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LIFE CYCLE ENERGY CONSUMPTION AND CO_2 EMISSIONS OF DIFFERENT CAR TYPES

Summary. In this research, the energy consumption and emissions of gasoline cars, battery electric cars, fuel cells electric (FCE) cars, compressed naturel gas (CNG) cars, liquid propane-butane gas (LPG) cars, etc., during their life cycles are presented. A set of flow charts presenting the production of cars and used fuel/energy is developed. These charts and the latest data for electricity production emission factor and raw materials prices are used. A comparative analysis is done. Results for primary energy and carbon emissions are presented in graphical form. They show the most economical and ecological car decisions.

1. INTRODUCTION

Owing to the impact of production processes and means of transport on the environment, technical solutions to reduce air pollution with harmful effects are being sought. Important tools in this respect can be methods for assessing the impact of the whole life cycle of production processes on the environment. Research on the effect of the production of fuels and the use of means of transport in terms of environmental protection illuminates the directions of development [1, 4, 5, 10]. The conditions of production and operation of means of transport are specific for individual countries, which necessitates the study of the specific operating conditions and production processes of the fuels used [9]. Due to the increase in the share of electric and alternative fuel cars, increasing attention is being paid to the requirements for the personnel who will service and maintain them, as well as their training [13, 25].

Based on the LCA, some prediction scenarios concerning emissions from different types of vehicles were developed [10]. The expectation is that the levels of emissions will decrease in the near future.

In [13], the LCA of the popular existing modes of electric vehicles was done. The authors showed and analyzed different stages of the life cycles of the models.

A team from the University of Ruse has a number of studies and publications on the efficiency of cars using different fuels and energy sources. Conventional cars using gasoline and LPG as fuel are covered, as are cars using methane and compressed air energy and electric cars powered by energy stored in traction batteries or using hydrogen fuel cells.

The analysis was made based on the used primary energy and the released harmful emissions related to carbon dioxide (CO_2) equivalent. For this purpose, an assessment was made of the entire life cycle of cars, covering production, operation, and recycling. The same has been done with regard to the used

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fuels and energy. The results are presented in a series of publications. They are also presented as a chapter in collective monograph [1].

For electric vehicles powered by the energy stored in traction batteries, an assessment has been made for the entire life cycle, including vehicle production, operation, and recycling, by considering the impact of the electrical energy production technology required for the production and charging of batteries. Concerning electric vehicles with fuel cells, the efficiency in the production of the electric vehicle, the fuel cell, and recycling, the operation during the life cycle with different hydrogen (H_2) production technologies has been investigated. For cars using compressed air as energy, the assessment was made respecting the accepted conditions of the study and the accepted pressures of the compressed air for propulsion, regardless of the fact that their real mass can be significantly less than the mass of conventional cars.

These life cycle assessments are based on information on the energy mix and emission factor of electricity production compiled in 2015 [7] and the latest available complete information for 2020 [6, 21]. Thus, the impact of means of transport and the possibilities for reducing air pollution with harmful emissions can be analyzed.

2. INFLUENCE OF DIFFERENT FUELS AND ENERGY SOURCES ON PRIMARY ENERGY USED AND HARMFUL EMISSIONS RELEASED DURING THE LIFE CYCLES OF CARS AND ELECTRIC VEHICLES

The energy consumed and the carbon emissions released by vehicles are evaluated for their entire life cycles based on existing international standards [4, 12, 23]. Schematic models of the processes of the production of cars and the fuel or energy used for their propulsion have been developed (Figs. 1-6).

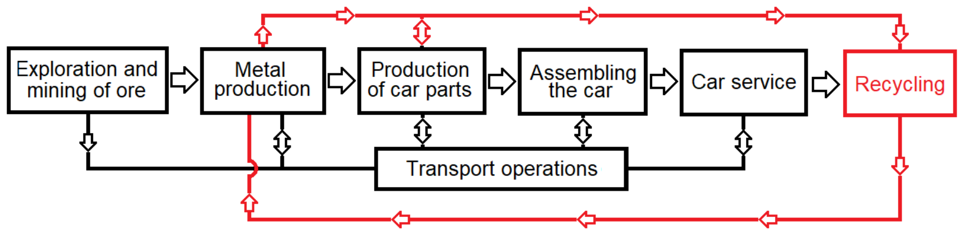


Fig. 1. Flow chart of the life cycles of cars, excluding battery and fuel production

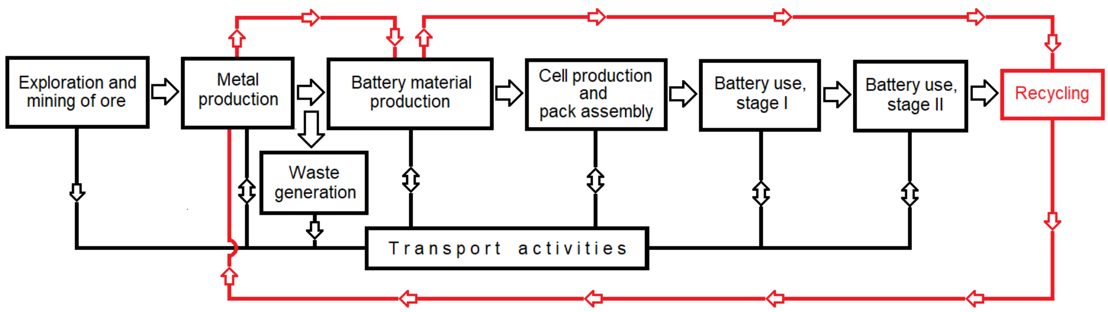


Fig. 2. Flow chart of the traction battery life cycle

The models include the main stages and activities of life cycle, as well as the energy consumption for them in percentages. Mathematical models have also been developed [1] describing the processes that enable a quantitative assessment of the primary energy consumed and the harmful emissions generated.

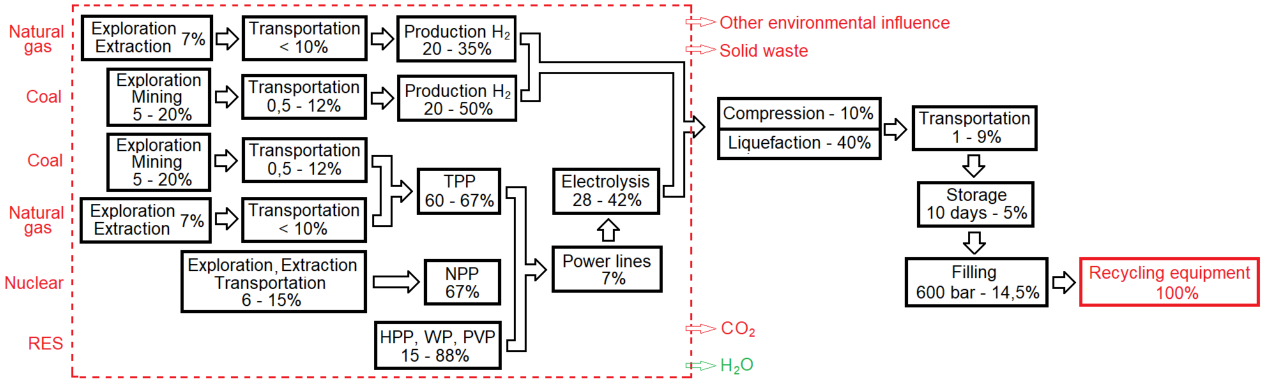


Fig. 3. Flow chart of the hydrogen fuel life cycle

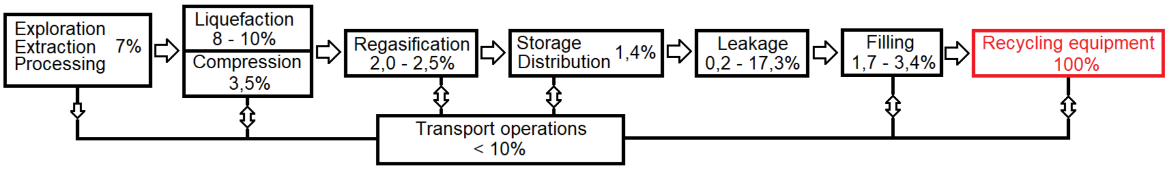


Fig. 4. Flow chart of the life cycle of natural gas

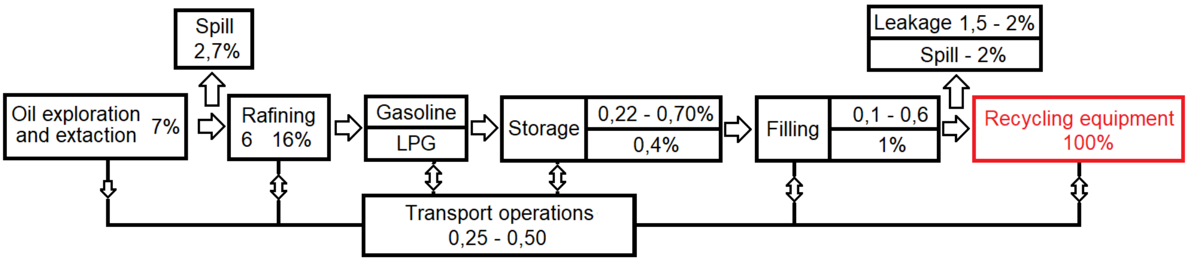


Fig. 5. Flow chart of gasoline and LPG life cycle

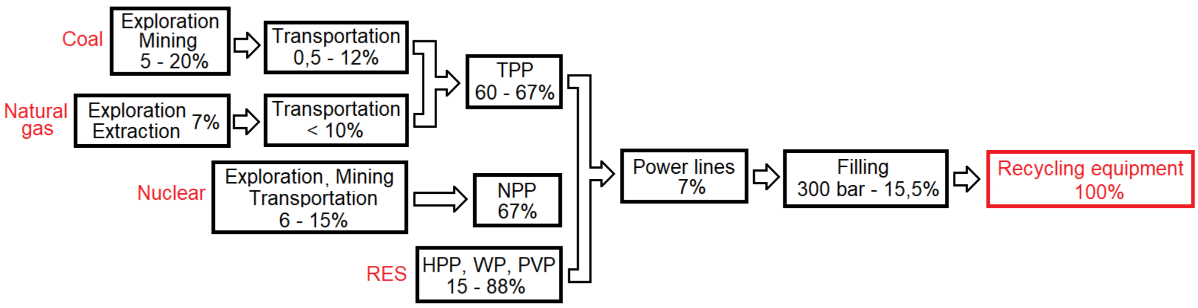


Fig. 6. Flow chart of the compressed air drive life cycle

In the assessment of vehicles' life cycles concerning the primary energy used and carbon emissions released, the following general conditions are adopted for comparability:

– equal masses of all vehicles;

– equal energy/fuel consumption of the vehicles – 0.210 kWh/km, which is equivalent to 7.6 l/100 km petrol, – 4.43 kg/100 km natural gas, 10.2 l/100 km propane-butane;

– the same mileage for the life cycle – 290,000 km;

– equal energy consumption (from the set) for vehicle production – 11,900 kWh [1];

– energy capacity of the battery for electric vehicles – 60 kWh;

– efficiency of a nuclear power plant (NPP) – 29.5% [3];

– efficiency of a thermal power plant (TPP) using coal – 26% [1];

– efficiency of TPP using natural gas – 40% [1];
– efficiency of TPP using liquid fuels – 40% [1];
– efficiency of a water power plant (WPP) – 60% [4];
– load on wind power plants (WiPP) – 23% [18];
– load on photovoltaic power plants (PVPP) – 16% [18];
– efficiency in the production of gasoline is assumed to be 89.1% [4];
– efficiency in the production of propane-butane gas – 94% [4];
– efficiency in the production of natural gas – 91% [4];
– losses from natural gas leakage – 1.5% and 7% [1];
– losses during compression of natural gas – 3.5% [1];
– losses during liquefaction of natural gas – 8% [1];
– energy losses when compressing hydrogen up to 700 bars – 15.5% [1];
– energy losses during liquefaction of hydrogen – 15.5% [1];
– specific CO_2 emissions from the combustion of gasoline – 240.82 g/kWh, natural gas – 183.96 g/kWh and propane-butane – 214.48 g/kWh [5];
– global warming potential (GWP) – 25 and 86 [15];
– the emission factors in the production of electrical energy in Bulgaria and the EU-27 countries (on average) in 2020 were 541 and 268 g/kWh, respectively [11].

It is important to note that the life cycle assessments of different cars do not include the energy losses and CO_2 emissions generated as a result of the transportation of the fuels and energy sources due to their different values depending on the individual country and distance. This enables a clearer picture of the advantages and disadvantages of using a certain type of car in a given country after a corresponding analysis is done on the energy required for transportation and the released CO_2 emissions.

In addition to the conditions mentioned above, information on the efficiency of power plants, assumed energy consumption, etc., was used [1].

Tab. 1 presents the energy mix for Bulgaria and the EU-27 for 2015, which corresponds to an analysis [1], and for 2020, which corresponds to the life cycle assessment of cars using different types of fuel or energy made in this publication.

The data in Tab. 1 indicate that the share of nuclear energy and RES in 2020 in Bulgaria increased compared to 2015 by 14.2% due to the reduction of energy from thermal power plants. This change has had a positive impact on the primary energy used during the life cycle, as well as on harmful emissions. This is due to the higher efficiency in the production of electricity from NPPs and RES compared to thermal power plants using coal as fuel.

Table 1

Percentage shares of different sources of electrical energy
in Bulgaria and EU-27 for 2015 and 2020 [6-8, 14, 16, 19]

Power Plants	**YEAR**			
	2015		**2020**	
	Bulgaria	**EU-28**	**Bulgaria**	**EU-27**
Nuclear power plants	**33.2**	**28.9**	**41.0**	**25.0**
RES, of which:	**17.2**	**28.4**	**23.6**	**37.5**
WiPP	2.4	8.0	4.0	15.0
PVPP	2.7	3.7	5.4	5.0
WPP	11.6	11.7	13.7	12.0
Bioenergy	0.5	5.0	0.5	5.5
TPP, of which:	**49.6**	**42.7**	**35.4**	**37.5**
Coal	48.7	18.9	30.3	13.2
Natural gas	0.7	14.0	5.0	23.8
Liquid fuels	0.2	9.8	0.1	0.5

For the EU-27, the share of energy from RES increased by 10.8% due to the decrease in the share of energy from nuclear power plants and thermal power plants. The increase in energy from natural gas TPP, regardless of the overall decrease in the share of TPP, reflects a decrease in primary energy. This is caused by the high efficiency of gaseous fuel. The increase in the share of RES to 37.5% is mainly due to the increase in the share of solar and wind energy of more than 8%.

2.1. Primary energy for the whole life cycles of vehicles

The results for consumed primary energy and generated CO_2 emissions are given in Figs. 7 and 8.

The results in Fig. 7 show a relatively small difference between the primary energies consumed by the EU-27 and Bulgaria. This is due to the relatively close overall efficiency in the production of electrical energy. In Bulgaria, this efficiency is 32.28%, and in the EU-27, it is 34.25%. This difference in electricity production efficiency was twice as large in 2015. This is due to a significant increase in the use of solar and wind energy, for which the load factor of the power plants is too low (Tab. 1). In addition, in Bulgaria, the production of electricity from nuclear power plants increased by 7.8%; in EU-27 countries, it decreased by 3.9%.

In 2015, 42,000 kWh of primary energy was needed for the production of a car; in 2020, 36,900 kWh was needed, which is 13.8% less. For the production of a fuel cell car, 58,300 kWh of primary energy is used, or 58% more than conventional ones. The difference arises because the manufacturing of fuel cells with different systems is required for their operation.

Cars using hydrogen and cars using compressed air energy use the largest amount of primary energy (Fig. 8, columns 7, 8 12 and 13). Electric vehicles use the least amount of primary energy throughout their life cycles, followed by LPG vehicles. Electric vehicles with fuel cells have the greatest consumption of primary energy because they have the highest costs in the exploitation stage. The difference in primary energy between petrol cars and electric cars is also due to the greater losses at different stages of the cars' life cycles—for example, due to the relatively low efficiency of fuel combustion in the engine cylinders (relatively low efficiency) of gasoline engines.

The primary energy for a distance of 1 km for investigated types of vehicles is given in Tab. 2. The results provide understandable information for the public about the economic and ecological efficiency of vehicles.

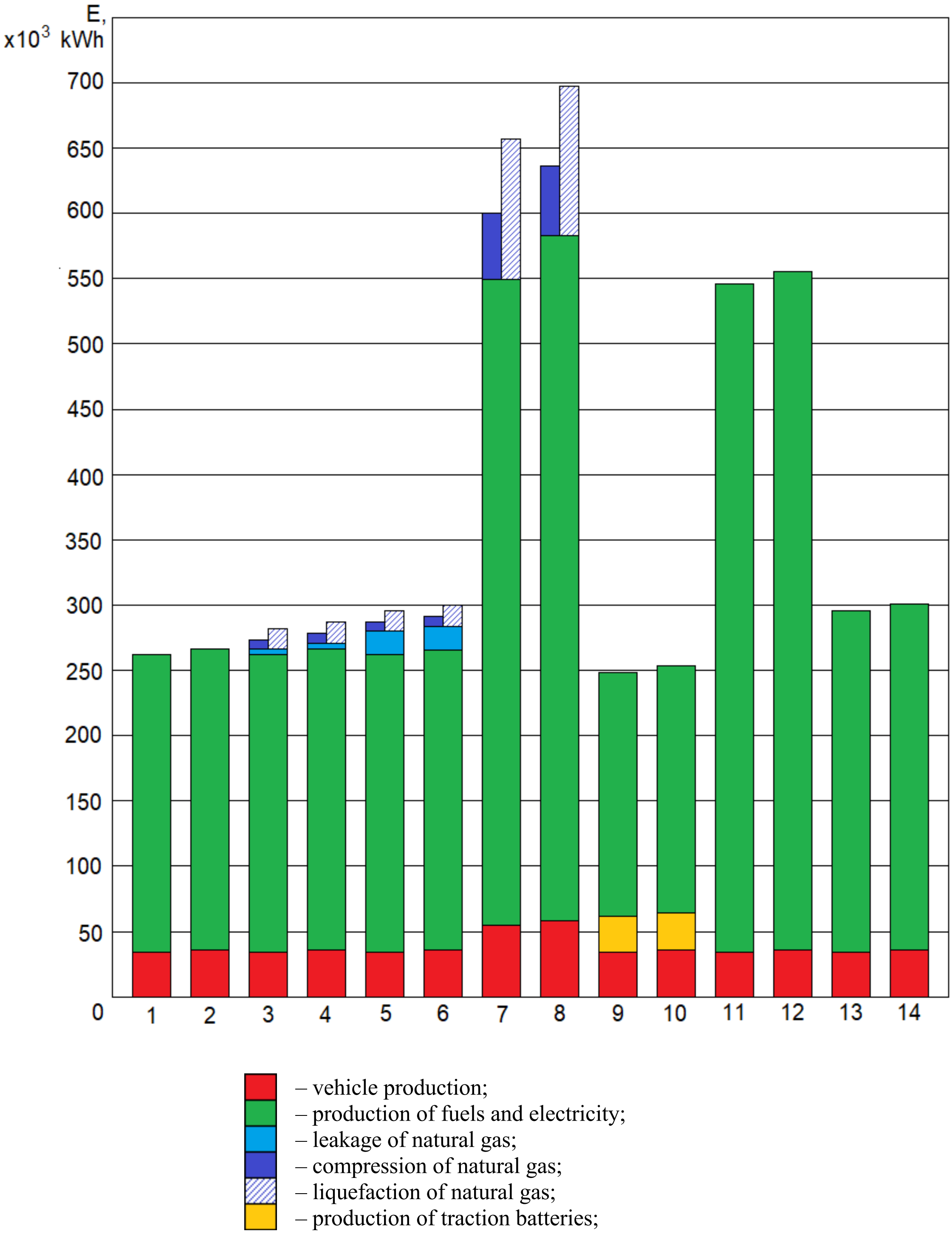
2.2. Carbon emissions for the whole life cycle

Usually, the amount of released harmful greenhouse gas emissions (g CO_2e/kWh) is defined as direct emissions only at the fuel combustion stage. However, if the losses related to the entire life cycle at the low voltage level of the grid are taken into account, the emission factor in 2020 in the EU-27 was 327 g/kWh, and in Bulgaria, it was 556 g /kWh.

As a basis for comparing the harmful emissions released by vehicles, the emissions released by a classic gasoline car are used. The release of harmful emissions from gasoline cars at the same level of fuel consumption varies around 60,000 kg for a distance of 290,000 km. This variation is mainly due to a country's energy mix, which depends on the emissions of the car and fuel production. In Bulgaria in 2020, gasoline cars, under the accepted conditions for life cycle assessment, released 67,140 kg of harmful emissions reduced to CO_2; in the EU-27 countries, this value was 58,440 kg. The difference is 13%.

Carbon emissions from LPG vehicles for their whole life cycles are 56,150 kg in Bulgaria and 49,600 kg in the EU-27 countries. These values are 16.4% and 15.2% less in Bulgaria and the EU-27 countries, respectively, considering the carbon emissions emitted by gasoline cars.

The use of natural gas (methane) as fuel presents a more complicated scenario. The problem is its leakage into the atmosphere during mining and exploitation. Its impact on global warming is tens of times greater than that of CO_2. The methodologies used to assess the life cycles of fuels have determined leakage within 1.5% of the annual production and GWP = 25.

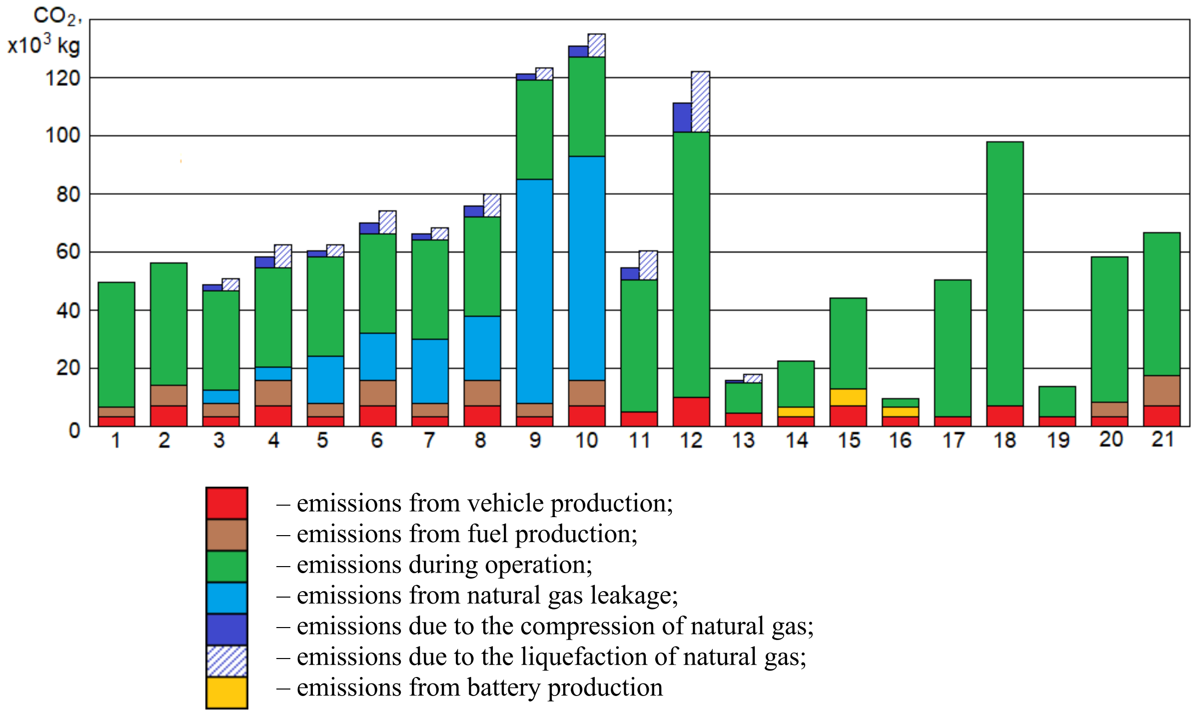


1 and 2 – cars with propane-butane fuel in the EU-27 and Bulgaria; 3 and 4 – cars with natural gas (methane) fuel when 1.5% of the fuel leaks in the EU-27 and Bulgaria; 5 and 6 – cars with natural gas (methane) fuel when 7% of the fuel leaks in the EU-27 and Bulgaria; 7 and 8 – electric vehicles with fuel cells in the EU-27 and Bulgaria; 9 and 10 – electric vehicles with lithium batteries in the EU-27 and Bulgaria; 11 and 12 – cars using compressed air as an energy source in the EU-27 and Bulgaria; 13 and 14 – cars with gasoline fuel in the EU-27 and Bulgaria

Fig. 7. Life cycle consumed primary energy of various types of cars produced and operated in the EU-27 countries and Bulgaria in 2020

Natural gas produces a variable and uncertain proportion of harmful emissions that are released into the atmosphere over its life cycle. In [11], it is stated (based on 26 publications in the period from 2012-2015) that methane leakage into the atmosphere varies widely, from 0.2 to 17.3%.

Global warming potentials are introduced to compare greenhouse gases' impacts. The greater the GWP, the more the gas will warm the Earth in comparison to CO_2. CO_2 has a GWP of 1, and it is a baseline against which other gases are compared. For instance, if methane has a GWP of 86, the warming caused by one ton of methane is the same as that caused by 86 tons of CO_2.



1 and 2 – with propane-butane for EU-27 and Bulgaria; 3 and 4 – with natural gas and 1.5% leakage (GWP = 25) for EU-27 and Bulgaria; 5 and 6 – with natural gas and 1.5% leakage (GWP = 86) for EU-27 and Bulgaria; 7 and 8 – with natural gas and 7% leakage (GWP = 25) for EU-27 and Bulgaria; 9 and 10 – with natural gas and 7% leakage (GWP = 86) for EU-27 and Bulgaria; 11 and 12 – with hydrogen for EU-27 and Bulgaria; 13 – with hydrogen and an emission factor of 58 g/kWh for EU-27; 14 and 15 – electric cars with lithium batteries in the EU-27 and Bulgaria; 16 – electric cars and an emission factor of 58 g/kWh; 17 and 18 – compressed air for EU-27 and Bulgaria; 19 – compressed air and an emission factor of 58 g/kWh; 20 and 21 – gasoline cars in the EU-27 and Bulgaria

Fig. 8. Life cycle carbon emissions of different vehicles in 2020

Different gases stay in the atmosphere for different periods. Comparisons between gases should be based on these periods. CO_2 can remain in the atmosphere for a very long time (for centuries). Methane remains in the atmosphere for much less time due to natural causes. As a result of oxidation and several other processes, methane remains in the atmosphere for about 12 years. This means that if a project is developed for the application of natural gas in some production processes for a period of 20 years, then we have to take into account the impact of global warming over a period of 32 years.

Researchers from NASA and the University of Columbia have evaluated a range of atmospheric processes and have estimated that methane's GWP could be 79 to 105 over a 20-year period. After an analysis concerning the last 100 years, scientists concluded that the GWP of methane is 26 to 41 times that of CO_2. The most recent report of the Intergovernmental Panel on Climate Change estimates the 20-year GWP of methane at 86 and its 100-year GWP at 34 [21, 22]. It is well known that there are differences in whether it is best to look at the impact of methane in 20-year or 100-year terms. However, the need for rapid action on climate change requires the shorter-term impacts of methane to be examined rather than the 100-year impacts. For this reason, a methane GWP of 86 was adopted in this study.

In general, the release of carbon emissions of methane at the combustion stage in LPG is significantly less than that of gasoline (≈ 25%). However, its leakage into the atmosphere and the additional pollution from its compression and liquefaction reduces its advantage at the combustion stage and even leads to twice the global warming impact at 7% leakage and GWP = 86. Based on the norms adopted in the methodology for determining the intensity of greenhouse gas emissions from the entire life cycles of fuels and energy in transport [23] and losses from 1.5% natural gas leakage by the Environmental Protection Agency in the USA, it is considered that natural gas, even when liquefied, emits 7% less harmful emissions than gasoline cars at GWP = 25 in Bulgaria and 3.4% less in the EU-27 countries. For GWP =86 and 1.5% leakage, natural gas loses its carbon advantage.

Regarding the pollution share of cars with fuel cells and existing technologies for the production of hydrogen by electrolysis and the specified emission factor in Bulgaria, electric cars pollute over 80% more when liquefied hydrogen is used and 65% more when compressed hydrogen is used versus gasoline. The results for the EU-27 countries show a much more favorable situation – the difference is minimal, and a significant improvement comparable to the results obtained in 2015 can be assumed. At that time, fuel-cell electric cars produced 80% more pollution than gasoline cars. If hydrogen is produced from the energy of photovoltaic power plants (column 13 in Fig. 7), then fuel-cell electric cars pollute nearly 3.5 times less than gasoline cars.

The situation is also favorable for electric vehicles powered by lithium-ion batteries. The development of production technologies and the reduced emission factor of electrical energy production give electric cars an advantage over gasoline cars in terms of carbon emissions. In Bulgaria, electric cars emit one-third as much carbon as gasoline cars, and in EU-27 countries, electric cars emit over 62% less. Even more favorable are the results when charging batteries are produced by a PVPP (column 16 in Fig. 7). This can reduce the emissions for charging the battery by five and 10 times compared to the release of harmful emissions in the current energy mix in the EU-27 and Bulgaria, respectively.

Table 2

Specific energy consumption and CO_2 emissions of cars powered by different fuels and energy sources over their entire life cycles based on a distance traveled of 1 km

№	Type of vehicle, depending on fuel or energy source	Country			
		Bulgaria		EU-27	
		Primary energy, kWh/km	CO_2, g/km	Primary energy, kWh/km	CO_2, g/km
1	**CV**	1.039	232	1.018	202
2	**BEV**	0.874	153	0.857	86
3	**H_C^EFCV**	2.196	383	2.069	190
4	**H_L^EFCV**	2.405	420	2.266	208
5	**LPG**	0.918	194	0.900	171
6	**NG_C^***	0.957	200	0.938	167
7	**NG_L^***	0.989	215	0.970	174
8	**NG_C^{**}**	0.957	241	0.938	207
8	**NG_L^{**}**	0.989	257	0.970	215
8	**NG_C^{***}**	1.001	260	0.982	267
9	**NG_L^{***}**	1.034	276	1.014	234
10	**NG_C^{****}**	1.001	450	0.982	417
11	**NG_L^{****}**	1.034	446	1.014	424
12	**CAV**	1.919	334	1.881	174

* 1.5% leaks, GWP = 25; ** 1.5% leaks, GWP = 86
*** 7% leaks, GWP = 25; **** 7% leaks, GWP = 86

The subject of cars using compressed air was relevant about 10 years ago. Due to problems with the relatively short distance that can be covered in such vehicles, their application is justified only for urban and suburban traffic conditions. Their advantage in terms of harmful emissions during movement is massive, especially when energy from a PVPP is used to charge the tank with compressed air.

The specific emissions from different vehicles for a distance of 1 km are given in Tab. 2. The information confirms the comments made above and is sufficiently clear. The following abbreviations are used: **CV** – conventional vehicle; **BEV** – battery electric vehicle; **HFCEV** – hydrogen fuel-cell electric vehicle using compressed or liquid H_2; **NG** – vehicle using natural gas (compressed or liquid); **CAV** – compressed air vehicle.

3. CONCLUSIONS

This research was carried out to assess the life cycle of different car types. Based on the findings, the following conclusions can be drawn:

1. Advanced flow charts and models enable an accurate assessment of the life cycles of different vehicles in terms of primary energy consumed and carbon emissions released.
2. The amount of primary energy spent on the production of vehicles, fuels, and electrical energy depends on the efficiency of electrical energy production. In Bulgaria in 2020, this efficiency was 32.28%, and, on average, among EU-27 countries, it was 34.25%. Therefore, an average of 2% more primary energy was invested into the entire life cycle in Bulgaria.
3. With the annual change in the energy mix, the advantage of electric cars over gasoline cars is consistently increasing, which is a prerequisite for the accelerated development of technologies for the production of electrical energy from RES.
4. The construction of charging stations for recharging electric cars using RES energy will make a significant contribution to reducing carbon emissions and slowing down global warming.
5. Using LPG cars instead of petrol is a quick and easy way to reduce carbon emissions by over 15%. This process of gasification is not to be neglected in the fight for cleaner air.
6. Natural gas (methane) as a fuel in cars, taking into account the real conditions of operation and its real impact on global warming, can have an impact that is more than two times harmful compared to gasoline cars.
7. The use of renewable energy opens many prospects for using electric cars as ecological vehicles that produce many times fewer emissions than gasoline cars. Methods for increasing the share of electric vehicles with fuel cells in the vehicle fleet are being discovered, with energy from RES providing an opportunity to reduce emissions by up to five times compared to cars.
8. With the change in the energy mix in the EU-27, the emissions of battery electric cars decreased to one-third of the emissions of conventional gasoline cars.

Acknowledgments

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