hungary

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Abstract: The regulation of vehicular CO₂ emissions determines the permissible emissions of vehicles in units of g CO₂/km. However, these values only partially provide adequate information because they characterize only the vehicle but not the emission of the associated energy supply technology system. The energy needed for the motion of vehicles is generated in several ways by the energy industry, depending on how the vehicles are driven. These methods of energy generation consist of different series of energy source conversions, where the last technological step is the vehicle itself, and the result is the motion. In addition, sustainability characterization of vehicles cannot be determined by the vehicle's CO₂ emissions alone because it is a more complex notion. The new approach investigates the entire energy technology system associated with the generation of motion, which of course includes the vehicle. The total CO₂ emissions and the resulting energy efficiency have been determined. For this, it was necessary to systematize (collect) the energy supply technology lines of the vehicles. The emission results are not given in g CO₂/km but in g CO₂/J, which is defined in the paper. This new method is complementary to the European Union regulative one, but it allows more complex evaluations of sustainability. The calculations were performed based on Hungarian data. Finally, using the resulting energy efficiency values, the emission results were evaluated by constructing a sustainability matrix similar to the risk matrix. If only the vehicle is investigated, low CO₂ emissions can be achieved with vehicles using internal combustion engines. However, taking into consideration present technologies, in terms of sustainability, the spread of electric-only vehicles using renewable energies can result in improvement in the future. This proposal was supported by the combined analysis of the energy-specific CO₂ emissions and the energy efficiency of vehicles with different power-driven systems.

Keywords: CO₂ emission; energy efficiency; electric vehicle; internal combustion engine



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1. Introduction

Due to the visible effects of global warming, there is increasing concern over the steady elevation of the levels of greenhouse gases in the atmosphere. In 2015, the monthly global average concentration of carbon dioxide (CO₂) passed a long-awaited milestone (400 ppm.) [1], which was a symbolic threshold that marked a clear red line into a danger zone of climate change.

To avoid intangible threats, in the medium-to-long term, a massive reduction in GHG emissions is of utmost importance. With the Paris Agreement [2], the EU has pledged to achieve GHG emission reductions of at least 40% by 2030 compared to 1990. For this purpose, the EU has made a new energy rulebook called the "Clean energy for all Europeans package" [3], which serves as the EU's long-term strategy for reaching carbon neutrality by 2050. Each member state must take into account the new goals; therefore, Hungary was

also obliged to make an integrated National Energy and Climate Plan (NECP) that was completed in January 2020 [4].

Several studies have addressed the energy consumption, environmental impact and emission of greenhouse gases (GHGs) of vehicles. These studies can be classified according to the fact that the analysis of the environmental impact and GHG emissions is based on the examination of the given type of fuel [5–9] or the comparison of vehicles using different fuels, such as conventional or renewable energy-based fuel [10–14]. Moreover, research on similar topics often takes into account other aspects, such as driving style [6], consumer preferences related to alternative fuels [15] charging behavior [16], the type of transportation [17–19] and the sustainability of transport systems [20,21].

Carbon dioxide is the primary greenhouse gas, and a significant part of its emissions is vehicle related. The full evaluation and comparison of the CO₂ emissions for different kinds of vehicles can be achieved by LCA (Figure 1), which is a powerful tool to estimate the entire environmental impact of a product, process or service [22,23].

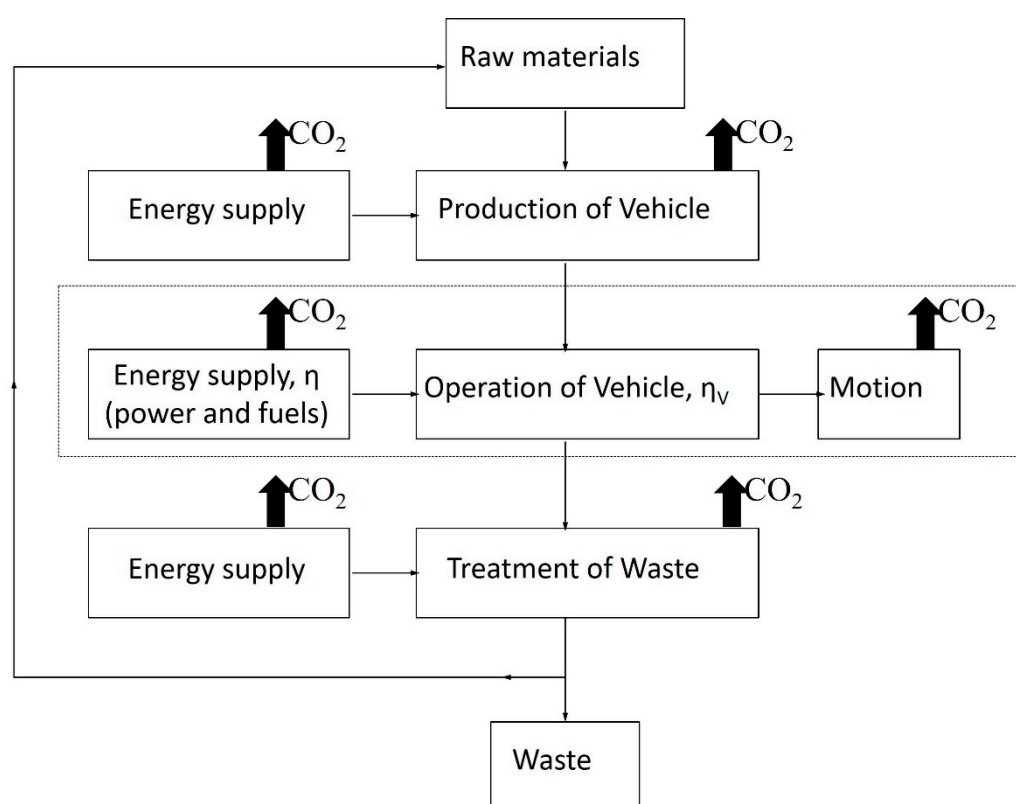


Figure 1. Life-cycle system of vehicles' CO₂ emissions (authors' creation).

However, in this article, the authors only intend to focus on a sub-area of the vehicle life cycle. The investigated scope of LCA is presented by the dashed line in Figure 1. The final energy used for the movement of a vehicle generated by the vehicle derives from a series of energy conversions. The technological process of energy conversion also produces CO₂ and is directly related to the CO₂ emissions of vehicles. Our approach includes the whole energy production line, wherein the last “energy transformer” is the vehicle. This method is a well-to-wheel (WTW) analysis and plays an important role in the transportation sector. WTW allows for summarizing the energy and GHG emissions derived from the production, transport and distribution of fuels and to calculate the efficiency of different powertrains [24]. WTW methods are widely used for the evaluation of specific situations and vehicle types [25–27]. In this paper, the specific CO₂ emissions of the steps of energy production will be discussed in terms of grams of CO₂ and not CO₂ equivalents.

The paper is also related to the new European method known as WLTP, which entered into force in September 2017 [28], and to the current regulation of vehicles' CO₂ emissions [29,30]. These regulations ultimately determine the permissible emissions of vehicles in units of g CO₂/km. However, these values do not take into account the energy industry that directly serves vehicles. Moreover, in the current regulations, neither the efficiency of the vehicles nor of the energy industry, which produces the energy needed to operate vehicles, nor the CO₂ emissions of the energy industry caused by the operation of vehicles, are included. Therefore, our research focuses on filling the gap of missing complex evaluations in terms of the total energy conversion effect on the overall CO₂ emissions of different vehicle types. This work evaluates and compares various vehicles based on the introduced method.

2. Methods

The energy used for motion (E_m) is mostly kinetic energy (E_{kin}), but it also includes potential energy (E_{pot}) due to the height differences during vehicle movement. The energy required for movement (E_m) is produced in multistep processes, which are called energy conversions (Figure 2). The final step in energy conversions is the energy conversion of the car itself when it converts the electrical energy or fuels used to its motion energy.

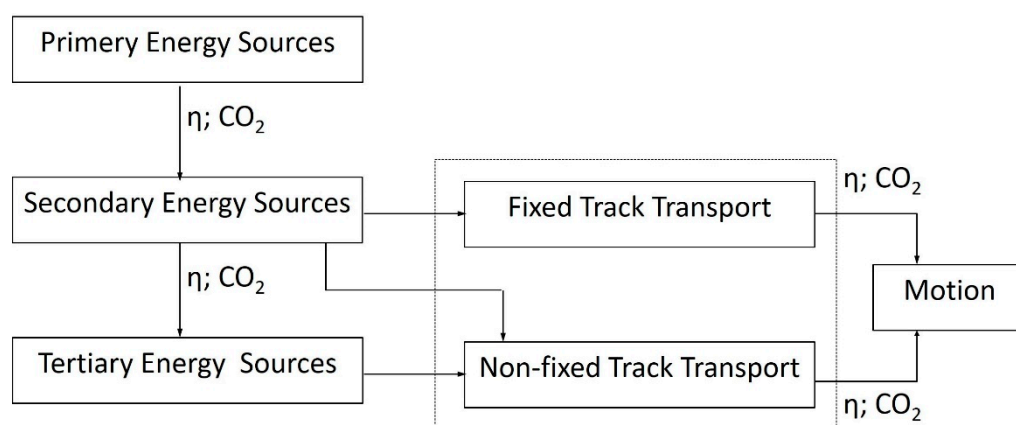


Figure 2. Total energy conversion system of vehicles (authors' creation).

The first objective was to determine the resulting efficiency (η) of all energy conversions for vehicles with different types of propulsion systems. The second objective was to calculate the energy-specific CO₂ emissions (ϵ) of vehicles with distinct types of engine, which includes the total CO₂ emitted during energy conversions. Finally, the third objective was to evaluate the results obtained.

Energy Conversions and Their Efficiencies

The energy industry produces secondary energy from primary energy sources, which are usually divided into three major groups. These are fossil energy sources (different raw carbon and hydrocarbon materials), non-fossil minerals (natural uranium), and renewable energy sources. Figure 3 shows the ways in which secondary energy sources are prepared from fossil fuels and how they damage the environment.

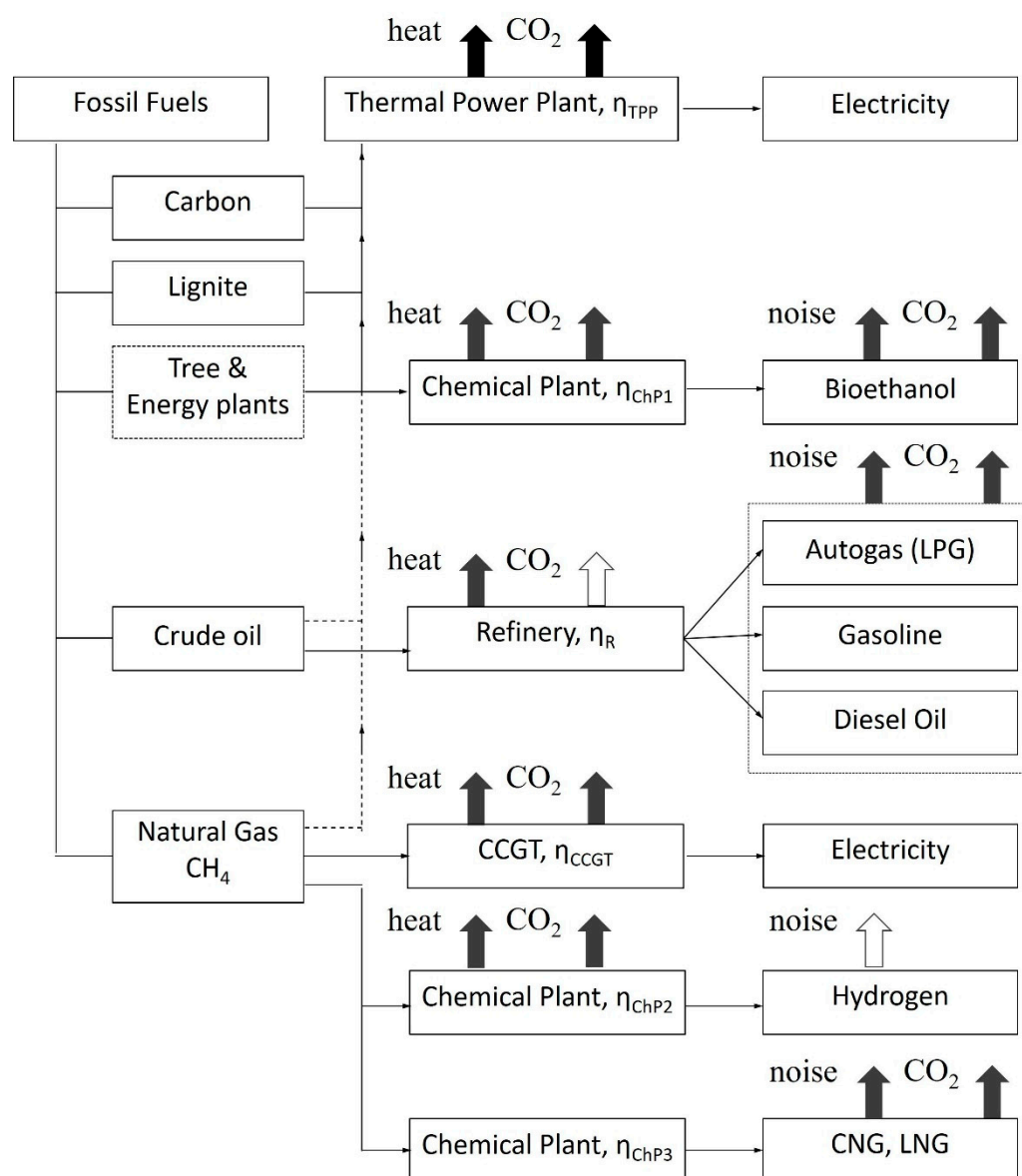


Figure 3. Primary-secondary energy conversions of fossil energy sources including their environmental damage (authors' creation).

In Figure 3, energy trees and energy plants as primary energy sources are indicated as dashed lines because according to current practice, the secondary energies (bioethanol and “bioelectricity”) produced from these sources are considered clean energies. Of course, this practice can and should be argued because this type of energy production reduces the Earth's CO₂ processing and food production capacity and, at the same time, can damage the fertility of the area. However, such issues are not the subject of this paper.

The production of secondary energy from a non-fossil energy source is electricity generation by nuclear power plants. Electricity produced by nuclear power plants can be considered clean energy in terms of CO₂ emissions.

The ways of generating electricity from the main types of renewable energy sources are secondary energy productions from primary energy sources. The electricity from this energy conversion can also be regarded as clean energy in terms of CO₂ emissions—despite the uranium enrichment process also contributing to CO₂ emissions, which can now be ignored because this contribution is negligible compared to the final energy produced.

The ways of generating electricity from the main types of renewable energy source (solar, wind, water) are secondary energy production from primary energy sources. The

electricity from this energy conversion can also be regarded as clean energy in terms of CO₂ emissions.

Figure 4 shows how vehicles can use secondary and tertiary energies. The following significant conclusions can be drawn from Figure 4.

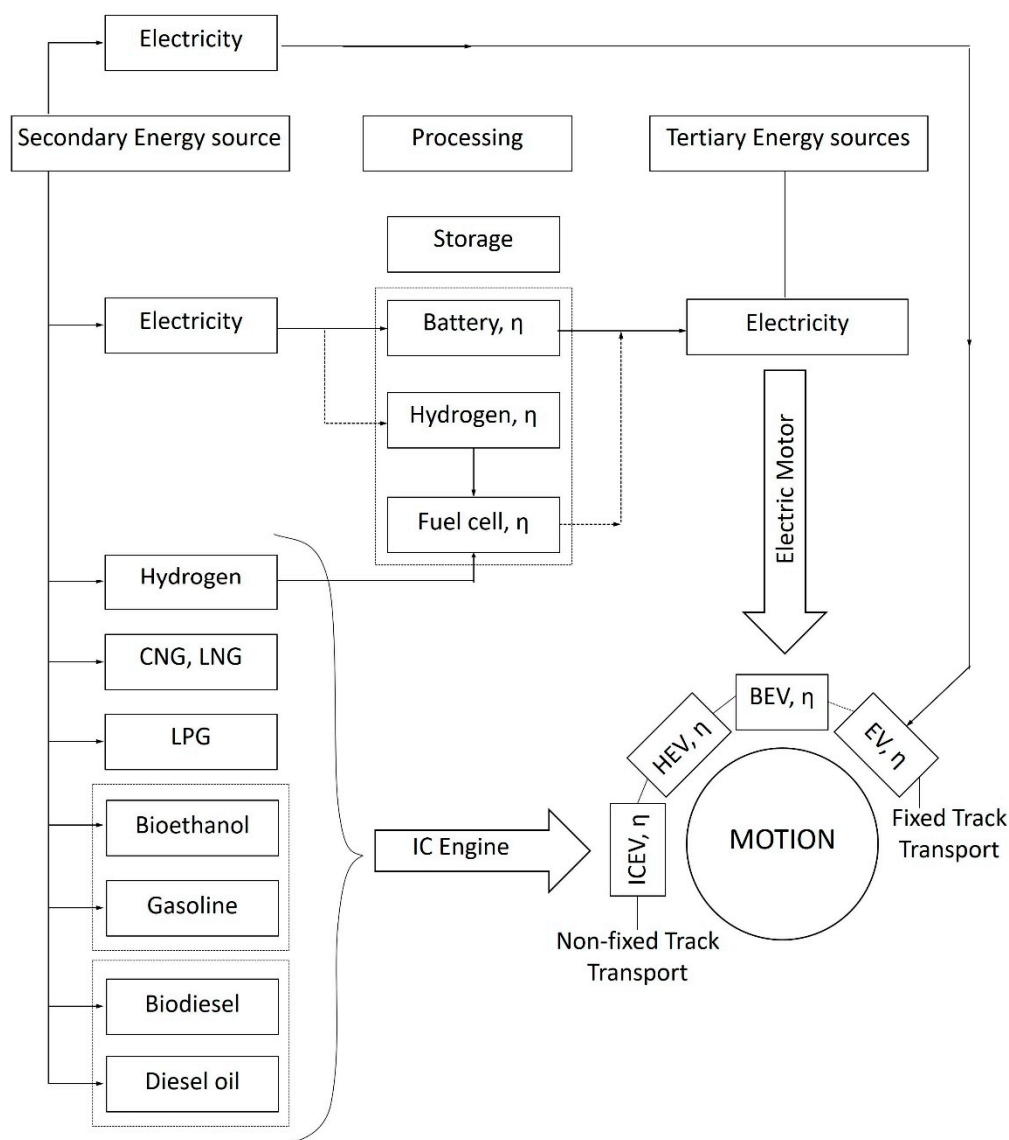


Figure 4. Different vehicles and their energy needs (authors' creation).

- It is evident that the direct use of electricity as a secondary energy source is only feasible with traffic on a fixed track (guided land transport). In such a case, complete CO₂-free transport can also be accomplished if the electricity generated comes from a CO₂-free source (renewable energy sources and nuclear power plants). Examples include rail, tram and trolleybus.
- Fuel cells and batteries are devices that convert secondary energy (electricity) to tertiary energy (electricity). During the process, energy storage also takes place. These devices allow electric vehicles to leave the fixed track. However, electrolysis is a very energy-intensive process; therefore, its widespread application is not expected in the near future. Thus, this article does not address fuel-cell electric vehicles.
- When hydrogen is produced from methane, it can no longer be considered clean energy in terms of carbon dioxide emissions.

- There are only two types of power-driven methods of vehicles. Vehicles use either internal combustion engines or electric motors. The hybrid electric vehicle (HEV) is merely an intermediate solution between the two basic types. These vehicles include both driving mechanisms. Similarly, the batteries in BEVs serve to store electric current, and afterwards, the vehicle can use this energy anywhere. Storage and energy conversion lead to energy loss as well.
- “Bioethanol” and “biodiesel” only decrease the CO₂ emissions of the ICEV but, for example, the currently prescribed 10% “bioethanol” rate in gasoline has no significant effect on emissions. As a consequence, although both the low bioethanol and biodiesel contents reduce CO₂ emissions, they do not entirely solve the emission problem of ICEV.

3. Results

3.1. The Efficiency of Energy Conversion

Energy conversions are always accompanied by energy losses. The extent of these losses can be expressed by efficiency (η), which is obtained by the following formula:

$$\eta = \frac{E_{\text{out}}}{E_{\text{in}}}, \eta = \frac{\text{energy output}}{\text{energy input}} [-] \quad (1)$$

For a series of connected energy conversions, the overall efficiency is the multiplication of the individual efficiencies:

$$\eta_{\text{total}} = \prod_i \eta_i, \eta_{\text{total}} = \eta_{\text{motion}} \quad (2)$$

where “ η_{total} ” or “ η_{motion} ” is the efficiency of the entire energy conversion, “ i ” is the number of energy conversions, and “ η_i ” is the i^{th} step of energy conversion. This equation is similar to that of PEF (primary energy factor) [31]. However, in this case, “ η_{total} ” or “ η_{motion} ” is extended with the energy efficiency of vehicles. This also includes the efficiency of the so-called “well-to-tank” and “tank-to-wheel” energy transformations.

There are currently five main energy supply pathways for vehicles:

1. Different primary energy sources → production of electricity (electrical energy mix) → electric vehicle (EV) on a fixed track.

In this case, the total energy efficiency (and CO₂ emissions) depends on the energy mix. For example, the electrical energy mix in Hungary in 2019 consists of the following sources [32–34]:

- NPP (Nuclear power plant)

$$E_{\text{NPP,output}} = 16.3 \text{ TWh, rate : } 35.7\%, \eta_{\text{NPP}} \approx 33\% \quad E_{\text{NPP,input}} = 49.4 \text{ TWh}$$

- TPP (Thermal Power Plant)

$$E_{\text{TPP,output}} = 3.9 \text{ TWh, rate : } 8.5\%, \eta_{\text{TPP}} \approx 50\% \quad E_{\text{TPP,input}} = 7.8 \text{ TWh}$$

This efficiency (η_{TPP}) is valid together with heat generation. Without heat service, the efficiency of a conventional thermal power plant is approximately 32%.

- CCGT (Combined Cycle Gas Turbine)

$$E_{\text{CCGT,output}} = 8.8 \text{ TWh, rate : } 19.2\%, \eta_{\text{CCGT}} \approx 55\% \quad E_{\text{CCGT,input}} = 16.0 \text{ TWh}$$

If power plants are cogeneration power plants, the energy efficiencies are relatively high.

- Renewables and biofuels (R&B)

$$E_{\text{R\&B,output}} = 4.1 \text{ TWh, rate : } 9.0\%, \eta_{\text{R\&B}} \approx 100\% \quad E_{\text{R\&B,input}} = 9.0 \text{ TWh}$$

The calculation of renewable energy efficiency is an interesting problem. For renewable energy sources, it is pointless to calculate energy efficiency by using the energy balance because the sources never run out. Therefore, the energy efficiency of renewable energy is considered to be 100%.

Of course, in practice, one can also define efficiency for renewable energy sources, e.g., the higher efficiency a solar panel has, the smaller the physical size required to produce the same amount of energy under the same conditions (same amount of incoming sunlight, same duration, etc.).

Otherwise, the efficiency of wind energy is approximately 26%, the efficiency of PV systems is approximately 12%, and the efficiency of biofuel thermal power plants is approximately 32%. However, these efficiencies are not relevant in our case.

- EU import

$$E_{\text{import,output}} = 12.6 \text{ TWh, rate : 27.6\%, } \eta_{\text{import}} \approx 50\% \quad E_{\text{import,input}} = 25.2 \text{ TWh}$$

- Electrical energy mix

$$E_{\text{mix,output}} = 45.7 \text{ TWh, rate : 100\%, } \eta_{\text{mix}} \approx 43\% \text{ (calculated)} \quad E_{\text{mix,input}} = 107.4 \text{ TWh}$$

- The magnitude of losses during electric power transmission is cc. 10% in Hungary; therefore, $\eta_{\text{transmission}} \approx 90\%$

Electric motors are more efficient than internal combustion engines. The efficiency of induction motors is taken into account at 90% in the current calculations, but there are also those with better efficiency [35].

$$\eta_{\text{electrical motor}} = 0.90 \% \rightarrow \eta_{\text{motion,EV}} = \eta_{\text{electricity mix}} \times \eta_{\text{transmission}} \times \eta_{\text{electrical motor}} \quad (3)$$

$$\eta_{\text{motion,EV}} = 0.43 \times 0.90 \times 0.90 \approx 0.35$$

2. Different primary energy sources \rightarrow production of electricity (electrical energy mix) \rightarrow Vehicle with battery and electrical motor (BEV, non-fixed track).

The energy efficiency, in this case, is as follows:

$$\eta_{\text{motion,BEV}} = \eta_{\text{electricity mix}} \times \eta_{\text{transmission}} \times \eta_{\text{battery}} \times \eta_{\text{electrical motor}} \quad (4)$$

LIBs can achieve high energy efficiency [36–38], and the value of $\eta_{\text{battery}} = 90\%$ is taken for the calculation.

$$\eta_{\text{motion,BEV}} = 0.43 \times 0.90 \times 0.90 \times 0.90 \approx 0.31$$

3. Crude oil \rightarrow refinery \rightarrow diesel oil \rightarrow ICEV

$$\eta_{\text{motion,ICEV,D}} = \eta_{\text{refinery}} \times \eta_{\text{ICEV,D}} \quad (5)$$

Since the overall petroleum refining energy efficiency is 90–92% in practice, for simplicity 91% is used as an estimation [39].

The mean thermal efficiency of conventional diesel engines is 37%, and that of diesel engines with turbocharging is 40% [40,41]. The favorable mean efficiency of 40% is used in the calculations, but it is known that, in practice, this value is already outstanding.

$$\eta_{\text{motion,ICEV,D}} = 0.91 \times 0.40 \approx 0.36$$

The total energy efficiency of ICEV vehicles using diesel oil is 36%.

4. Crude oil \rightarrow refinery \rightarrow gasoline or autogas (LPG (Liquefied Petroleum Gas), propane 40%-butane 60%) \rightarrow ICEV

$$\eta_{\text{motion,ICEV,G}} = \eta_{\text{refinery}} \times \eta_{\text{ICEV,G}} \quad (6)$$

$$\eta_{\text{motion,ICEV,LPG}} = \eta_{\text{refinery}} \times \eta_{\text{ICEV,LPG}} \quad (7)$$

The maximum thermal efficiency of common gasoline engines is 20–35% [41]. The mean efficiency used in the calculations is approximately 30%. The same value is also applied to LPG internal combustion engines.

$$\eta_{\text{ICEV,G}} \text{ and } \eta_{\text{ICEV,LPG}} >> 30\%$$

thus,

$$\eta_{\text{motion,ICEV,G}} = 0.91 \times 0.30 = 0.27 \text{ and } \eta_{\text{motion,ICEV,LPG}} = 0.91 \times 0.30 = 0.27$$

are equal.

It is important to note that the amount of LPG will be reduced if the production of gasoline is reduced because it is virtually a byproduct of gasoline production.

5. LNG and CNG are not discussed in this paper because no significant increase in LNG usage for vehicles in the world is expected, as natural gas can be more difficult to liquefy than propane and butane gases.

Similarly, the use of CNG is not advantageous because it requires a larger tank. The results are summarized in Table 1. As shown above in detail, the energy efficiency of HEVs is between the values of a BEV and an ICEV. It is worth noting that the resulting efficiencies of energy conversions are similar at present and are within a narrow range (0.27–0.36).

Table 1. The estimated values of the efficiency of energy conversions in Hungary in 2019 *.

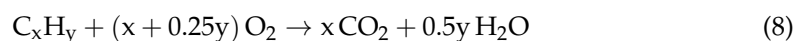
$\eta_{\text{motion,EV}}$	$\eta_{\text{motion,BEV}}$	$\eta_{\text{motion,HEV}}$	$\eta_{\text{motion,ICEV,G}}$	$\eta_{\text{motion,ICEV,LPG}}$	$\eta_{\text{motion,ICEV,D}}$
0.35	0.31	0.27–0.31	0.27	0.27	0.36

* Source: the calculation presented in this article.

If the ratio of renewable energy sources increases in electricity generation, $\eta_{\text{motion,EV}}$ and $\eta_{\text{motion,BEV}}$ efficiency will also improve, and they can exceed the values of others. Keeping the current technical solutions in mind, this is the only way to improve the production efficiency of the energy that is used directly for motion.

3.2. Energy-Specific CO₂ Emission Parameter

In the combustion of fossil fuels, the carbon content determines the amount of CO₂ produced. The general equation of the chemical reaction is as follows:



Let us introduce a new complex indicator called “energy-specific CO₂ emissions” denoted by ε and calculated by the following formula:

$$\varepsilon = \frac{m_{\text{CO}_2}}{E_{\text{motion}}}, \quad \varepsilon = \frac{\text{total mass of CO}_2 \text{ produced during the energy conversions}}{\text{final energy of motion of vehicle}} \left[\frac{\text{gCO}_2}{\text{MJ}_{\text{motion}}} \right] \quad (9)$$

Table 2 shows the calculated amount of CO₂ produced in each type of electric power generation, as well as the calculated values of the energy-specific CO₂ emission parameters for each car type.

Table 2. Calculated emissions of CO₂ from electricity generation and the energy-specific CO₂ emission parameter [42].

Primary Energy Sources	Heat Value [MJ/kg]	Carbon Content [w/w %]	kg CO ₂ Produced from 1 kg	Secondary Energy Produced [MJ/kg]	Secondary Energy-Specific CO ₂ Emission [g CO ₂ /MJ]
Lignite (raw, air-dried)	19.7	49.6	1.84	electricity, TPP 9.85	$\epsilon_{E,\text{lignite}} = 186$
Natural gas	34	71	2.60	electricity, CCGT 18.7	$\epsilon_{E,\text{CCGT}} = 139$
Tree and energy plants	14–20 \approx 17	45–47 \approx 46	1.69	electricity, TPP 8.5	$\epsilon_{E,t\&ep} = 0$ ($\epsilon_{E,t\&ep} = 199$)
Renewables					$\epsilon_{E,Rs} = 0$
NPP					$\epsilon_{E,NPP} = 0$

It is clear that electrical vehicles using exclusively renewable electricity and nuclear electricity would have zero CO₂ emissions. However, the electricity used comes from several sources (Table 3); therefore, an average CO₂ emission value has to be calculated ($\epsilon_{E,HU\text{mix}}$) by using the Hungarian electricity combination (Table 4). It is also known that the Hungarian energy combination has significant imports. Electricity imports are the mean value of the EU electricity combination. Therefore, the composition of imports is needed (Table 3) to calculate the average CO₂ parameter in Hungary (Table 4).

Table 3. The estimated emissions of CO₂ from electricity generation in the EU in 2018 [43,44].

		Contribution of the Sources to the Production in %	EU Import Electricity in PJ (=10 ⁹ MJ)	Secondary Energy-Specific CO ₂ Emission [g CO ₂ /MJ]	CO ₂ Emission in kt (=10 ⁹ g)
EU energy mix in 2018	NPP	$\approx 26\%$	11.79	$\epsilon_{E,NPP} = 0$	0
	Conventional TPP	$\approx 46\%$	20.87	$\epsilon_{E,TPP} = 186$	3882
	Rs+t&ep	$\approx 28\%$	12.70	$\epsilon_{E,Rs+t\&ep} = 0$	0
	Total	100%	45.36	$\epsilon_{E,EU\text{total}} = 86$	3882

Table 4. The estimated emissions of CO₂ from the electricity industry in Hungary in 2019 [32].

		Output Electricity Produced in TWh (=10 ⁹ kWh)	Output Electricity Produced in PJ (=10 ⁹ MJ)	Secondary Energy-Specific CO ₂ Emission [g CO ₂ /MJ]	CO ₂ Emission in kt (=10 ⁹ g)
HU energy mix in 2019	NPP	16.3	58.68	$\epsilon_{E,NPP} = 0$	0
	TPP	3.9	14.04	$\epsilon_{E,\text{lignite}} = 186$	2611
	CCGT	8.8	31.68	$\epsilon_{E,\text{CCGT}} = 139$	4404
	Rs+t&ep	4.1	14.76	$\epsilon_{E,Rs+t\&ep} = 0$	0
	EU import	12.6	45.36	$\epsilon_{E,\text{import}} = 86$	3901
	total	45.7	164.52	$\epsilon_{E,HU\text{mix}} = 66$	10916

Table 5 shows the calculation of energy-specific CO₂ emission values for internal combustion vehicles. It is noteworthy that ϵ of diesel oil is better than that of gasoline, and

we are not considering the ground level ozone and particulate matter emissions of diesel engines. Table 5 shows that the heating values of E10 and E85 fuels are lower than the heating value of gasoline. Significant improvements in emissions can only be achieved if the share of renewable fuels is high. However, this again leads to the “food or fuel” problem, and it will be shown later that it does not improve energy efficiency. It should be noted that this work does not consider the amount of arable land needed for bioethanol production as well as the impact on food-crops production.

Table 5. The calculated energy-specific CO₂ emission parameters of fossils and biofuels * [45–54].

Secondary Energy	Lower Heat Value [MJ/kg]	Lower Heat Value [MJ/l]	Density at 15 °C [kg/l]	kg CO ₂ Produced from 1 kg	kg CO ₂ Produced from 1 l	Total Energy Efficiency of Vehicle η [-]	Motion Energy Specific Total CO ₂ Emissions [g CO ₂ /MJ _{motion}]
LPG	45.5–46.5 (\approx 46)	(23.5)		1.82		0.35	$\epsilon_{\text{ICEV,LPG}} = 113$
Gasoline	43.5–46.5 (\approx 45)	34.7	\approx 0.74–0.75	3.07	2.29	0.35	$\epsilon_{\text{ICEV,Gasoline}} = 195$
Diesel oil	42–46 (\approx 44)	38.3 (35.8)	0.82–0.85 \approx 0.835	3.09		0.36	$\epsilon_{\text{ICEV,Diesel}} = 195$
E10 10% bioethanol 90% gasoline	41.3–43.9	\approx 31.5 (31.2–32.4)	0.735–0.75		2.21×0.9	0.35	$\epsilon_{\text{ICEV,E10}} = 180$
E85 85% bioethanol 15% gasoline	29.2–33.1	\approx 24.5	\approx 0.78–0.79		1.61×0.15	0.35	$\epsilon_{\text{ICEV,E85}} = 28$
B5 5% biodiesel 95% diesel oil	\approx 44 \times 0.997 \approx 43.9	\approx 37.8	0.86–0.89 \approx 0.86		2.65×0.95	0.36	$\epsilon_{\text{ICEV,B5}} = 185$
B20 20% biodiesel 80% diesel oil	\approx 44 \times 0.961 \approx 42.3	\approx 37.6	0.86–0.89 \approx 0.89		2.62×0.8	0.36	$\epsilon_{\text{ICEV,B20}} = 155$

* The values of commercial products fluctuate and may have \pm 5% uncertainty.

4. Discussion

Both indicators, the efficiency of energy conversions (η_{motion}) and energy-specific CO₂ emissions (ϵ), together characterize the types of vehicles with regard to sustainability. Table 6 summarizes the calculated parameters, and Figure 5 illustrates the energy-specific CO₂ emission values of vehicles with different power-driven systems.

Table 6. The calculated energy efficiencies (η [–]) and motion energy-specific total CO₂ emission parameters (ϵ [g CO₂/MJ_{motion}]) of vehicles.

$\eta_{\text{motion,EV}}$	$\eta_{\text{motion,BEV}}$	$\eta_{\text{motion,HEV}}$	$\eta_{\text{motion,ICEV,LPG}}$	$\eta_{\text{motion,ICEV,G}}$
0.35	0.31	0.27–0.31	0.27	0.27
ϵ_{EV} 67	ϵ_{BEV} 75	ϵ_{HEV} 100–170	$\epsilon_{\text{ICEV,LPG}}$ 113	$\epsilon_{\text{ICEV,G}}$ 195
$\eta_{\text{motion,ICEV,E10}}$	$\eta_{\text{motion,ICEV,E85}}$	$\eta_{\text{motion,ICEV,D}}$	$\eta_{\text{motion,ICEV,B5}}$	$\eta_{\text{motion,ICEV,B20}}$
0.27	0.27	0.36	0.36	0.36
$\epsilon_{\text{ICEV,E10}}$ 180	$\epsilon_{\text{ICEV,E85}}$ 28	$\epsilon_{\text{ICEV,D}}$ 195	$\epsilon_{\text{ICEV,B5}}$ 185	$\epsilon_{\text{ICEV,B20}}$ 155

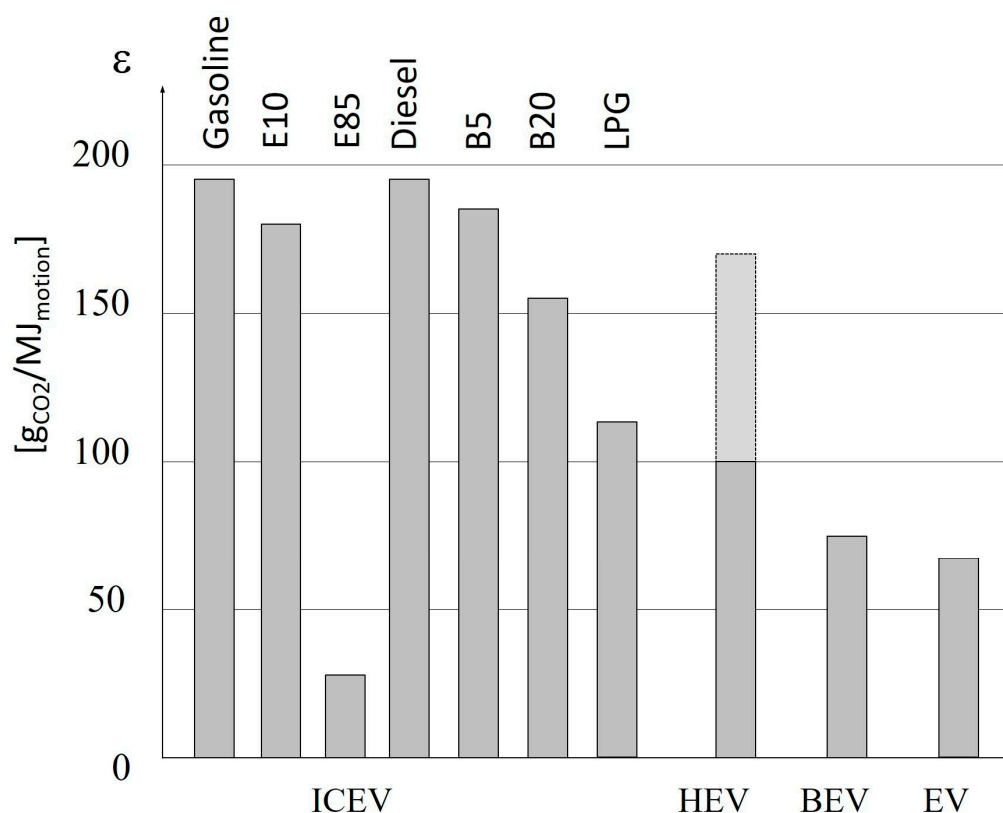


Figure 5. Energy-specific CO₂ emission values of vehicles with different power-driven systems (authors' creation).

A sustainability matrix was constructed to facilitate the interpretation of the results (Figure 6). The matrix shows that the energy efficiency is currently very similar for all vehicles. The energy efficiency can only be improved by increasing the share of renewables in electricity generation, which would also reduce CO₂ emissions in addition. The arrows show possible paths for development.

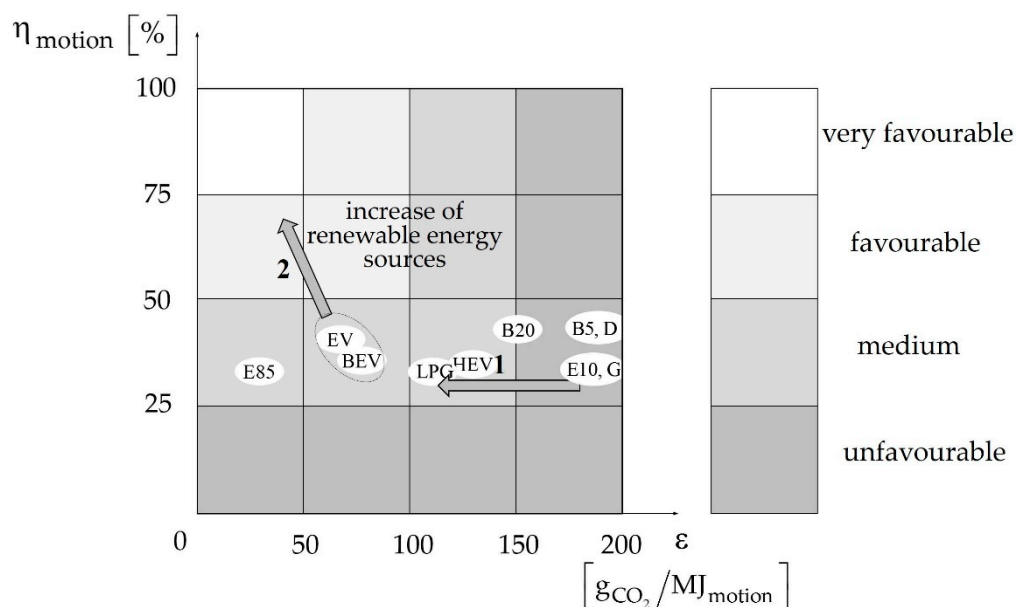


Figure 6. Sustainability matrix (authors' creation).

5. Conclusions

The authors think that CO₂ emissions from vehicles should be related to energy directly used in motion. The relationship is shown through a new indicator called “energy-specific CO₂ emissions” (ϵ). However, energy efficiency (η) is also included in the characterization of vehicles. By using these two indicators, it is possible to obtain more accurate information about which power-driven systems are better from the point of view of sustainability. The total CO₂ emissions calculated to the final motion energy produced can be applied to a vehicle of any mass.

There are two ways to reduce the CO₂ emissions of vehicles. One way is to increase the proportion of biofuels in fossil fuels (arrow 1 in Figure 6.), and the other way is to increase the share of renewables in electricity generation (arrow 2 in Figure 6).

According to the sustainability matrix and the calculations, the increase in the share of biofuels in the fuels of vehicles using internal combustion engines does not significantly change the energy efficiency of the vehicle, so this solution does not move the vehicle into a more favorable sustainability range (arrow 1 in Figure 6).

Increasing the share of renewable energy sources in electricity generation reduces CO₂ emissions for various electric cars and simultaneously increases the efficiency of energy conversions. With these two effects, the electric vehicle can already reach more favorable areas of sustainability (arrow 2 in Figure 6).

Author Contributions: I.Á. was responsible for the conceptualization and methodology. He took part in the formal analysis and the visualization. J.T.K. was involved in draft preparation, visualization and supervision. G.B. took part in the review, editing and validation parts. D.K. was responsible for review and editing, visualization, supervision and project administration. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

BEV	Battery electric vehicle
CCGT	Combined cycle gas turbine
ChP	Chemical plant
CNG	Compressed natural gas
EV	Electric vehicle
FCEV	Fuel cell electric vehicles
GHG	Greenhouse gas
HEV	Hybrid electric vehicle
IC	Internal combustion
ICEV	Internal combustion engine vehicle
ICEVD	Internal combustion engine vehicle operating with diesel oil
ICEVG	Internal combustion engine vehicle operating with gasoline
ICEVNG	Internal combustion engine vehicle operating with LNG or CNG
LCA	Life cycle assessment
LIB	Lithium-ion battery
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas (propane and butane)

NPP	Nuclear power plant
PV	photovoltaic
TPP	Traditional thermal power plant (solid fossil fuel/oil/gas) with a normal water-steam cycle
WLTP	Worldwide Harmonised Light Vehicle Test Procedure
WTW	Wheel-to-wheel

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