Thermodynamic Analyses of Global Carbon Dioxide Reduction Perspectives in Transport

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Abstract.
The world now recognises that the climate change problem forces us to rethink the technological configuration of every branch to reduce carbon dioxide (CO_2) emissions. In the case of transport, it results in wide adoption of electric vehicles. However, EVs with undisputable zero emission in situ lead to excessive CO_2 emissions in the place of power generation. Thus, the broad adoption of EVs must match the current and future electricity generation capacities. A brief analysis proposed in the paper shows that current EVs with superior efficiency leads to global CO_2 emission at 141 gCO_2/km, while “grey” hydrogen fuel cell vehicle results in just 71 gCO_2/km. Furthermore, it has been shown that intensive adoption of EVs could reach the goal of CO_2 emission of 95 gCO_2/km not earlier than 2050, subject to intensive use of natural gas for electricity generation using a combined thermodynamic cycle.

Keywords: Electric vehicle, carbon dioxide, emission, hydrogen, fuel cell.

1 Introduction

Recent decades show the exponential concern of world communities and elites by global warming and carbon dioxide reduction in particular [1]. Many summits, international agreements and projects, emissions quoting, philanthropic initiatives, and popular science publications have filled the information area [2,3]. In the framework of transport, the recent success of Tesla Inc. in the mass production of comfortable and affordable electric vehicles (EV) has been perceived by the leading players in the automotive industry as a sign and general call to shift toward electric transport to reduce CO_2 emission. EU cities have already outlined the internal combustion engine (ICE) ban dates [4]. Leading automakers shut down ICE factories, reduce research activities to improve ICE efficiency, aggressively increase EV production and fund the appropriate research activities [5]. In a moment, the ICE transport could fall into oblivion. However, EV’s CO_2 “zero emission” mark is not indisputable, while the electricity is entirely produced from renewables without CO_2 emission. Unfortunately, this is not the case; electromagnetic waves charging EVs carry the shadow emissions of CO_2 from fossil burning. Thus, the electrification of the transport sector shifts CO_2 emissions from the transport sector to the power sector. This CO_2 shadow emission differs by country and region. Generally, the exploitation of EVs in the area of wind and solar power stations will cause zero emissions. In other places, EV's shadow CO_2 emission could still be even higher in other sites than from ICE.

Nomenclature

HHV	high heat value, MJ/kg
m	molar mass, g/mol
S	shadow CO_2 emission by EVs, $kgCO_2/kWh$ or $kgCO_2/km$
F	total fossil fuel consumption, TL
N	EVs electricity demand, TWh
d	yields, kg/kg
W	fuel cell electricity yields, kWh/kgH_2
G	average mass rate of fuel consumption, kg/100km
E_t	total electricity generation, Wh
E_i	electricity generation by i-th source, Wh
Greek symbols	
α	share of generated electricity
η	efficiency of energy conversion
μ	emission of CO_2 per kWh of generated electricity, $kgCO_2/kWh$
β	CO_2 emission factor, $kgCO_2/kWh$
σ	average rate of fuel consumption, L/100km
ψ	EVs efficiency, kWh/100km
ρ	density, kg/L
Subscripts	
f	fuel
i	i-th source
g	electricity distribution
ch	charging
b	battery
r	steam methane reforming
fc	fuel cell
CO_2	carbon dioxide
H_2	hydrogen
CH_4	methane
Abbreviations	
ICE	internal combustion engine
EV	electric vehicle
FCV	fuel cell vehicle
SMR	steam methane reforming

Many investigations have already been done on the costs of EV exploitation in terms of CO_2 emission in local regions and countries, e.g. more recent results for the USA [6], Ireland [7], Montreal, Canada [8], Thailand [9], Germany [10], Europe [11-13], China [14], and worldwide estimations [15,16]. The mentioned papers use different statistical methods for the predictions, with the breakdown analyses to minor details. However, those studies need the global thermodynamic clarity of the energy conversion cycle from the power plant to the chemical energy accumulated in the EV battery. This fact motivates us to represent the most straightforward conservative thermodynamic approach of EV and ICE comparison by CO_2 emissions.

2Methodology

2.1 EV's shadow CO_2 emission

Worldwide, electricity mix is produced from different sources and using various thermodynamic cycles. Table 1 represents the breakdown of electricity production by the sources in a time-lapse of 1990-2020 (IAE data [17]). Apparently, fossils burning (coal, oil and natural gas) emit CO_2. At the same time, biofuel burning can be considered zero-emission or even negative emission [26] since emitted CO_2 is part of the base organic carbon cycle. The waste burning in the electricity generation process can contribute to CO_2 emissions depending on the sort of waste. However, considering its negligible role compared to the other fossils, let's exclude it from the analyses for simplification.

Table 1. - Electricity production (E_i, 1000·TWh) by the sources [17],

Source/Year	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Coal	4.4293	4.9937	5.9954	7.3258	8.6699	9.5363	9.4525
Oil	1.3235	1.2293	1.1876	1.1286	0.9686	1.0210	0.6679
Natural gas	1.7478	2.0179	2.7714	3.7008	4.8555	5.5496	6.3350
Biofuels	0.1054	0.0951	0.1125	0.1694	0.2752	0.4099	0.5713
Waste	0.0241	0.0350	0.0497	0.0581	0.0869	0.0993	0.1133
Nuclear	2.0129	2.3320	2.5906	2.7680	2.7563	2.5701	2.6739
Hydro	2.1908	2.5459	2.6957	3.0183	3.5360	3.9813	4.4530
Geothermal	0.0364	0.0399	0.0522	0.0583	0.0677	0.0810	0.0949
Solar PV	0.0001	0.0002	0.0008	0.0037	0.0321	0.2448	0.8238
Solar thermal	0.0007	0.0008	0.0005	0.0006	0.0016	0.0096	0.0137
Wind	0.0039	0.0080	0.0314	0.1043	0.3422	0.8340	1.5981
Tide	0.0005	0.0005	0.0005	0.0005	0.0005	0.0010	0.0010
Others	0.0199	0.0239	0.0220	0.0330	0.0337	0.0371	0.0342
Total, E_t	**11.8955**	**13.3222**	**15.5104**	**18.3694**	**21.6264**	**24.3750**	**26.8326**

The following expression can define the emission of CO2 per kWh of generated electricity:

$$\mu = \sum \frac{\alpha_i}{\eta_i} \beta_i \tag{1}$$

$$\alpha_i = \frac{E_i}{\sum_i E_i} \tag{2}$$

The fossil power station uses the Rankine thermodynamic cycle. The generation-weighed efficiency (η_i) of existing coal power plants is at most 33 % [18,19]. On the other hand, the weight efficiency of oil-fired power plants is 38% and 45% for natural gas [20]. At the same time, using combined cycles in natural gas power plants could increase efficiency to 65% [21].

The CO_2 emission factor of hard coal and natural gas derives from the simplified chemical reaction:

$$C + O_2 = CO_2 \tag{3}$$

$$CH_4 + O_2 = CO_2 + 2H_2O \tag{4}$$

Thus, the CO_2 emission factor of fuels can be defined by the following equation:

$$\beta_i = \frac{1}{HHV_i} \cdot \frac{m_{CO2}}{m_i} \tag{5}$$

The high heating value (HHV) is the upper limit of the thermal energy produced by a complete fuel combustion. According to the fossil thermodynamic properties, HHV can be taken as 24 MJ/kg for the hard coal and 50 MJ/kg for the natural gas [22]. Hence,

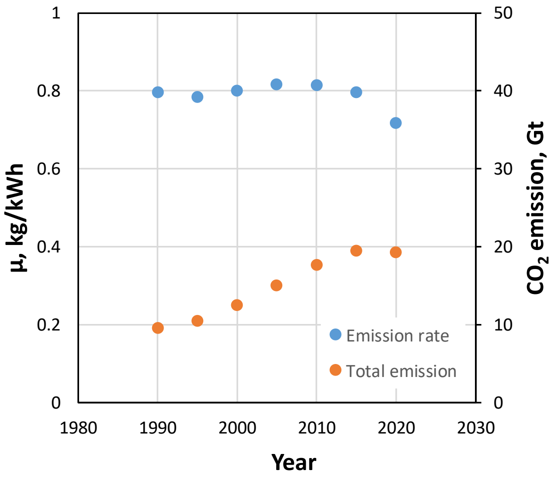

Fig. 1. – CO_2 emission per generated electricity

from Eq.5, the CO_2 emission factor of natural gas burning (β) is 0.055 $kgCO_2/MJ$ or 0.2 $kgCO_2/kWh$. This factor for the hard coal equals 0.153 $kgCO_2/MJ$ or 0.55 $kgCO_2/kWh$. Here, 1kWh references the thermal energy.

In the case of oil (heavy fuel oil), for the first approximation, it is feasible to use the mean value of the CO_2 emission factor between natural gas and coal. This simplification will not give a significant error since the minor role of oil as a source in electricity generation.

Figure 1 shows the dependence of CO_2 emission per generated electricity (μ) determined based on the Eq. 1 approach. The average CO_2 emissions per kWh of electricity is 0.717 $kgCO_2/kWh$. The average emission yield does not fully represent the particular cases by country. For instance, the USA contributes CO_2 emission with an average intensity of 0.41 $kgCO_2/kWh$ [6], while in India, with 67% of electricity produced from coal and oil [23], it is well above 1.0 $kgCO_2/kWh$.

Total CO_2 emission from electricity in Figure 1, determined as (μ·Et), indicates the sign of stabilisation during the last decade (2010÷2020) at a level of 20 Gt due to the widespread use of renewables. However, further reduction of CO_2 emission in the power generation industry worldwide will require much more effort since the power consumption grows with the population, level of life and, in particular, with the intensive replacement of ICE with EV.

Electricity must go to charging stations before being converted to the chemical energy of an EV battery. The dissipation of electromagnetic energy on leads and corresponding transmission tools depends on the distance between the power generation site and the charging point. Electricity power transmission and distribution losses vary by country and geography, but the world-averaged value (ηg) is close to 8÷9% [24]. Notably, the losses in the world's third-largest electricity producer, India, are close to 20 % due to the highly ageing transmission lines [25]. Compared with the losses in Germany, which are 4%, each year, India has up to 280 GWh of unnecessary electricity losses, more than 57% of the total electricity produced in Germany.

Additional electromagnetic energy losses occur directly in charging tools (AC-DC conversion). For the fast, powerful charger (50kW), efficiency values (ηch) at ambient temperature (25 0C) are around 90% [26] with a clear trend of efficiency reduction with the ambient temperature decrease.

The efficiency of electrical batteries determined as the ratio of the total charge extracted from the battery to the total amount put into the battery over a complete cycle, so-called Coulombic efficiency (η_b), is very high for lithium-ion batteries. For the EVs, the battery's Coulombic efficiency equals 98% at 40 A charging current [27].

In this way, the shadow CO_2 emission of EVs can be evaluated as follows:

$$S = \frac{\mu}{(1-\eta_g)\eta_{ch}\eta_b} = \frac{0.717}{0.92 \cdot 0.9 \cdot 0.98} = 0.884\ \mathrm{kgCO_2/kWh} \tag{6}$$

So, every charged kWh of electromagnetic energy to an EV battery generates 884 g of CO_2 emissions in situ of fossil-source power generation. Without breaking into details of energy conversion from the battery to the wheel of an EV, the performances declared by manufacturers can be used for straightforward analyses. For instance, the best-selling worldwide Tesla Model 3, with a claimed efficiency of 0.16 kWh/km, gives 141 gCO_2/km.

So, it does not comply with the target emission of new cars stated by the EU regulation, which is 95 gCO_2/km [28]. In addition, the efficiency declared by the manufacturer is always too optimistic, which needs to consider the power-consuming options like fast driving, conditioning, lighting, multimedia, etc. The countries with the largest share of electricity produced from renewables, e.g. Norway (99%), Sweden (67%) and Canada (68%), show good statistics for CO_2 reduction from transport due to the use of EVs. However, global warming is a worldwide problem. It does not matter how small the CO_2 emission in your country is if you use the wares, materials, and, in particular, EVs produced in the regions with the much wider use of the power from fossils. From this point of view, worldwide exploitation of EVs does not support the climate change goals until the world-averaged CO_2 emission rate of electricity generation declines by 35%. The primary trend (Figure 1) has yet to promise it could be any soon.

2.2 EV's electricity demand

EV exploitation becomes a separate electricity consumption factor. It means that a complete transport transition toward electrical gear will cost a qualitative jump in power consumption with the new challenges to the electricity distribution system and peak power load. The current fossil fuel consumption in the transport sector can conservatively evaluate the EV power demand:

$$N = \frac{F}{\sigma_f} \frac{\psi}{(1-\eta_g)\eta_{ch}\eta_b} \tag{7}$$

Despite the growth in the global car fleet (Figure 2), according to IEA data, the oil demand for petroleum products, including diesel and gasoline, has been stabilised at a level of 3.2 TL per year since the improvement in ICE efficiency as well as due to the use of hybrid solutions with EVs technology (Figure 3).

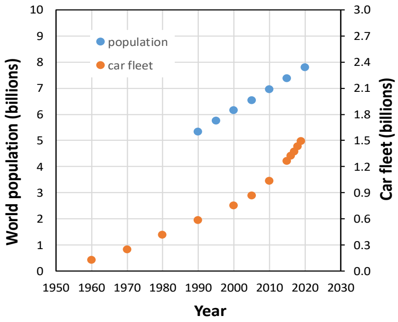

Fig. 2. – World population and global car fleet per year

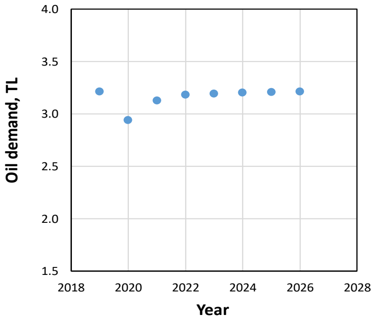

Fig. 3. – Global oil demand for petroleum products (diesel, gasoil, gasoline) per year

Assuming roughly 50% of ICE fuel yields from crude oil, the current demand for diesel and gasoline can be fixed as 1.6 TL per year. With that, neglecting those petroleum products for heating, power generation and marine consumption, the total EV power demand can be assessed at average as:

$$N = \frac{F}{\sigma_f}\frac{\psi}{(1-\eta_g)\eta_{ch}\eta_b} = \frac{1.6\cdot 10^{12}L}{8.0\frac{L}{100km}}\frac{16}{0.92\cdot 0.9\cdot 0.98}\frac{kWh}{100km} = 3943\,TWh \tag{8}$$

In Eq.8, individual transport's average fuel consumption rate is taken reasonably as 8 L/100km. The EV power demand will increase following the car fleet trend according to the global population growth. As follows from Table 1, the EV power demand (N) estimate is commensurable with the gain of electricity produced from renewables for the last 20 years. Assuming the current trend of electricity generation from renewables and the total demand for electricity due to the linear growth of the population, it is not expected that world-averaged CO_2 yields per kWh generated electricity will substantially be reduced in the next several decades. This means that shadow CO_2 emission of EVs will exceed the established standards. Hence, intensive substitution of ICE by EVs will contribute little to the global warming problem solution shortly.

2.3 CO_2 emissions with EV's power demand grows

Let's consider the reasonably optimistic scenario. The global power consumption for needs other than EV charging increases with the population growth trend. Power generation from renewables follows the current trend. Coal power generation stabilises, and there will be no power generation from oil in 2030. EV share in the global car fleet will increase linearly and achieve 100% in 2050. The global car fleet is steady. Natural gas power generation compensates for electricity shortage due to the intensive EV adoption with an average efficiency of 45%. Electricity power transmission and distribution losses are steady at 8%. Based on Table 1 data, Figure 4 and Figure 5 show a simplified prognosis of electricity generation and CO_2 emission by EVs.

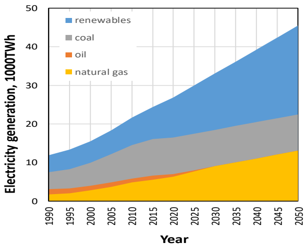

Fig. 4. – Global electricity generation prognosis

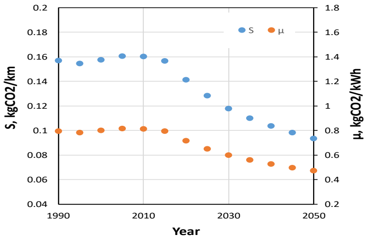

Fig. 5. – CO_2 emission prognosis

Thus, according to the selected scenario, CO_2 emission of 93 gCO_2/km will be achieved by EVs in 2050, and it is in line with EU regulation goals [28]. First, however, power generation from renewables and natural gas must intensify.

2.4 Hydrogen alternatives to EV

An apparent alternative to EVs in terms of CO_2 emission is hydrogen as the energy source of vehicles. Hydrogen can feed fuel cells, which produce electricity due to the electrochemical reaction of hydrogen oxidation or can burn in ICE as a zero-emission fuel. Both cases give in-situ zero CO_2 emission. However, the production of hydrogen is not always free of CO_2 emissions.

There are two main ways of hydrogen production on the Industrial level: water electrolysis and steam methane reforming (SMR). Hydrogen produced by water electrolysis with electricity consumption is often “green”, meaning zero CO_2 emission at generation. However, it is not valid in the framework of global power generation processes. The high irreversibility of electrolysis excludes the role of “green” hydrogen as the industrial energy source. Water electrolysis is mainly considered as excessive electricity accumulation produced from renewables (wind, solar) in hydrogen with further use in fuel cells for electricity return or in the chemical industry.

Steam methane reforming (SMR) with carbon dioxide capture (blue hydrogen) or without (grey hydrogen) is the most energy-effective hydrogen production way [29]. Unfortunately, the CO_2 capture technology in the SMR process is not yet well commercialised. Thus, the majority of existing generation facilities produce “grey” hydrogen with the CO_2 emission through the endothermic chemical reaction taking place at high pressure and temperature:

$$CH_4 + 2H_2O = 4H_2 + CO_2 \tag{9}$$

The process allows the generation of 4 moles of H_2 on each mole of emitted CO_2. Additional CO_2 emission comes from the heat and power supply of the reaction. The average efficiency of SMR can be taken as 80% on the high heat value basis [30, 31]. Based on SMR efficiency, the relation between yielded hydrogen and consumed methane can be approximately defined as:

$$d_{CH4} = \frac{1}{\eta_r} \cdot \frac{HHV_{H2}}{HHV_{CH4}} = \frac{1}{0.8} \cdot \frac{141.7\ MJ/kg}{55.5\ MJ/kg} = 3.19\ \text{kgCH}_4\text{/kgH}_2 \tag{10}$$

In turn, CO_2 emission per released H_2:

$$d_{CO2} = d_{CH4} \cdot \frac{m_{CO2}}{m_{CH4}} = 3.19 \cdot \frac{44}{16} = 8.77\ \text{kgCO}_2\text{/kgH}_2 \tag{11}$$

The electrical efficiency of hydrogen fuel cells ranges from 40 to 60 %. On average, 1 kg of hydrogen in a fuel cell can produce:

$$W = \eta_{fc} HHV_{H2} = 0.5 \cdot 141.7 \frac{MJ}{kg} = 19.7\ \text{kWh/kgH}_2 \tag{12}$$

Assuming that fuel cell vehicle (FCV) does not differ much from EV with an average efficiency of 0.16 kWh/km, the CO_2 emission per 1 km of FCV equals 8.77·0.16/19.7=**0.071 kgCO$_2$/km**. So, FCV seems more effective than EVs in CO_2 emission reduction.

The thermal efficiency of an ideal Otto Cycle of ICE depends on the compression ratio and heat capacity ratio of combustion products. The flame temperature of hydrogen and gasoline in the atmosphere is similar [22], as well as the heat capacity ratio of combustion products (H_2O and CO_2, both triatomic gases). Thus, the efficiency of hydrogen ICE should not differ much from gasoline ones. In [32], the achievable efficiency of hydrogen ICE is mentioned at a level of 40%. Thus, at the first approximation, the hydrogen consumption of ICE per km can be evaluated as follows:

$$G_{H2} = \sigma \rho_f \frac{HHV_f}{HHV_{H2}} = 8 \frac{L}{100km} \cdot 0.74 \frac{kg}{L} \cdot \frac{46.4 \frac{MJ}{kg}}{141.7 \frac{MJ}{kg}} = 1.94\ \frac{kgH2}{100\ km} \tag{13}$$

Hence, hydrogen as ICE fuel will lead to CO_2 emission on a level of 1.94·8.77=**17.0 kgCO$_2$/100km** or **0.17 kgCO$_2$/km**. Thus, simple estimations show that "grey" hydrogen ICE will not support CO_2 emission in transport. However, with further improvement in steam methane reforming technology and ICE efficiency on a level of the thermodynamic cycle and by careful recuperation of exhausted thermal energy, for instance, with two-phase loops and ammonia as a hydrogen carrier [33-35], the hydrogen ICE could remain as an option of CO_2 emission reduction in transport.

3 Conclusions

The main goals and motivation of the proposed brief analysis deal with presenting a simple and transparent way of the global CO_2 emission trend in transport based on a thermodynamic approach. With the majority of various studies breaking down to minor details of emissions in separate countries, a clear quantitative understanding of the factors impacting global CO_2 emission was essential, at least to the author of the current activity. In particular, it has been clearly shown that, at the moment, the new EV does not comply with the global goals of CO_2 emission reduction down to 95 gCO$_2$/km. Broad adoption of EVs instead of ICE transport demands substantial rebuilding of the power generation industry, including the distribution system. With the current trend, electricity produced from renewables does not match the future EVs demands. Therefore, more attention must be paid to improving the efficiency of fossil-burning power plants. In particular, intensive electricity generation from natural gas in the combined thermodynamic cycle is vital to compensate for future EV demand with an acceptable level of CO_2 emission. At the same time, adopting fuel cell vehicles, even with the “grey” hydrogen, is a more effective way of CO_2 emission reduction as compared to EVs.

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