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Comparative analysis of powertrains based on Well-to-Wheel efficiency metrics

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Abstract: The transition towards sustainable transportation requires a deep understanding of how different powertrain technologies impact the environment. This paper presents a literature-based well-to-wheel (WTW) assessment comparing internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) passenger cars, integrating well-to-tank (WTT) and tank-to-wheel (TTW) metrics from recent sources. The WTT phase evaluates energy extraction, processing and distribution, while the TTW phase assesses operational energy consumption, emissions, and efficiency.
Results reveal significant variations in environmental performance across vehicle types. ICEVs demonstrate higher emissions and energy consumption during operation, whereas BEVs and FCEVs exhibit zero tailpipe emissions during this phase. HEVs and PHEVs present intermediate values, combining conventional and electric propulsion benefits. Additionally, this study examines the impact of several energy production methods on the environmental footprint of electric vehicles (EVs).
In conclusion, adopting a comprehensive WTW framework that considers both upstream and operational stages is essential for evidence-based decisions and advancing the move toward more sustainable mobility systems.

Keywords: Well-to-Wheel analysis, Internal combustion engine vehicles, Hybrid electric vehicles, Plug-in hybrid electric vehicles, Battery electric vehicles, Fuel cell electric vehicles, Greenhouse gas emissions, Energy efficiency

1. Introduction

1.1. Scope and objective

The current paper outlines the environmental performance of modern vehicle powertrain solutions using the WTW methodology. As global decarbonisation

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targets become increasingly stringent, every sector, including transport, must contribute to reducing greenhouse gas (GHG) emissions. The WTW methodology was selected because it enables the evaluation of both conventional and EVs from an efficiency and emissions perspective, as it considers not only tailpipe emissions, like conventional assessments, but also the upstream energy processes such as fuel production and distribution along with the emissions associated with these processes. This study primarily aims to emphasize the differences between different vehicle types in a comparable manner by using the WTW metrics, providing a comprehensive review.

1.2. Context and motivation

Accounting for close to one quarter of GHG emissions within EU in 2021, the transport industry represents a key emitter. Of these, passenger cars are responsible for more than half. While many sectors have reduced their emissions over the last 30 years, transport related emissions have continued to rise, increasing by 16% between 1990 and 2021 [24]. As the Climate Law [23] adopted by the EU in 2021 aims for a 55% or greater mitigation in GHG emissions relative to 1990 levels, the ongoing increase in transport-sector emissions is alarming [59]. These trends underscore the need for comprehensive lifecycle analysis tools for an accurate comparison between different powertrain technologies.

2. The Well-to-Wheel framework

The WTW framework is broadly utilized in the transport sector to quantify both energy demand and GHG emissions throughout the vehicle lifecycle. This methodology integrates two phases, the WTT, which includes extraction, processing, and fuel distribution, and the TTW, covering energy consumption as well as the emissions produced during vehicle operation. In conclusion, using this methodology enables the evaluation of energy use and associated emissions emitted per unit distance covered, thereby enabling comparison between different powertrain types [52].

2.1. System boundaries, limitations and assumptions

Although the WTW methodology is based on a Life Cycle Assessment, its boundaries in this methodology are carefully defined, focusing solely on energy production, distribution and utilization in vehicles, not considering GHG emissions from processes like vehicle manufacturing, maintenance or infrastructure needed. While this limits the completeness of the environmental footprint analysis, it improves consistency across different powertrain types and fuel sources. One of the main limitations or assumptions present in these types of studies is the lack of spatial precision. For example, the electricity mixes are usually averaged at a national level, providing an indication of the carbon intensity across an entire country, without capturing regional variations [52].

3. Well-to-Tank analysis: energy supply chains

3.1. Fossil fuels

For fossil fuels, the WTT stage includes extracting crude oil or natural gas, processing and transporting them, and refining and distributing the resulting fuel [68]. Petroleum based fuels (gasoline and diesel) have a WTT efficiency of about 80–90% [53], while for Compressed Natural Gas (CNG) and Liquefied Petroleum Gas (LPG), the efficiencies are 75–88% [54], respectively 88–94% [21]. From an emissions perspective, the average emissions for gasoline and diesel are 12.5 and 14.2 g CO_2/MJ, while for CNG EU-mix is 8.4 g CO_2/MJ (increasing to 14 g CO_2/MJ if transported over 4000 km or to 21.7 g CO_2/MJ if transported over 7000 km), and 15.6 g CO_2/MJ forLPG [49], [64]. There are also variations in the GHG emissions of the same fuel depending on the region, as it can be observed in table 1:

Table 1. WTT GHG emissions of fossil fuels across different zones [6]

World zone	**Fuel type**	**Biofuel share, %**	**WTT GHG emissions, g CO_2/MJ**	
			2021	2030
Europe	Gasoline	5	21.5	21.4
	Diesel	7	27.4	26.7
	Natural gas	3	16.5	16.5
USA	Gasoline	10	22.2	22.2
China	Gasoline	5	21.8	21.8
	Gasoline	5–20	20.5	20.2
India	Diesel	0–5	21.8	21.7
	Natural gas	0–10	19.2	19.6

Within the complete WTW cycle, the share of the WTT phase to GHG emissions for fossil fuels, according to standards EN16258 and ISO14083 is shown in figure 1 [58].

3.2 Electricity

The GHG emissions included in the fuel–cycle analysis account for the generation and transmissions of electricity, plus the distribution and charging losses [6]. Since BEVs have no tailpipe emissions, the carbon footprint of their lifecycle depends solely on the upstream processes. Therefore, both the efficiency and GHG emissions associated with electricity generation must be carefully assessed. This subsection examines variations in efficiency and emissions from different fuels or technologies used for electricity production. Additionally, it highlights the regional differences in terms of emissions, this being due to the different energy mixes worldwide.

Both efficiency and emissions from electrical energy generation vary significantly depending on the energy source or technology employed, as highlighted in table 2.

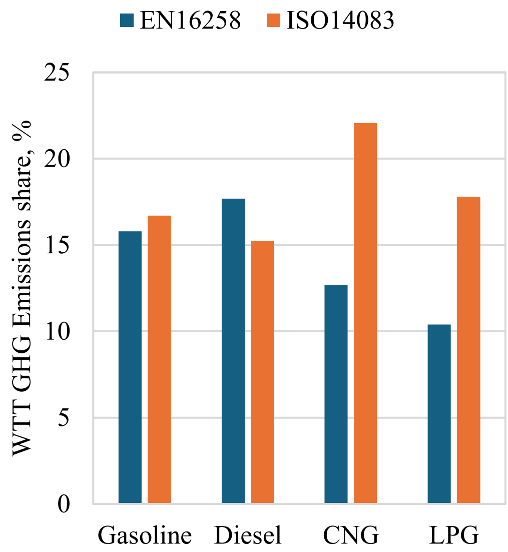

Fig. 1. WTT GHG Emissions share [58]

Table. 2. Electricity generation efficiency and GHG emission

Energy source, technology	Efficiency, %	GHG Emissions, g CO_2/MJ
Coal, subcritical	34–40 [104]	≥244 [3]
Coal, supercritical	42–45 [104]	222–244 [3]
Coal, ultra-supercritical	47 [70]	206–222 [3]
Natural gas, simple cycle	33 [20]	222 [67]
Natural gas, combined cycle	59.8 [1]	161 [67]
Hydroelectric	90 [60]	6.7 [83]
Wind	25–45 [30]	1.9–10.6 [86]
Solar, photovoltaic	27.4 [28]	7.8–27.8 [86]
Biomass	30 [74]	63.9 [83]

Also, due to different electrical grids, in 2024, emissions associated with electricity generation were approximately 155.6, 106.7 and 59.2 g CO_2/MJ in China, the USA, and the EU, respectively. These differences result from the fact that, for example, China's coal-based electricity accounted for 58%, while USA's electricity generated from fossil fuels had a share of 58% (mostly based on gas). In the EU the renewable sources increased their share to 47%, from 34% in 2019, with only 29% of electricity generated based on fossil fuels in 2024 [33], [81].

3.3 Hydrogen

Efficiency and emissions can significantly vary based on the hydrogen generation pathway [8]. Although hydrogen production pathways are usually divided into more categories, the most important ones are gray hydrogen, meaning that the H_2 is usually generated with natural gas in the Steam Methane Reforming (SMR) process, without Carbon Capture and Storage (CCS), blue hydrogen, which implies using also SMR, but with CCS, and green hydrogen generated using renewable energy, typically via water electrolysis [99].

In terms of efficiency, the SMR technology used for producing gray hydrogen ranges between 74–85% [75], while using CCS techniques reduces the efficiency by 1% (from 76.6% to 75.6%) [12], while the electrolysis process used for producing green hydrogen is situated at aproximately 60% [44].

As expected, the gray hydrogen exhibits the greatest carbon footprint, succeeded by blue and green hydrogen. According to ICCT, even though green hydrogen could reach almost zero emissions, if the EU grid is used for electrolysis instead of renewable sources, the result is a carbon intensive fuel that may not reduce the emissions, compared to fossilfuels [105]. Literature reports a wide variation in carbon intensity values for hydrogen production. For example, for grey hydrogen, Patel [77] indicated emissions of 13.9 kg $CO_{2\text{-eq}}$/kg H_2 for a LNG route from the USA and 12.3 for a pipeline route from Russia, while Henriksen [40] and Salkuyeh [55] reported values of 10.4 and 11.5 kg $CO_{2\text{-eq}}$/kg H_2. For blue hydrogen, Patel [77] reported emissions of 7.6 kg $CO_{2\text{-eq}}$/kg H_2 for the pipeline route and 9.3 kg $CO_{2\text{-eq}}$/kg H_2 for the LNG route. In contrast, Maniscalco [66] highlighted a mean value of 6.02 kg $CO_{2\text{-eq}}$/kg H_2 according to analyses from various research works. Green hydrogen, characterized by the lowest emissions, outputs, according to Patel [77], 0.6 kg $CO_{2\text{-eq}}$/kg H_2 when using wind energy and 2.5 kg $CO_{2\text{-eq}}$/kg H_2 when using solar energy. Kim [57] reported values between0.11 and 1 kg $CO_{2\text{-eq}}$/kg H_2 for hydroelectric or onshore wind power, these being the lowest emission sources for green hydrogen.

To facilitate comparison with fossil fuels, figure 2 highlights the average emission values derived from the individual values presented before.

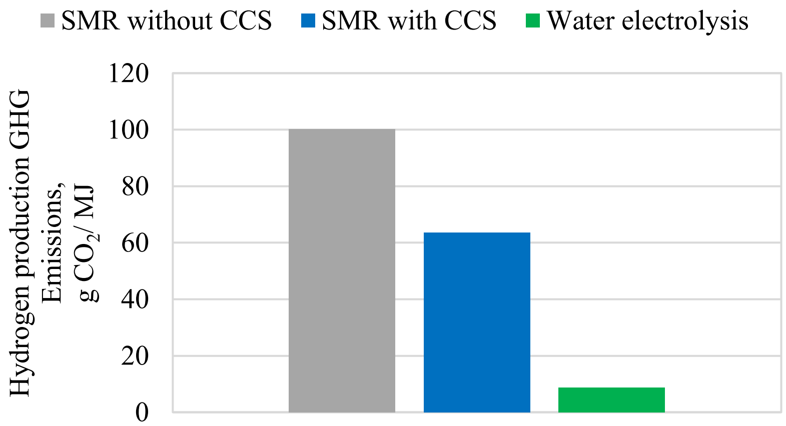

Fig. 2. Hydrogen production GHG Emissions [40], [55], [57], [66], [77]

3.4. Biofuels and synthetic fuels

To analyze the upstream emissions of biofuels one must take into consideration crop cultivation or waste collection, transportation, fuel production and distribution. Additionally, emissions related to direct-land use change may also be taken into account [68]. Although biofuels could help reduce dependency on petroleum-based fuels, the net carbon reduction associated with liquid biofuels so far have shown to be limited. In some cases, biofuels might even increase the net carbon emissions [26]. Furthermore, compared to fossil fuels, the WTT phase of biofuels is significantly more important than the TTW phase. Biofuels are produced from different agricultural feedstock, thus requiring accounting of both feedstock variations and regional agricultural characteristics [72]. Both efficiency and emissions for ethanol and biodiesel are presented in table 3, with several feedstock variations:

Table. 3. Biofuels production efficiency and emissions

Fuel	Feedstock	Conversion efficiency, %	GHG Emissions, g CO_2/MJ
Ethanol	Corn	93.2 [14]	57 [14]
Ethanol	Sugar cane	63.3 [62]	35.2 [62]
Ethanol	Wheat	93 [97]	63 [6]
Biodiesel	Palm Oil	61.82 [69]	36 [6]
Biodiesel	Mixed Oils	98 [7]	21 – 31 [101]
Biodiesel	Soybean oil	95 [103]	58 [6]

Synthetic fuels, or e-fuels, are an option to reach carbon neutrality while operating the already existing fleet. The synthesis plants for these kinds of fuels take a long time to set up, but after that, they can help with the GHG emissions reduction [29]. Similarly to biofuels production, e-fuels production could negatively impact the environment if the energy source is not carefully assessed. For their production to be CO_2 neutral, it should be done only when there is excess renewable electricity. In any other scenario, the production of e-fuels generates CO_2 emissions [76].

The procedure for e-fuels production is often called Power-to-X (PtX), and it all starts with water electrolysis, converting electrical energy to e-hydrogen, which will further be used for the other e-fuels production [76]. The PtX processes efficiency and emissions may differ from fuel to fuel, as presented in table 4:

Table. 4. Efficiency and emissions generated by e-fuels production

Fuel	Power-to-fuel efficiency, %	GHG Emissions, g CO_2/MJ[a]
e-Hydrogen (700 bar)	75 [87]	139 [34]
e-Hydrogen (liquid)	49.3–57.9 [11]	139 [34]
e-Methanol	48–61 [87]	176 [34]
e-Diesel	42–51 [87]	190 [34]
e-Ammonia	55.7–64.3 [11]	173 [34]
e-DME	55 [76]	174 [34]
e-Methane (220 bar)	50 [76]	180 [34]
e-Methane (liquid)	49 [76]	180 [34]

[a]Assuming the average carbon intensity from Ireland in 2018 (375 gCO2/kWh. If only renewable sources are used, e-fuels production can be almost carbon free

4. Tank-to-Wheel analysis: use-phase efficiency and emissions

4.1. Internal Combustion Engine Vehicles

Under normal driving conditions, the TTW efficiency of ICEVs usually varies between 14 and 42% with values at the higher end achieved only by diesel engines. In other words, between 58% and 86% of the energy stored in the tank is dissipated through heat and friction [2]. In urban conditions, ICEVs tend to have lower efficiencies due to factors like idling, approximately 20%, while on the highway they may reach ~30% (gasoline) [27].

In terms of tailpipe CO_2 emissions of ICEVs, according to EPA (USA Environmental Protection Agency), using a liter of gasoline produces 2.34 kg CO_2, while 1 liter of diesel emits 2.68 kg CO_2, the difference resulting from the higher carbon content of diesel [22]. EPA has averaged 4.6 metric tons of CO_2 anually for a passenger car, assuming ~18500 km covered per year, which means 248 g CO_2/km [22]. In comparison, in Europe, using the WLTP cycle, passenger cars have emitted in 2021, an average value of 115 g CO_2/km. The target for that year was 119 g CO_2/km, while for the 2025-2029 period the target will be 15% less [47].
A comparison between the projection made by JRC for the 2025 emissions, under the WLTP cycle, and the Real Driving Emissions (RDE) reported by other studies is presented in figure 3:

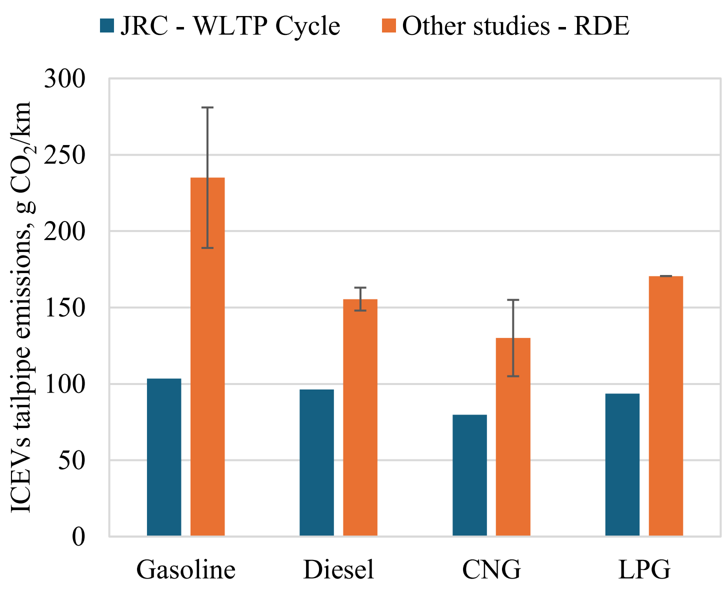

Fig. 3. ICEVs emissions, WLTP projection by JRC vs RDE [5], [18], [31], [52], [100]

Several technological improvements were introduced in ICEVs to enhance their efficiency and mitigate their emissions. Among these, advanced combustion techniques like RCCI or HCCI are presenting improvements for ICEVs [82]. RCCI (Reactivity Controlled Compression Ignition) means that two fuels are being used (a less reactive fuel and a highly reactive fuel), while HCCI (Homogeneous Charge Compression Ignition) refers to the fact that the charge is homogeneous before combustion
begins [15], [65]. According to Sadeq's [82] review paper, both HCCI and RCCI can exceed 50% efficiency while also reducing reducing NO_x emissions.

4.2. Hybrid Electric Vehicles

HEVs are hybrid vehicles which cannot be externally charged [48]. In terms of efficiency, they present a clear advantage over conventional vehicles, achieving almost double the efficiency according to Lohse-Busch [63], with values of 45% compared to 23% for the ICEVs on the EPA cycle.
With respect to fuel use and emission levels, Charadsuksawat [10] compared a HEVs to ICEVs various driving conditions, reporting fuel consumption reductions of 56% in urban driving conditions, 46% in suburban and 26% on highways, confirmed by other studies, which also highlighted a decrease of 40–60% in fuel consumption [85] or 35% in HEVs emissions [88]. This fact is also highlighted by other studies, as presented in figure 4:

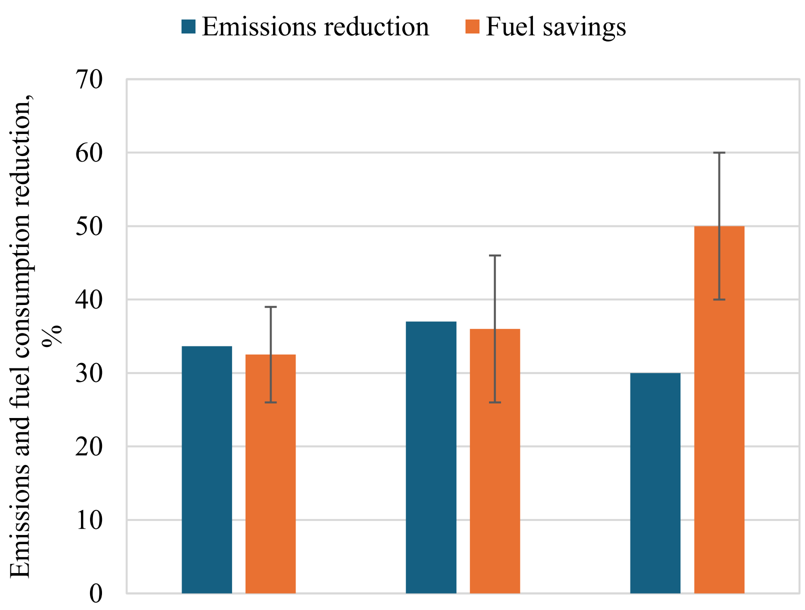

Fig. 4. Emissions or fuel consumption reduction, HEVs vs ICEVs [4], [42], [85], [98], [106]

Several technological advancements were made for HEVs like the introduction of 48V mild hybridization which further enables electrically heated catalysts and electrical turbochargers [17]. According to Isenstadt [51], the primary potential for enhancing HEV's efficiency is integrating large electric motors. These motors are intended for low-load, low-speed operations, ensuring the internal combustion engine maintains maximum efficiency.

4.3. Plug-In Hybrid Electric Vehicles

The energy sources used in PHEVs powertrains usually operate separately. Unlike HEVs, PHEVs can be externally charged, and they can also function in an electric only mode, resulting in both zero tailpipe emissions and high efficiency during this phase [48]. As long as they are in the electric mode, PHEVs have a similar electricity consumption to the BEVs. As expected, the efficiency of PHEVs is higher than HEVs, but it can also greatly vary depending on the electric only mode share [39].

Some studies show that PHEVs could achieve a fuel consumption reduction of about 50% compared to ICEVs [98]. However, other research suggest that, in Europe, the actual fuel consumption of PHEVs can be between 3 and 5 times higher than the values reported by the WLTP test, as a result of the small electric driving share.

For example, in [48], the average fuel consumption was three times higher than WLTP values for personal vehicles and five times higher for company vehicles, in real–life world driving conditions. Compared to HEVs, PHEVs can still present a reduction in emissions – Pielecha's [78] study found a reduction of 3%, 2%, 25% and 13% in the emissions of CO_2, CO, NO_x and HC, while the fuel consumption was 3% lower, under WLTC conditions. Under real driving conditions, the differences were significant, PHEVs having 30% lower CO_2 emissions and 50% NO_x emissions.

As PHEVs represent the bridge to BEVs, both follow the same patterns. For example, in the USA, PHEV's Li-Ion battery average capacity increased from 11.7 kWh in 2012 to 14.6 in 2021, while BEV's Li-Ion battery average capacity also increased from 33.6 kWh in 2012 to 73 kWh in 2021 [32]. Along with this increase in battery capacity, the possible electric only mode also increases, with some modern PHEVs reaching a range of up to 100 km [16]. Similarly to HEVs, in order to let the internal combustion engine operate at its peak efficiency, many PHEVs use it as a range extender [51].

4.4. Battery Electric Vehicles

As it can be observed in figure 5, BEVs TTW efficiency is the highest of all powertrain technologies. According to the data presented below, BEVs average efficiency would be at 76% with a peak efficiency of 90%.

Often called zero emission vehicles, BEVs and FCEVs present the feature of having no tailpipe emissions [61]. While the statement of Zero-Emission Vehicles is true only from a TTW perspective, they bring some advantages to the table like local noise reduction and air quality improvement, but they also have their limitations when dealing with environmental issues like climate change [35]. In terms WTW emissions, Vieira's [95] study shows that BEVs consistently achieved lower emissions compared to ICEVs in small, medium and large vehicle segments. The authors took into consideration multiple energy grids, and BEVs showed an improvement even when a carbon intensive energy grid is used. It is worth mentioning that this study is an LCA which also includes battery manufacturing which is well known to be a carbon intensive process. Other LCA studies confirm these findings, BEVs lifecycle emissions being 69% less than ICEVs for a medium sized car in 2022, using EU's average grid, with the potential to reach a 78% reduction by 2030 [25].

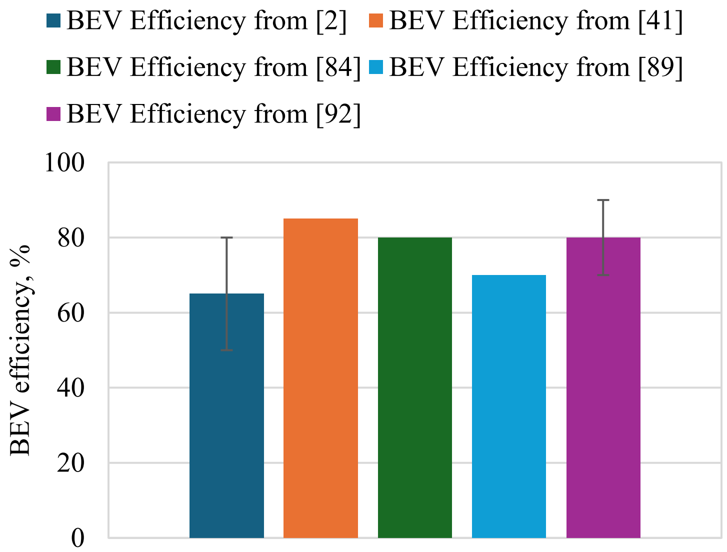

Fig. 5. BEVs efficiency [2], [41], [84], [89], [92]

As mentioned in the previous subsection, BEV's battery average capacity has continuously increased, and, consequently, the average range a BEV can travel has also grown from an average of 200 km in 2015, to 350 km in 2020 [50]. Along with this, the latest developments in BEVs are related to different battery chemistries, for example solid-state or lithium-sulfur batteries [94], using 800V systems [9] or more effective thermal management systems [90].

4.5. Fuel Cell Electric Vehicles

FCEVs are EVs that generate the electricity on-board, with water vapor as the only byproduct [37]. A fuel cell system efficiency usually reaches up to 50–60% [52].

In agreement with the efficiency reported before, Lohse–Buch [63] reported a maximum efficiency of 63.7% of the fuel cell, while the FCEV had an efficiency of 62%, while Heid reported a TTW vehicle efficiency of 50% for FCEVs [38]. Even though both FCEVs and BEVs are EVs, there are some differences. For example, a high power demand will drop the efficiency of the fuel cell from 50 to below 40% [71]. Due to this reason, FCEVs also have a battery that is used solely for peak power demand and regenerative braking energy storage [73]. As it can be observed in figure 6, FCEVs tend to have a higher efficiency than ICEVs but lower than BEVs:

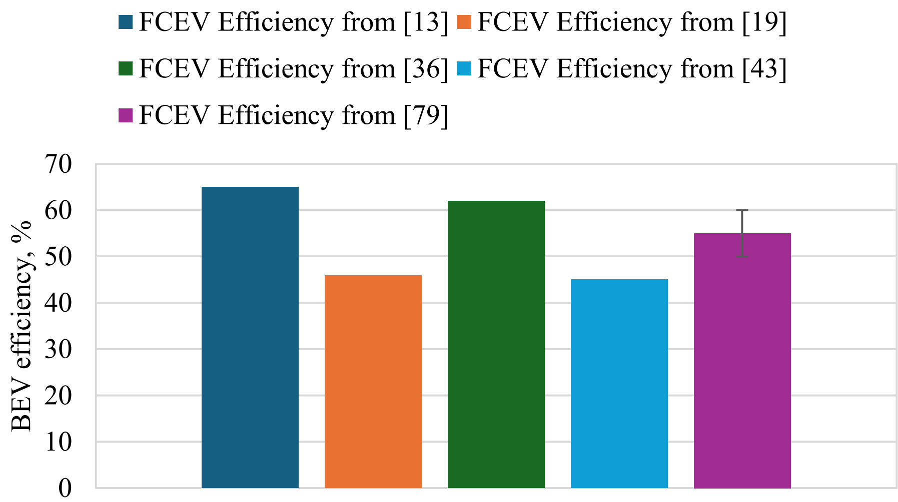

Fig. 6. FCEVs efficiency [13], [19], [36], [43], [79]

Recent developments were made in multiple areas of FCEVs including improved cold start capabilities to temperatures as low as –30°C, reduced platinum usage and increased durability from 5,000 to 20,000 hours [80]. As claimed by the manufacturer, another advancement in the FCEVs is the air purification system introduced by Toyota in the new Mirai model, designed to capture fine particles as small as $PM_{2.5}$, going from 'zero emissions to minus emissions', as the manufacturer describes it. Toyota also improved the Mirai's range, increasing from approximately 650 km to 850 km in the new model. Additionally, the output density has increased by 64%, reaching 5.4 kW/L [93].

5. Well-to-Wheel: overview and assessment

Comparing different vehicle types through the WTW framework allows the assessment of different powertrains from the perspective of energy use and total lifecycle emissions.

To evaluate the metrics mentioned before, a representative vehicle for each powertrain category (compact SUVs) was selected, as summarized in table 5, all data being sourced from manufacturers.

Table. 5. Selected vehicles parameters

Vehicle model	Powertrain type	Energy consumption (WLTP combined)	Energy source capacity
Hyundai Tucson 1.6T 2025 [45]	ICEV	6.8 l/100 km	54 l
Hyundai Tucson Hybrid 1.6T HEV 2025 [45]	HEV	6.3 l/100km	54 l + 1.49 kWh
Kia Sporage1.6T Plug-In Hybrid 2025 [56]	PHEV	1.23 l/100km + 18.89 kWh/100km	42 l + 13.8 kWh
Wolkswagen ID.4 Pro 4MOTION 2022 [96]	BEV	17 kWh/100km	77 kWh
Hyundai NEXO 2025 [46]	FCEV	0.95 kg H_2/100km	6.33 kg H_2

Assuming a lower heating value of 32 MJ/L for gasoline and 120 MJ/kg for hydrogen, figure 7 highlights the energy consumption per distance traveled for each powertrain:

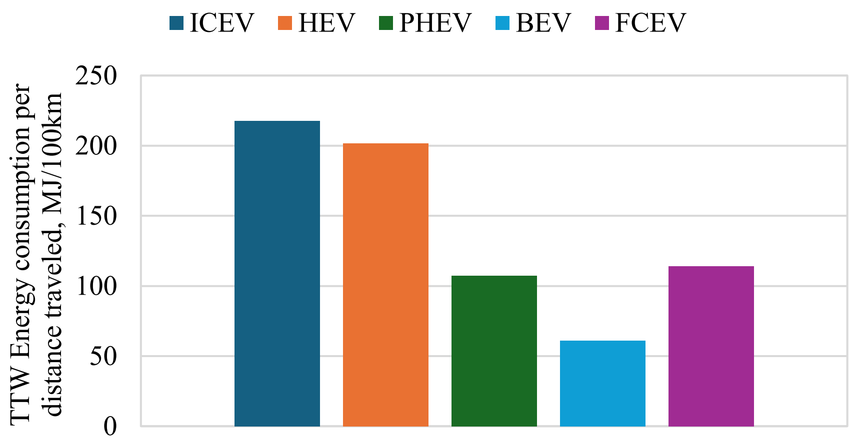

Fig. 7. TTW energy consumption per distance traveled

To estimate the WTW energy demand, the TTW consumption values present before were divided by the corresponding WTT efficiencies (minimum and maximum values, as shown in section 3). For PHEV, a 50% electric drive share was assumed. Based on the mean values reported in figure 8 and the data presented in section 3, the GHG emissions for each powertrain type are presented in figure 9. For gasoline CO_2 WTW emissions, other than the WTT factor, the TTW combustion factor of 2.307 kg CO_2/L reported by The Climate Registry was also used [91]. As gasoline WTT emissions exhibit little variation, a mean value was used for ICEV and HEV.

For PHEV and BEV, the bars in figure 9 represent GHG emissions based on the USA's 2024 electricity grid, while the error bars indicate the variation when using China's and the EU's grids, with the highest values corresponding to China and the lower to the EU. For FCEV the calculation was done take into consideration gray hydrogen, as it is the most spreaded worldwide currently.

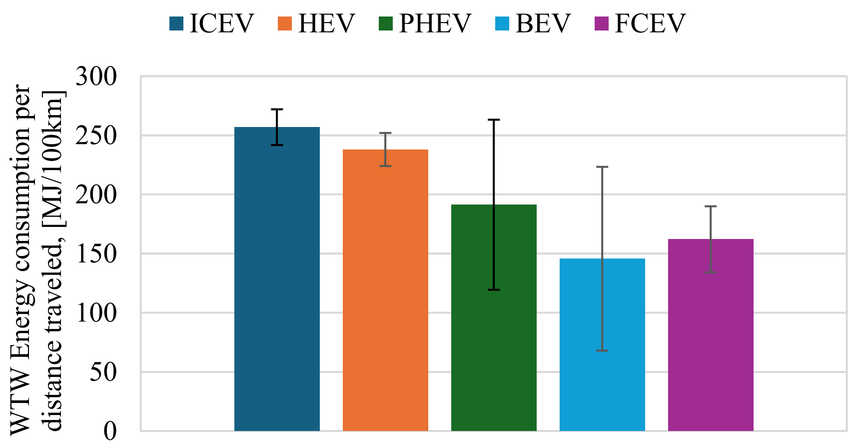

Fig. 8. WTW energy demand per distance traveled

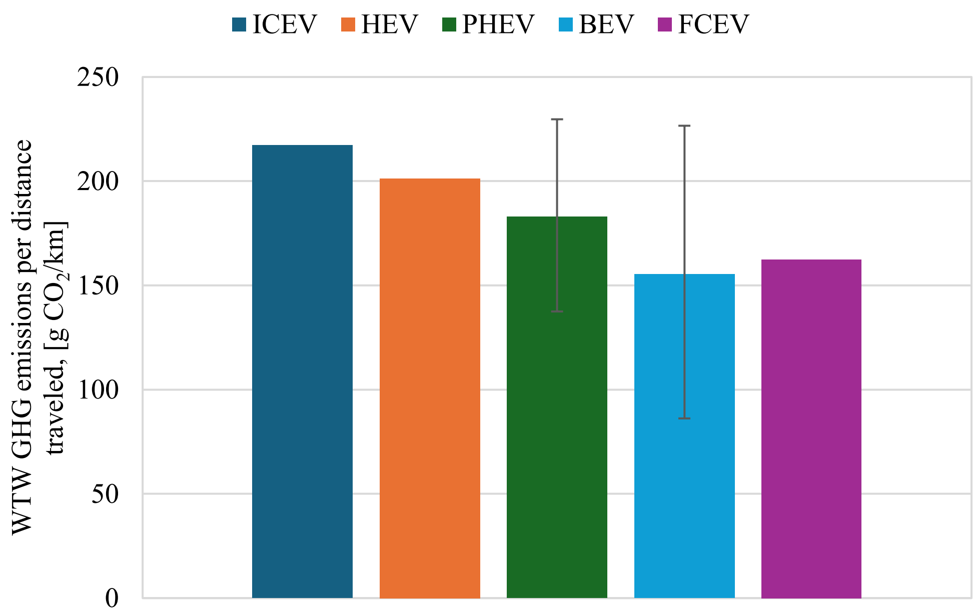

Fig. 9. GHG Emissions per distance traveled

As can be observed, in terms of TTW energy use, BEVs are clearly the most efficient, followed by FCEVs, PHEVs, HEVs and ICEVs. When also considering the WTT phase, BEVs and PHEVs exhibit significant variations due to the variability in electricity production efficiency, whereas FCEVs present lower variations. ICEVs and HEVs exhibit the least variation owing to the maturity of their upstream processes.

Also, in terms of emissions, PHEVs and BEVs exhibit substantial variability, as the electricity grid mix strongly influences their environmental footprint (with China generating more than two and a half times the carbon emissions from electricity compared to EU in 2024). For the purpose of emission calculations, only gray hydrogen was considered, since low-emission hydrogen accounted for under 1% of worldwide hydrogen production in 2023 [102].

6. Conclusions and potential development directions

From a WTT perspective, fossil fuels have the highest efficiency under normal conditions, with other fuels achieving high efficiencies only under specific conditions (certain feedstocks or energy sources used). The emissions generated by fossil fuels production present minor variations, compared to the other fuels, which strongly depend on feedstock (biofuels) or energy sources/ technologies used for generating electricity (also the case of e-fuels and green hydrogen if non-renewable sources are used).

Gray hydrogen also presents high emissions during its generation due to the fossil fuels use, but these can be reduced if CCS technologies are employed.

In terms of TTW analysis, BEVs have the highest efficiency, followed by FCEVs, PHEVs, HEVs and ICEVs. With respect to emissions, ICEVs present the highest emissions, followed by HEVs and PHEVs, while BEVs and FCEVs exhibit no tailpipe emissions.

In terms of average overall WTW energy consumption, when considering average values, the most effective are BEVs, followed by FCEVs, PHEVs, HEVs and ICEVs. BEVs can also be energy-intensive if the energy source used for electricity generation is not carefully chosen. On the other hand, regarding GHG emissions, BEVs exhibit the lowest emissions, succeeded by FCEVs and PHEVs, and then HEVs and ICEVs after. The order may change if very carbon-intensive processes are used to generate electricity, the emissions of PHEVs and BEVs may even exceed those of ICEVs. In conclusion, this paper highlights the importance of evaluating vehicles across their entire lifecycle, as significant differences can appear when upstream processes are also considered.

Potential development directions include the assessment of technology maturity and readiness, the analysis of regional variations in electrical grid at a regional level, and the integration of additional parameters like cost and local pollution for each powertrain type.

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