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Battery electric vehicles and fuel cell electric vehicles, an analysis of alternative powertrains as a mean to decarbonise the transport sector

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ABSTRACT

There is a debate among members of the scientific community concerning the transition to renewable-energy-operated modes of transportation to reduce carbon emissions and address the impact of climate change. This paper studies the individual strengths and concerns that the adoption of the alternative powertrains of battery electric vehicles and fuel cell electric vehicles possess. The analysis is mostly done from a qualitative point of view that includes the current state of the market, infrastructure, raw-materials mining issues, powertrain cost analysis, energy-efficiency analysis and technology-specific advantages and disadvantages. The study offers an insight into how, despite the differences, both technologies can easily complement each other. The study also addresses briefly the status quo of the internal combustion engine vehicle as a means to offer a wider perspective and contrasting effect on the current situation of alternative powertrains. The conclusions highlight the importance of embracing the strengths of all the different powertrains as an approach to overcome their weaknesses or limitations and leave aside the one-solution-fits-all narrative. Further development of vehicle technologies pushes civilization one step closer to independence from fossil fuels and averting climate change.

1. Introduction

The changes occurring to climate patterns and the acceleration of global temperature trends during the past decades continue to convince an increasing number of individuals of the necessity to take additional and stricter measures to decelerate and reverse global warming. Because of this, members of the international community at the 2019 UN Climate Action Summit in Madrid established a clear goal of cutting down 45 % of the global carbon dioxide (CO_2) emissions by 2030 and a long-term aspiration of a carbon-neutral world by 2050. In the report written by the Secretary-General of the UN, ten priorities for the reduction of CO_2 emissions in 2020 were highlighted, including the securing of more ambitious national commitments from the highest emitter countries and the acceleration of the transition towards 100 % renewable energy sources. [1]. Today, three years after the signing of the agreement, the need for more impactful actions to reduce the effects that human activity has on the climate is still present. This is displayed in the data from [2] and [3] where global CO_2 emissions continue to increase worldwide in line with the growth of Asian economies.

It is relevant to clarify that not only Carbon dioxide (CO_2), but also several other gases contribute to the effects of global warming: Methane (CH_4), Nitrous oxide (N_2O) and several hydrofluorocarbons (commonly grouped and referred to as F-gas). Nonetheless, CO_2 is the most impactful and most common type of greenhouse gas (GHG) emission, representing more than 70 % of the total GHG emissions every year [4]. To simplify matters, the effect of different GHG are often grouped and given as 'CO_2-equivalents' (CO_2.eq) by transforming their given amount into the equivalent amount of CO_2 based on their global warming potential.

When considering the different sources of GHG, the transportation sector represents the second largest CO_2.eq emitter of the last three decades (shown by data of [3;5] and previously pointed out in several other studies like [6,7,8]. Surpassed only by the electricity & heat generation sector, the amount of CO_2 emissions from the transportation sector has increased worldwide by 78 % since 1990. Even in the European Union (here EU-27 plus the United Kingdom) a region that by 2020 had reduced the total GHG emissions by 31 % [9] (compared to the levels of 1990), the transportation sector has, conversely, increased its emissions by almost 23 %. Furthermore, transportation and refrigeration are the only sectors in Europe that did not experience any reduction in GHG emissions from 1990 to 2018 [10].

An in-depth look at the emissions data for the transportation sector in the EU-28 reveals that most of its emissions are coming from the

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Nomenclature

Abbreviations

AC	Alternate current
Bar	100,000 Pascal (Pa);
BEV	Battery Powered Electric Vehicle
Bl	US oil barrel: 158.987 L
CO_2	Carbon Dioxide
Db	Decibel
DC	Direct current
ESOI	Energy Stored over Energy Invested
EU	European Union
EU*	group including the 27 Member States of the European Union, the United Kingdom, Norway, Switzerland and Iceland
EU-28	refers to the 27 Member States of the European union plus the United Kingdom
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas Emissions
GWh	Gigawatt-hour
HRS	Hydrogen Refuelling Station
HVO	Hydrogenated Vegetable Oil
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
K	kelvin
kg	Kilogram ≡ 1,000 g
km	Kilometre ≡ 1,000 m
kt	Kilotonne: 1Mg ≡ 1,000,000 g
t	tonne:1,000 kg
km/h	Kilometre per hour
L	litre
Li-ion	Lithium Ion
LFP	Lithium Iron Phosphate
LMO	Lithium Manganese Oxide
M1	Vehicles carrying passengers with no more than eight seats additional to the driver
NEW	North-West Europe
NCA	Lithium Nickel Cobalt Aluminium
NMC	Lithium Nickel Manganese Cobalt
PHEV	Plug-in Hybrid Electric Vehicle
PEMFC	Proton Exchange Membrane Fuel Cell
TWh	Terawatt-hour
UN	United Nations
USD	United States Dollar
SUV	Sport Utility Vehicle

transportation of passengers (44 %), followed by freight (27 %), aviation (14 %) and shipping (13 %) [11]. These numbers are not that different from those of the rest of the world. Data from the International Energy Agency for 2018 [12] placed the share of transport passenger emissions worldwide as ~44.4 %, freight ~29.6 %, aviation ~11.1 % and shipping ~11.1 %. The similarities in the numbers hint at the importance of decarbonising the transport sector and set the motivation of the present paper.

The alternatives to achieve the reduction of GHG emissions in the transportation sector can be mainly classified into (1) non-technological (e.g. encouraging the use of public transport, promoting walking and bicycle use, banning motorised vehicles, etc.) and (2) technological alternatives that refer to improving or even replacing the state-of-the-art technology powering vehicles (e.g. use of battery electric vehicles (BEV), Plug-in Hybrid Vehicles (PHEV), fuel cell electric vehicles (FCEV), etc.). It is this second alternative that is of interest to the present work.

Numerous studies related to the topic can be found in the literature. For instance, recently Forrest et al. (2020) studied how feasible it is to transition medium and heavy-duty vehicles to BEVs and FCEVs in the State of California (USA) [13]; among their findings, they highlight the potential increase in electricity demand and how the different technologies offer different levels of feasibility that vary as a function of the vehicle type, range and infrastructure. Sinha et al. (2021) made a life cycle assessment for the use of renewable hydrogen for FCEVs in California; they analysed the carbon footprint of both fuel and vehicle, taking into account regional policies and the electricity mix for the north and south of the state [14]; they point out that carbon footprint of both powertrains is comparable and only about half of that of an internal combustion engine vehicle (ICEV) [14]. Breuer et al. (2021) studied how to reduce GHG emissions and air pollution caused by light and heavy-duty vehicles by replacing them with BEVs, FCEVs and catenary trucks; they evaluated the German state of North Rhine-Westphalia through a model considering two scenarios, one for the main regional highways and another for the city of Cologne [15]; their conclusions point out that, taking into account the building-up of the necessary hydrogen infrastructure, FCEVs are more beneficial as they are more flexible and cost-efficient [15]. Rösler et al. (2014) made a direct comparison of the feasibility and convenience of using BEVs and FCEVs tied to strict climate control policies and stable oil prices between 100 and 150 $/bl in Europe for the remainder of the century [16]; their study found that massive introduction of BEV is possible when battery costs are reduced by at least 60 % of their taken reference and will require additional electricity generation while FCEVs may gain massive adoption only during the second half of the century [16]. The comparison of alternative powertrains and other forms to decarbonise the transportation sector also appears in other broader studies that analyse different economic sectors or renewable energy like Akinyemi et al. (2019) [17], Kosai et al (2022) [18] or Staffel et al. (2019) [19]. Yet other types of research focus directly on the potential to improve specific powertrain technologies and how their improvement is linked to the reduction of CO_2-eq like that of Tanç et al (2020) [20].

Considering that the take of recent works is fundamentally based on future projections and quantitative approaches to analysing specific properties of the powertrain technologies in specific regions, it is of interest to the authors of the present work to yield a wider vision of the technological status-quo of BEVs and FCEVs powertrains. The objective of this study is to offer a mostly qualitative-centred general vision of the current state, strengths and concerns that alternative powertrains (namely BEVs and FCEVs) possess; focusing the analysis from the European perspective; considering the countries of the EU-27, the United Kingdom, Norway, Switzerland and Iceland (referred to as EU*). In most cases, special attention will be given to the situation in Germany since it is the place of residence of the authors.

This study is structured as follows: the current state of affairs regarding infrastructure and amount of vehicles for BEVs, FCEVs and ICEVs is presented in Section 2. The fundamental strengths and concerns of each powertrain technology are discussed in Section 3. The cost analysis for the production of different powertrains and how geographic location influences their cost is explored in Section 4. An overview of other transportation areas aside of passenger vehicles is given in Section 5. A short introduction to synthetic fuels and their relevance for the future of transportation is given in Section 6. The conclusions, accompanied by a graphical comparison matrix of the different powertrains are displayed in Section 7.

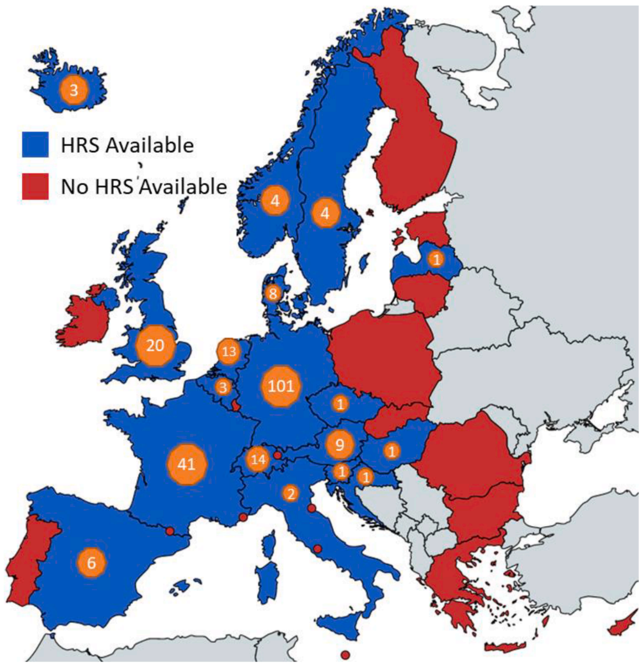

Fig. 1. Distribution of the total number of HRS for the EU* (April 2022). Data from [21]. Map from [24]. [Single Column Image, Colour].

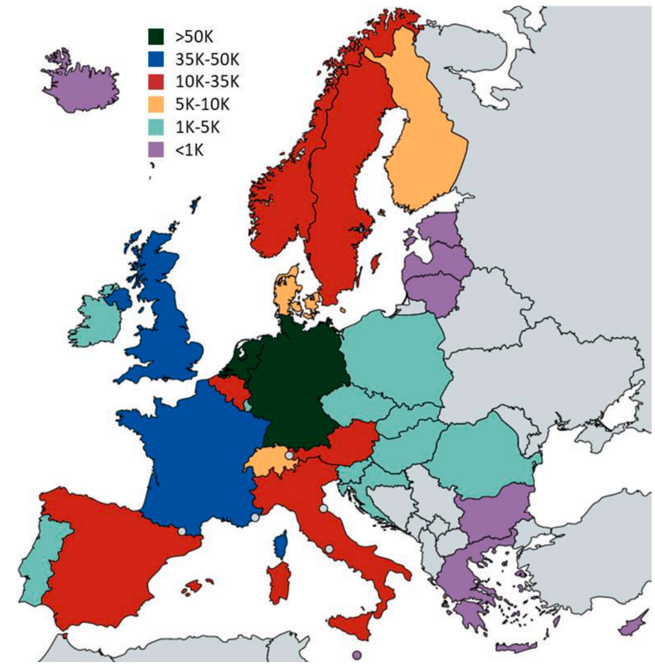

Fig. 3. Distribution of the total number of charging stations in the EU* (end of 2021). Data from the European Alternative Fuels Observatory[22]. Map from [24]. [Single Column Image, Colour].

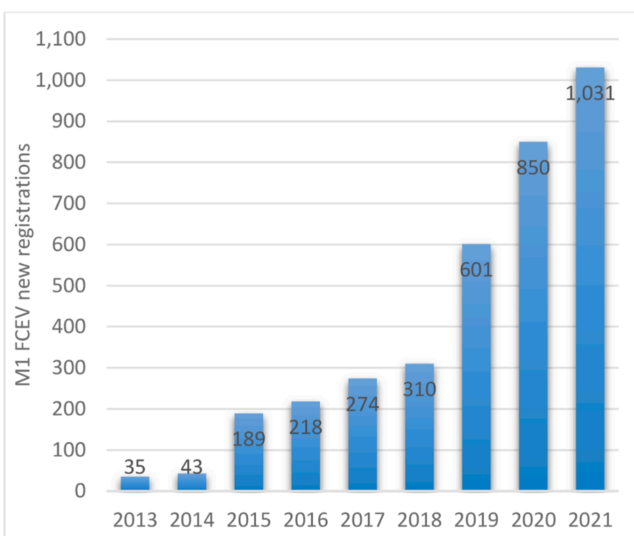

Fig. 2. Total of M1-type FCEV new registrations in the EU*. Data from the European Alternative Fuels Observatory[22]. [Single Column Image, Colour].

2. Current state of affairs regarding infrastructure and number of vehicles

2.1. With regard to FCEVs and present H_2 fuel infrastructure

At the beginning of April 2022, there were 233 operational Hydrogen Refuelling Stations (HRS) installed across the EU* with other 146 HRS in the planning phase [21]. However, of the 31 states of the EU*, only 18 countries possess HRSs in their territories. Most of them (41 %) are currently installed within Germany, while there are still 13 states from the EU* that don't have a single HRS, see Fig. 1.

In the case of vehicles, different reports and different sources display numbers that diverge slightly from each other. Thus, the European Alternative Fuels Observatory reports a total of 2,923 FCEVs (all categories: light-, medium- and heavy-duty trucks, buses and passenger cars) in Europe at the end of 2020 [22] while Samsun et al. (2021) report a total of 2,677 FCEVs for the same period [23]. These numbers are relatively close to each other and account for ~8 % of the total worldwide distribution of FCEVs. Meanwhile Asia (22,736 FCEV) and North America (9,380 FCEV) lead the market with 65 % and 27 %, respectively [23]. In the case of the EU*, considering solely the M1 (not more than eight seats in addition to the driver) type of vehicle, the five leading countries in new registrations of FCEV for 2021 were Germany (498 FCEVs), Netherlands (122 FCEVs), Denmark (76 FCEVs), Poland (74 FCEVs) and France (62 FCEVs)[22].

Looking at the trend in Fig. 2, it is possible to infer that the FCEVs sector has been experiencing sustained growth over the years. Nonetheless, a chicken and egg situation has been slowing down the potential take-off of this technology [25]; there are not enough FCEVs incentivising investors to build new HRSs, while the lack of fuelling infrastructure diminishes the public interest in FCEVs and thus, the interest of manufacturers to justify their development and marketing.

A possible solution is for the pertinent government entities to grant funding stimuli and warrants allowing the different industrial players to increase their market participation. This may translate into market growth, competition and cost reductions that would help with the mass adoption of the technology. Germany is already taking action in this regard through the National Hydrogen and Fuel Cell Technology Innovation Programme (NIP) and its continuation phase (NIP II) [26,27]. Their goal is to accelerate the maturity of the hydrogen market and fuel cell technologies in different areas, taking into account climate protection and sustainable economic development.

It is relevant to highlight the existence of a sort of "*hydrogen colour code*" which classifies hydrogen by assigning a colour that indicates the approach used for hydrogen production and how environmentally friendly it is. Hydrogen produced exclusively through electrolysis using renewable electricity is referred to as green hydrogen, which is ideal to decarbonise the transportation sector since its production is considered free of CO_2-eq emissions [28]. More information on hydrogen colours is presented in Appendix A.

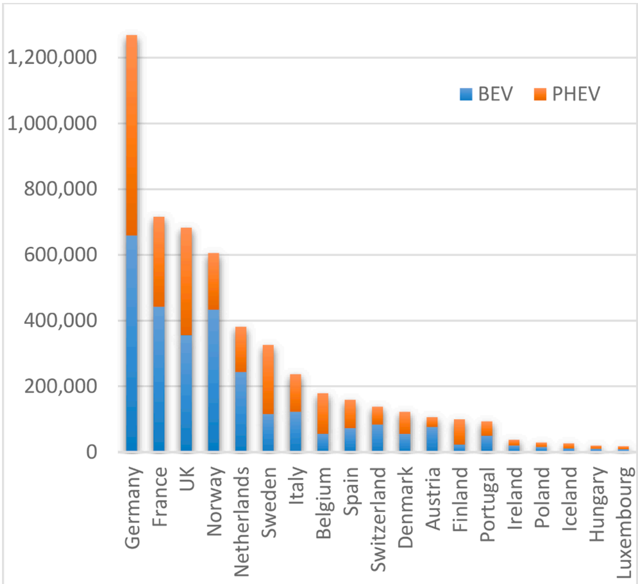

Fig. 4. List of countries in the EU* with at least 10K M1 BEV. Data from the European Alternative Fuels Observatory [22]. [Single Column Image, Colour].

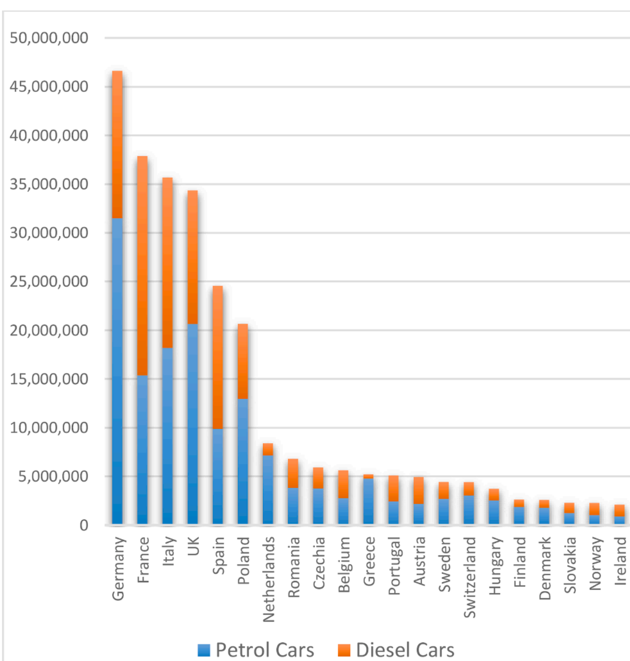

Fig. 5. Fleet of M1-type ICEVs at the end of 2019 for EU* countries with at least 2 million of such vehicles. Data from [33]. [Single Column Image, Colour].

2.2. With regard to BEVs, PHEVs and present charging infrastructure

The current state of affairs of the charging infrastructure for BEV and PHEVs shows a higher level of development than that of the HRS and FCEVs. This sector is experiencing a significant influx of investment as more and more legacy automakers are forced into the transition towards "electromobility" due to tightening regulations associated with the CO_2 emissions of new vehicles [29].

By the end of 2021, there were 373,600 charging stations across the EU* [30]. Nonetheless, 67.2 % of those charging points were comprised in five states, namely Netherlands (24.17 %), Germany (15.9 %), the United Kingdom (10.45 %), France (9.94 %), and Sweden (6.74 %) [22].

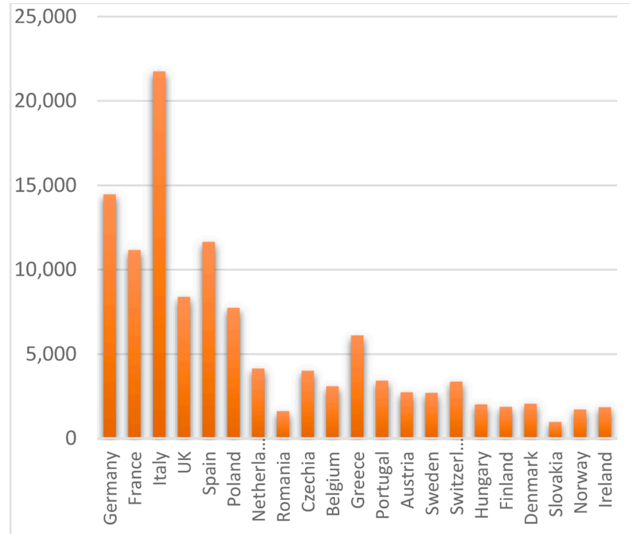

Fig. 6. Total number of petrol stations at the end of 2019 for EU* countries with at least 2 million M1-ICEVs. Data from [34]. [Single Column Image, Colour].

Fig. 3 gives a visual of the current distribution of charging points across the EU* and Fig. 4 displays the countries with at least 10,000 BEVs in the EU*. As expected, there is a close relationship between the number of BEVs, PHEVs and the level of development of the charging infrastructure.

The technology used in the charging stations is classified based on the socket and the power that the station can deliver. This renders the existence of two types of charging networks, the so-called normal charging infrastructure and the fast-charging infrastructure. The former is aimed for general use and it is widely distributed in urban and non-urban areas while the latter is scarcer, with presence mainly on the vicinities of highway interconnections as it aims to improve long-distance travelling using BEVs. In Germany, various public and private actors are actively involved in the expansion of the charging infrastructure; this has made possible a rapid increase in the number of charging points throughout the country, increasing from ~25,000 in 2017 to almost 60,000 in 2021 [22].

Several standards worldwide define the combinations of electric plugs and sockets to be used by vehicles. The plug type often depends on several factors like the brand of the car, type of current (AC, DC or both) and nominal charging power of the station [31]. Since different manufacturers tend to favour one standard over the others, most of the different plugs live conjointly and charging stations tend to offer several plug types to attract potential users. Nonetheless, the lack of a unified standard generates a situation where not all vehicle models can be charged at any station [32]. A list of the most common connectors available across the EU* and their annual growth distribution in Germany is shown in Appendix C.

The data from Fig. 1 and Fig. 3 points to Germany as the leader of the EU* in the implementation of both HRS and charging points for BEVs and PHEVs. Simultaneously, both images display how the development of the HRS network is lagging behind that of the charging points with differences that reach up to two orders of magnitude. It can also be seen how the countries on the eastern side of Europe have a less-developed infrastructure than those on the western side.

2.3. With regard to ICEVs

The relative reach of the infrastructure and penetration of alternative powertrains into the market can be better understood when it is directly compared to the petrol infrastructure and market share of ICEVs. The

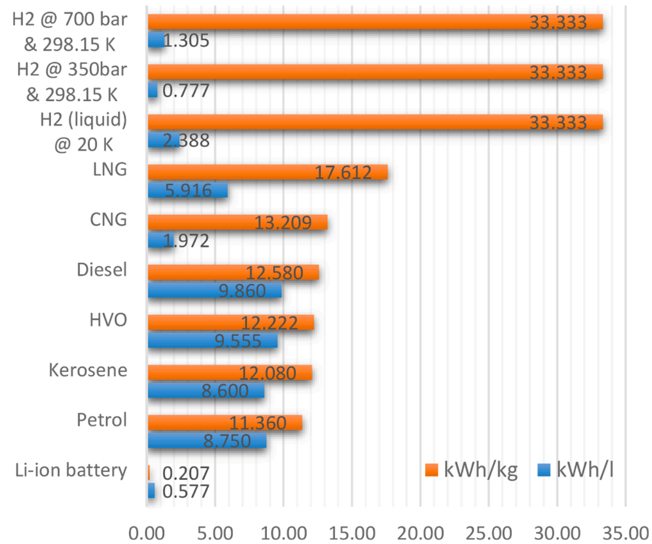

Fig. 7. Comparison of the energy content of different fuels. Information from [36] for the Li-ion battery; from [37] for HVO; from [38] for H_2 @ 350 and 700 bar and from [39] for the rest. [Single Column Image, Colour].

approximated total number of M1-type ICEVs for the EU* at the end of 2019 reached 285.23 million. Most of them (53.6 %) were powered by petrol and the rest by diesel. Fig. 5 offers a comparison of the EU* countries with most M1-type ICEVs vehicles and Fig. 6 gives the number of petrol stations for the same group of countries.

From Fig. 5 and Fig. 6, it is visible that having the highest number of ICEVs does not mean having the highest number of petrol stations. Another point to highlight is that the country with the highest number of petrol stations (Italy) has 21,750 of them servicing ~35.6 million ICEVs, but Germany and the Netherlands have already more than 50 K charging points each servicing a number of BEV and PHEV that combined account for just over 1.65 million vehicles. This contrasting difference may be explained by the low energy density and specific energy of lithium-ion batteries (compared to petrol or diesel, see Fig. 7) in combination with the required refuelling time (minutes for ICEVs versus hours for BEVs or PHEVs).

3. Individual strengths and concerns for the different powertrains.

3.1. Fuel cell electric vehicles

The specific energy of hydrogen (33.3 MWh/kg [38]) is almost 3 times higher than that of petrol (11.36 MWh/kg [38]) or diesel (12.58 MWh/kg [38]) and around 160 times higher than that of the batteries of commercial BEVs (0.207 kWh/kg [35,36]). These numbers seem to give a significant advantage to the use of hydrogen and therefore to FCEVs, however, from the point of view of energy density, hydrogen requires a significant amount of volumetric space when compared with diesel or petrol. Fig. 7 displays a comparison of the volumetric and gravimetric energy densities of different commercial fuels, Li-ion batteries and hydrogen; it shows how hydrogen, even pressurised to 700 bar, requires ~6.7 times more storage volume than petrol or diesel to account for the same equivalent energy.

FCEVs offer clean motion with no direct CO_2-eq emissions, water vapour being the only gas released to the atmosphere. Altogether, they offer a mobility range and refuelling times comparable to those of a petrol car. Nevertheless, FCEVs are essentially hybrid vehicles; the fuel cell uses hydrogen to generate electricity that charges an on-board battery which, although smaller than those of BEVs, is still bounded to the particular problems and advantages related to battery technology. This battery allows taking advantage of regenerative braking, operating the fuel cell on a stable generation point (avoiding transient behaviours) and coping with the oscillations in power demand associated with normal driving actions. Hydrogen could also be used to directly power an internal combustion engine (ICE), however, the efficiency of an ICE peaks around 30 % [40] and varies greatly depending on a multitude of conditions; meanwhile the efficiency of a fuel cell sits around 60 % and they are considered the most energy-efficient devices for extracting power from fuels [41].

3.1.1. Scaling-up green hydrogen production

A significant challenge for the HRS infrastructure to overcome is how to set up a reliable and scalable way to mass-produce green hydrogen. Presently, most hydrogen production is aimed at processes in oil refining and chemical production, this hydrogen is mainly produced from natural gas through steam-methane reforming and inexorably binds such hydrogen to the production of CO_2-eq.

Electrolysers are a relatively common technology used for the production of hydrogen in different industrial sectors and the alkaline electrolyser represents the state-of-the-art technology that dominates the market [42]. Concurrently, there are efforts to push forward other types of electrolyser technology with diverse advantages from the point of view of efficiency and operational flexibility [42]. To produce only green hydrogen, such electrolysers need to be powered with renewable energy, turning the problem of green hydrogen mass production into a problem of renewable electricity generation.

By 2020, all states of the EU* produced approximately 1,233 TWh of renewable electricity (Solar, Wind, Hydro, Geothermal and Tide generation). Compared with the 3,349 TWh of total generation, the renewable sector comprised ~36 % of the electricity generation in the EU*. From the renewable sources, 39 % (482,727 GWh) of that energy came from wind generation and 12.6 % (155,592 GWh) from solar photo-voltaic panels [43]; these technologies experienced the highest growth during the last decade. During the same period in Germany, solar and wind generation also experienced growth, while electricity from coal and nuclear sources have been reduced [43]. By the end of 2019, the most significant energy sources in Germany were coal (25.46 %), wind (22.5 %) and natural gas (17.11 %); together accounting for 65.07 % of the total electricity generation (581,995 GWh) [43].

The aforementioned numbers show how dependent the EU* is on non-renewable energy sources; a situation that does not favour the local production of green hydrogen. Furthermore, the cascade of processes related to compression, cooling, transportation and storage of hydrogen must also use renewable electricity for hydrogen to be considered "green" at the point of use. Appendix B illustrates the emissions that may arise when using electricity from the local energy grid to produce hydrogen.

3.1.2. Scarcity of Platinum-group metals

There are different types of fuel cells with diverse technical capabilities but for FCEVs, the Proton Exchange Membrane Fuel Cell (PEMFC) is ubiquitous among the current global fleet. Among its perks are the relatively low-temperature operation (<120 °C), a quick start-up, quick load following (compared with other fuel cells) and the use of a membrane instead of the liquid electrolyte [41]. The PEMFC uses platinum in the catalyst layer [44] which, being a precious metal, is a considerably expensive component. Platinum belongs to the so-called Platinum group metals [45] and its concentration in the earth's crust accounts for approximately-five parts per billion by weight [46]. This scarcity makes it expensive and highly relevant for the expected growth of the market since each FCEV uses approximately 10–20 g of metal [44].

Most of the current uses of platinum are concentrated in 3 branches; automotive production (42.1 %), where it is used for the manufacturing of catalytic converters of ICEVs [44], jewellery (31.9 %) and other industrial uses (25.8 %) [44]. The remaining 0.2 % is used as a commodity for investment purposes [44].

Data from 2012 indicates that the platinum reserves are large enough to cover 134 years of the market demand even with no future reserve discoveries [45]. Additionally, the required amount of platinum for the construction of PEMFCs is forecasted to decrease during the upcoming years as research and development improve the technology. It is expected that the required quantity of platinum per FCEV in China decreases from 0.4 g/kW in 2015 to 0.125 g/kW in 2030 [44].

One more concern is related to the location of the current platinum-proven reserves. Most of the world-proven platinum-group-metals reserves are concentrated in the Bushveld Complex in South Africa and account for 88.7 % of the total identified reserves [45]. Historically, crises have occurred with other materials whose concentrations were much lower in different regions like cobalt in Zaire (now the Democratic Republic of the Congo) during 1977 and Palladium in Russia in 1997 [45]. Another concern is the amount of energy needed to obtain platinum (54,000–235,000 kWh/kg) since it surpasses greatly that of other relevant metals in car manufacturing like aluminium (55.83 kWh/kg) or iron (3.33 kWh/kg) [45] (see Appendix D for an expanded list). Also relevant is the fact that platinum production is directly associated with large amounts of CO_2-eq emissions estimated at $1.58x10^4$ kg of CO_2-eq/kg of platinum [45] and its price is highly volatile, changing from ~45K USD/kg in 2014 to 28K USD/kg in 2021 [47].

The high costs and elevated environmental impact could be partially toned down through recycling. Platinum recycling requires only 5 % of the energy needed for extraction [45] and 95 % of the metal reaching the recycling facility can be recovered [48]. The main challenge is the open-loop nature of the automotive sector which makes it impossible to know whether the goods have been properly disposed of for recycling and there is little to no financial motivation for the users to properly dispose of their products [49].

Germany is a country where the economy benefits from high exports in the automotive sector. In 2020, "cars and car parts" was the sector with the biggest share of exports (15.5 % of the total) [50]. The open-loop nature of the automotive industry means that all the platinum forming part of those vehicles is not traced by the manufacturers and its final disposition is uncertain. Despite all this, a significant amount of platinum is still being recycled; data from 2005 shows that recycling of the platinum group metals accounted for approximately 50 % of the local gross demand [51]. However, a closed-loop usage of the metal (like in the glass manufacturing industry) could achieve recycling rates of 95 %-98 % [46].

3.2. Battery electric and plug-in hybrid vehicles

Current market trends show that these vehicles are increasing their presence at a significant pace. The number of BEVs (of all types) in the EU* by the end of 2020 was ~2.1 million units while for PHEVs the number reached ~1,4 million [22]; one year later, the total of BEVs reached ~3.4 million and PHEVs ~2.4 million.

BEVs are often referred to as being zero emissions but this is only true at the usage point and when the energy to power the battery comes from a renewable source. They require materials and components (powertrain, battery and electronics) whose production methods are often overlooked when considering how polluting they can be. The supply chain of such components can have a significant impact on freshwater eco-toxicity, freshwater eutrophication and metal depletion [52]. Moreover, depending on the energy sources, local policies and production methods, the overall environmental impact can vary significantly. Nanaki et al. (2013) [53] calculated the amount of CO_2-eq emissions during the production phase (also called cradle-to-gate) of different types of powertrains in Greece, their findings showed that BEVs production releases 4,311 kg of CO_2-eq; around 3.6 % more than a PHEV and ~25 % more than an ICEV. Meanwhile, Qiao et al. (2017) [54] made a similar study for China; they analysed the production phase emissions for BEVs using two different types of Li-ion batteries: NMC (Li(NiCoMn)O2) and LFP (LiFePO4). Their results showed that BEVs using LFP batteries produce 15,174 kg of CO_2-eq, roughly the same amount as the case of NMC batteries (15,005 kg of CO_2-eq) but ~52 % more emissions than the production of ICEVs.

Both studies concluded separately that the contribution of CO_2-eq occurring during the manufacturing process of BEVs and PHEVs is significantly higher than that of the ICEVs. Furthermore, a significant amount of CO_2-eq is generated during the battery manufacturing process as indicated in [54], [44] and [55]. The local electricity mix also influences the emissions released during the production of the battery pack [56], introducing an additional layer of complexity that also affects the lifetime emissions associated with the vehicles. A visual comparison considering different regions and different sub-processes of Lithium-ion battery manufacturing can be found in the works of Kelly et al. (2019) [56].

Turning attention to PHEVs, they may be considered transitional technologies that combine the best of both worlds (BEV and ICEV). PHEVs can positively impact the urban environment when mostly used in electric driving mode, not only through the reduction of CO_2-eq emissions but also through noise reduction. Most PHEVs available during 2020 had a fully-electric range of 30–60 km [57], which may be able to cover most of the trips within city limits. PHEVs (and by extension BEVs) can achieve noise reductions of up to 7 Db (compared to ICEVs) when driving at low speeds (up to 40 km/h) [58]. Maximising their noise-reduction potential may be achieved through regulations limiting urban maximum driving speed [59].

3.2.1. Superior efficiency of BEVs compared to FCEVs

Efficiency is one of the recurrent topics of comparison between FCEVs and BEVs, particularly the so-called well-to-wheel efficiency. That is the efficiency value resulting from considering the whole chain of interconnected technologies, from energy generation to its use as propulsion at the wheels.

In the case of petrol, its energy has been stored by natural processes that took place over millennia turning biological mass into oil. FCEVs and BEVs require the transformation of a primary energy source (wind, solar, etc.) into the corresponding energy vector (hydrogen or electricity) to be used by the vehicle. Each energy conversion step introduces losses and reduces the energy available for locomotion at the wheels. In this regard, BEVs possess an intrinsic advantage due to the lower number of conversions needed for electricity; they offer a well-to-wheel efficiency that is 1.25–3.9 times higher than that of FCEVs [60].

Numerous aspects affect the well-to-wheel efficiency. For starters, different primary energy sources have different efficiency levels, e.g. large hydropower plants have 95 % efficiency while simple structure wind turbines have 15 % [61]. The electricity can be generated far away from the charging station (Hydro or Nuclear) and be affected by transmission losses or be generated in a distributed manner (local wind or solar) requiring an energy buffer (usually a battery). Such buffer introduces other losses (extra AC/DC conversions and charge/discharge battery cycles) and it is necessary because of the intermittent nature of renewable sources. Therefore, for a BEV charged either at the charging station, workplace or home, the energy stored in its battery may have travelled different paths each time.

In contrast, the case of hydrogen is considerably more complex. Hydrogen production may use different electrolyser technologies whose overall system efficiency (kWh/kgH_2) vary between 83 % and 45 % [62]. After production, hydrogen is compressed and cooled to be stored for transportation, which typically happens in tube trailers at 200 bar [60]. Each truck carries between 200 and 1100 kg of hydrogen [63]. The trailer is then pulled by a truck (an ICEV) whose efficiency may be affected by conditions like route, state of the road, traffic, driving behaviour, and ambient temperature among others. At the HRS, additional steps of compressing and cooling take place before hydrogen reaches the FCEVs [60]. This is because hydrogen on-site is usually stored at pressures of up to 950 bar and it requires to be cooled to 233.15 K to avoid vehicle tank underfilling and to protect the composite

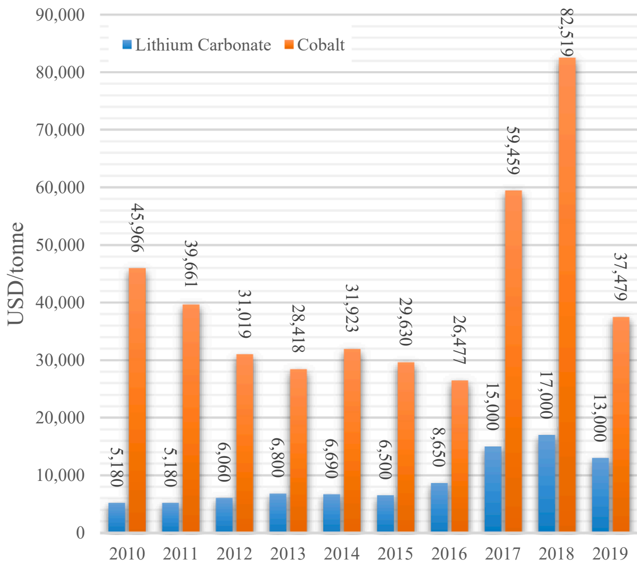

Fig. 8. Variation of the prices for lithium carbonate and Cobalt in the United States. Information from [67] for the lithium carbonate and from [68] for the cobalt data. Edited by IZES gGmbH. [Single Column Image, Colour].

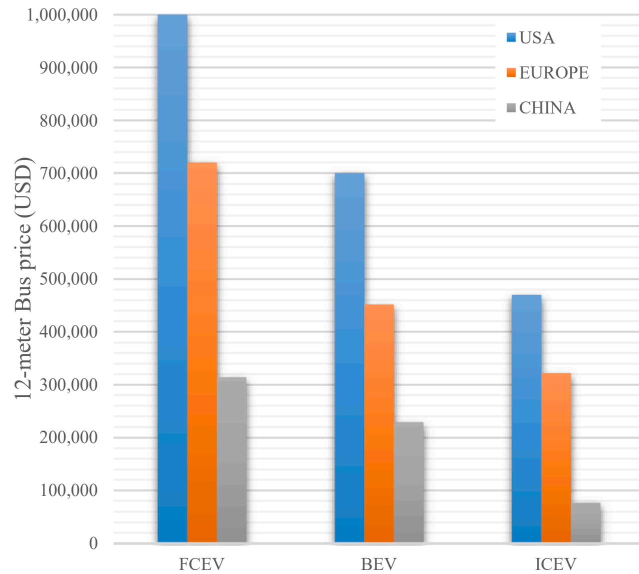

Fig. 9. Comparison of the purchase cost of a 12-meter bus in different regions for 2019. Data from [44]. Edited by IZES gGmbH. [Single Column Image, Colour].

Table 1
Comparison of range vs weight of different vehicle types. Information from [83] and [84] for the Toyota Mirai; [85] and [86] for the Hyunday Nexo; [87] for the Tesla vehicles and [88] and [89] for the BMW vehicles. The range of ICEVs is calculated using fuel tank capacity data, WLTP combined range and a petrol density of 737.22 kg/m^3. [Single Column Image, Colour].

Vehicle	Type	Segment	Weight (kg)	Fuel Weight (kg)	Range (WLTP) (km)
Toyota Mirai II	FCEV	Premium Sedan	1,950	5.6	850
Tesla Model S Maximum Range Plus	BEV	Premium Sedan	2,184	Not available	652
BMW 620d Gran Turismo	ICEV	Premium Sedan	1,910	48.65	1,100–1,245
Hyunday Nexo	FCEV	SUV	1,873	6.33	666
Tesla Model X	BEV	SUV	2,466	Not available	561
BMW X4 xDrive20d	ICEV	SUV	1,925	50.10	970–1,101

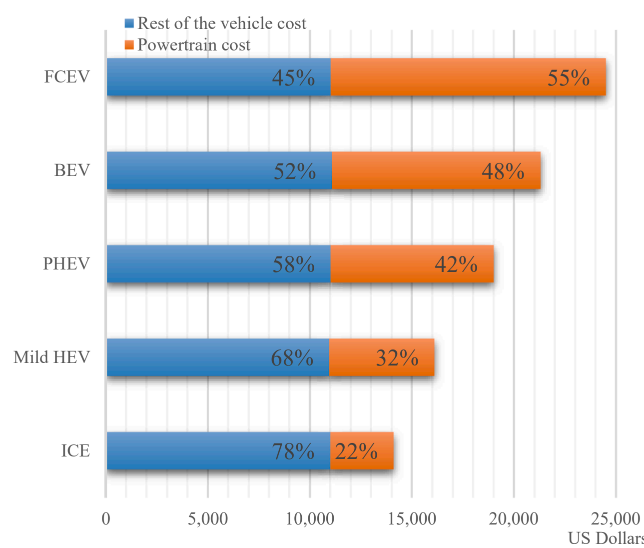

Fig. 10. Share of total the direct costs of a vehicle for different power trains. It assumes a compact-segment car and a 40 kWh battery. Information for the United States of America for the year 2018 [99]. [Single Column Image, Colour].

layer of the storage tank [60]. The energy consumption for such a chain of processes using energy sources other than renewables can yield significant quantities of CO_2-eq emissions as explored in Appendix B.

At the vehicle, the fuel cell, battery, electronics, DC/AC conversions and mechanical components of the powertrain also cause energy losses and affect the efficiency of the vehicles. As it may be evident already, the number of variables to be considered for the energy efficiency comparison of both powertrains is high; therefore different results can be found in the literature.

The work of Li et al. (2015) [61] compiles different values of well-to-wheel efficiency considering different electricity generation technologies and different operating modes for the vehicles. Their results display how difficult it is to define the efficiency gap between BEVs and FCEVs. From their findings, FCEVs have a well-to-wheel efficiency that varies between 4 % and 9% when using solar generation, between 4 % and 11 % when using wind generation and between 19 % and 29 % when using hydropower generation. In contrast, BEVs display a well-to-wheel efficiency of 12 % using solar generation, between 10 % and 24 % when using wind generation and between 56 % and 64 % when using

Table 2
Comparison matrix for different powertrain technologies.

	ICEV	BEVs	PHEVs	FCEVs
Medium Range (600 km)	++	+	++	++
Long Range (+800 km)	++	–	++	+
Refuelling Time	++	–	**o**	+
Emissions	–	++	–	++
Acceleration	+	++	++	++
Max. Speed	++	+	+	+
State of Infrastructure	++	**o**	+	–
Grid support capabilities	–	++	–	+
Efficiency	–	++	–	+
Price	++	–	**o**	–

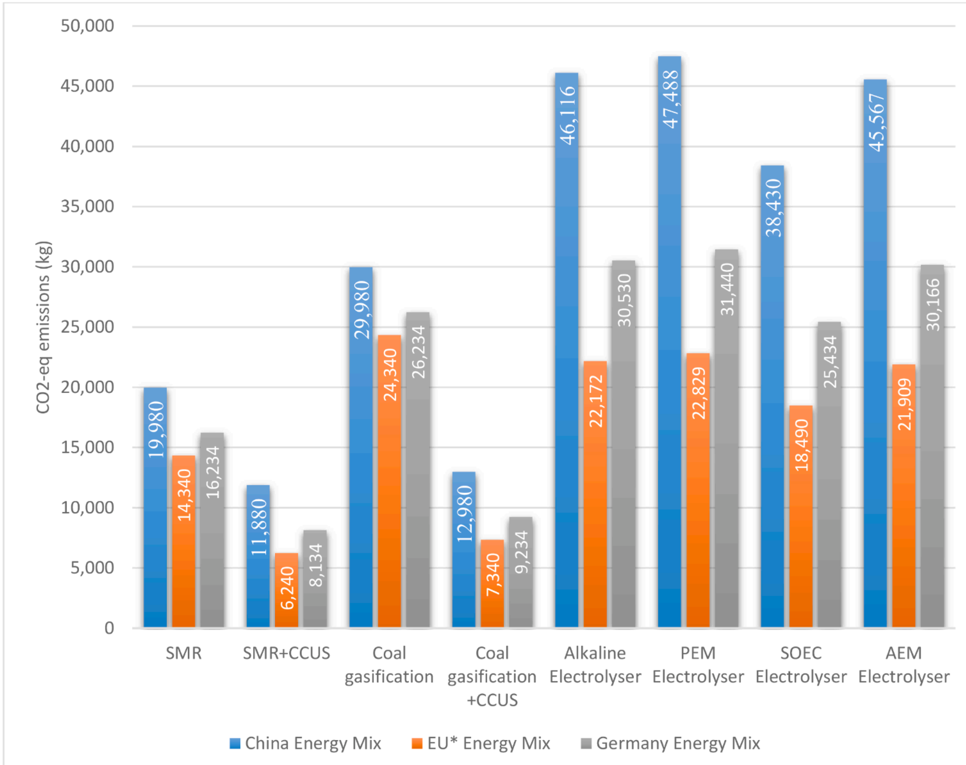

Fig. B1. Estimated CO_{2}-eq emissions to produce 1 tonne of non-green H_2 for 700 bar-capable vehicles at 233.15 K using different energy mixes. [Double Column Image, Colour].

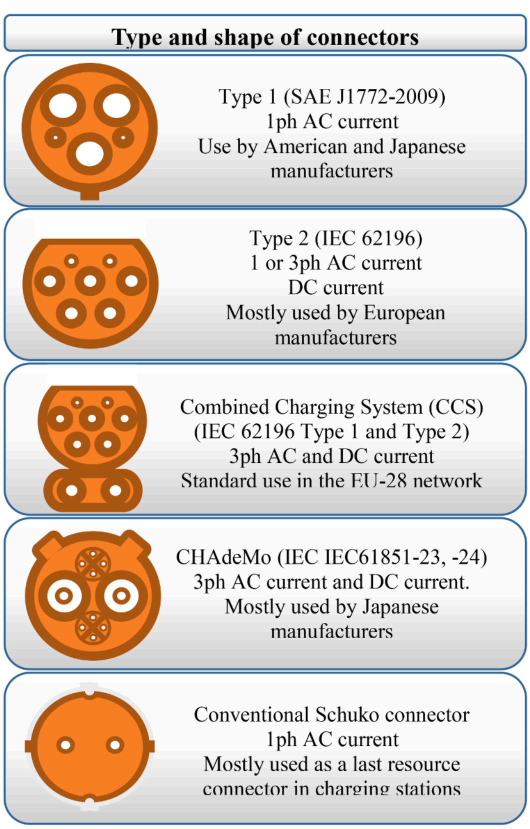

Fig. C1. Common connector types available in EU* charging stations. Source: IZES gGmbH. [Single Column Image, Colour].

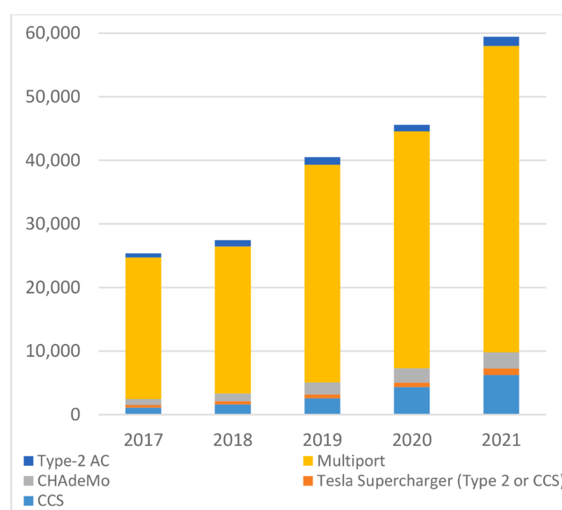

Fig. C2. Evolution of the charging infrastructure in Germany considering the type of connector. Data from [22]. [Single Column Image, Colour].

hydropower generation. [61].

3.2.2. *Scarcity of cobalt and lithium*

Most automakers base their battery technology on the Lithium-ion battery type. There are five different types: Lithium Cobalt Oxide (LCO), Lithium Nickel Manganese Cobalt (NMC), Lithium Nickel Cobalt Aluminium (NCA), Lithium Iron Phosphate (LFP) and Lithium Manganese Oxide (LMO). Of the two variants that do not contain Cobalt, LMO has (relative to the other four) low cell durability and thus, it is not suitable for the automobile industry [64]. Therefore, the production chain of these batteries is highly dependent on cobalt and lithium. Both

Table D1
Comparison of energy consumption required to obtain different type of metals versus the price per tonne [45]. Edited by IZES gGmbH.

Metal	Price ($/t)	Energy (kWh/kg)
Magnesium	2,982	71.39
Aluminium	2,168	55.83
Iron	471	3.33
Lead	2,153	5.83
Zinc	2,160	23.61
Copper	7,566	17.77
Nickel	21,914	54.16
Tin	20,362	90.00
Cobalt	43,105	36.66
Platinum	51,832,053	54,444.44–235,000

Table E1
Amount of particle emissions from car tyres [81]. Edited by IZES göGmbH.

Country	Total particle emissions from Tyres (tonnes/year)	Emission per capita/ year (kg)
Netherlands	8,834	0.52
Norway	7,884	1.5
Sweden	13,238	1.3
Denmark	6,721	1.2
Germany	95,594	1.1
United Kingdom	63,000	0.98
Italy	50,000	0.81
Japan	239,762	1.9
China	756,240	0.55
India	292,674	0.23
Australia	20,000	0.87
United States	1,524,740	4.7
Brazil	294,011	1.4
Total	3,369,698	0.95

metals are expensive and account for up to 75 % of the price of each battery pack [44].

One concern about lithium is its projected increase in demand compared with the projected increase in extraction capacity. The predicted increase in demand for 2025 rounds the 893 kt of lithium carbonate equivalent (the most common form of extraction) while the expected increase in extraction capacity is 447 kt that expect to grow up to 1,206 kt by relying on big mining consortium expansions and new developments taking place in Latin-America, Australia and China [64].

In Europe, in the German state of Saxony, the Zinnwald Lithium Project aims to extract (during 30 years) around 125 kt of lithium and other minerals from the cross-border mountainous region of the same name [65]. Another initiative is the MERLIN project, which attempts to get lithium from water that accumulates in old coal mine tunnels in the Ruhr and Saar area [66]. This water is pumped out daily to rivers to avoid contaminating freshwater sources, resulting in approximately 1,900 tonnes of lithium being lost every year [66].

In the case of cobalt, the metalloid is heavily region-dependent in availability (similar to platinum). By the end of 2017, almost 70 % of worldwide cobalt extraction was concentrated in the Democratic Republic of the Congo while approximately 50 %-60 % of cobalt refinement was located in China [64]. Additionally, cobalt extraction occurs mainly as a by-product of the extractions of other elements like copper or nickel, making it indirectly dependent on the dynamics of other markets [64]. Another problem is the artisanal mining and the child labour situation; the need for proper traceability of the origin of cobalt to counteract the child labour problem would increase the metalloid prices, making battery prices go up. Finally, the expected cobalt demand for 2025 is placed at 272 kt of refined metal, while the expected supply capacity (considering expansions of the different mining companies) is about 250–265 kt of refined metal [64]. This difference denotes a serious problem of availability that will most likely increase the prices of cobalt and consequently affect the development of alternative powertrains.

Fig. 8 displays the historical fluctuation of cobalt and lithium prices, and shows how cobalt prices have changed more drastically over the years.

3.2.3. Battery recycling

Another source of raw materials of increasing importance for the forthcoming future is the recycling of discarded batteries. By the end of 2020, there were already 10 million BEVs worldwide [69]. A gross estimation, considering each having a 250 kg and 0.5 m^3 battery, implies that there will be around 250,000 tonnes and 500,000 m^3 of unprocessed materials per million vehicles at the end of their lives [70]. Nonetheless, recycling batteries state a different set of challenges when compared with mining raw materials. Improper handling and storage of disposed batteries represent a risk of fire due to the possible remaining energy and flammable materials used for their construction [70]. Different manufacturers use different methods for battery construction and there is no unified standard either for the design or proper labelling of the components. All of these make the disassembling of units difficult to automate and the people executing the task are at risk of electrical discharge because of the high-voltage nature (up to 800 V [71]) of the units [70]. Other difficulties are associated with the chemical processes that may be used for isolating and separating the different elements in the batteries; however, they go far beyond the scope of the present work.

To overcome the lack of standardization and the hurdles of battery recycling, governments and private companies in Europe are taking action towards the development of knowledge and techniques to improve such processes. That is the case of LithoRec, a 2-phase project executed between 2009 and 2015 which had the objective of developing an economic and ecological approach for the industrial recycling of lithium-ion batteries inside Germany [72]. Their developed approaches rely mostly on mechanical, thermodynamic and hydrometallurgical processes that separate and recover the battery constituents with an efficiency of up to 91 % (opposed to traditional pyrometallurgy topping at 31 % [73]). Such approaches are currently in use by the company Duesenfeld [74]. Another project funded by the EU is ReLieVe which began in 2020 and aims to develop recycling processes and well-integrated recycling industry for vehicular batteries [75].

Another recycling alternative consists of giving a second life to discarded batteries that have concluded their life cycle as part of a BEV in applications where their performance is less critical. These applications would represent a profitable investment offsetting the eventual costs associated with recycling and improving the batteries' ESOI (Energy Stored over Energy Invested) ratio, making them more environmentally friendly [70].

Finally, it is worth mentioning that battery recycling is complex and most of the current recycling processes have the sole purpose of giving proper handling to the toxic materials and avoiding their climate impact, disregarding the possibility of taking back or reusing the battery materials [64]. Despite this, estimations for 2025 expect recycling to contribute between 20 and 25 kt of cobalt and around 4 kt of lithium [64].

3.2.4. Weight of the vehicles and mass compounding

One sensible factor affecting the range of BEVs is weight. BEVs tend to be heavier than ICEVs, and contrary to ICEVs and FCEVs whose weight diminishes as fuel is consumed, BEVs carry the same battery weight wherever they go. However, there are certain benefits to the added weight. For instance, that same additional weight from the batteries allows for better weight distribution and centre of mass which translates to improved safety behaviour and less likelihood of rollover in the event of an accident [76].

The non-linear feedback relationship between the extra battery weight needed to increase the range of a vehicle and the increase in weight that other parts require to properly support the new battery weight (thus reducing the desired range extension) is known as "mass compounding" [77]. In other words, for those additional kilograms of battery added to increase the range, it is necessary to adjust and resize other components in the vehicle: the mechanical frame (to support more weight); the braking system (to safely stop the heavier vehicle); the entire suspension (to properly damp the new weight), the electrical system (to properly accommodate the new interconnections and battery modules) and maybe the entire frame of the vehicle (to comply with minimum legal safety features). All those changes and resizing translate into yet additional weight that limits the initially aimed range extension.

Heavier vehicles require more energy to be set in motion and regenerative braking allows for recovery of just a fraction (16 %–70 % [78]) of the initial energy consumption. A heavier vehicle also puts more stress on the tyres; worsening a problem that is often overlooked when addressing the climate impact of vehicles and the pollution caused by its tyres' wear and tear. Traditional tyres can wear out up to 30 % faster in a BEV than in an ICEV [79]. Moreover, unlike engine emissions, tyre pollution emissions are not regulated [80], turning this into yet another challenge for BEVs.

Car tyres are made of a mixture of natural and synthetic rubbers. As these materials wear out, they release polluting particles that fit the definition of microplastics (particles $\leq$ 5 mm). It is estimated that 3–7 % of the particulate matter in the air whose size is $\leq$ 2.5 mm is coming from the wear and tear of car tyres [81]. These particles can remain airborne for weeks and travel more than one thousand kilometres. In the end, the deterioration of car tyres releases particles of different sizes that are washed down to the ocean, contaminating river beds and being ingested by marine fauna in the process [81]. Kole et al. (2017) [81] made an in-depth analysis of the particulate matter coming from tyre wear and tear in different countries; part of their results are briefly summarized in Appendix E.

Another contributor to the emissions caused by the increased weight of vehicles is the brakes. The brakes wear out as they are pressed against the rotating part of the wheel to create friction and reduce vehicle speed. It is estimated that the amount of particles released by the braking process of vehicles in Germany sums up to 12,350 tonnes per year [82]. A number that adds around 13 % more particulate pollution when considered (see Appendix E).

FCEVs are also bounded to the effects of mass compounding. However, due to the specific energy of hydrogen, the extra weight of gas needed to increase the range is negligible when compared to the weight of the vehicle. Doubling the value of pressure inside the tank (from 350 bar to 700 bar) allows for a 67 % increase in the mass of hydrogen stored [77]. Taking into account that five kilograms of hydrogen are enough to travel up to 212 km [77], doubling the pressure of the tank may roughly add over 50 % of additional range to the vehicle without making further changes.

Table 1 illustrates the differences in weight for two different types of vehicle segments (premium sedan and SUV) and different powertrain technologies (BEV, FCEV and ICEV). Although no official data regarding the weight of the battery pack of the Tesla vehicles were available at the moment of writing this document; it can be seen how both BEVs display the highest weights and the shortest ranges.

3.2.5. *Vehicle to grid capabilities*

Vehicle to grid is a concept where BEVs are used to avoid energy curtailment of volatile renewable sources and thus, help to balance the network [32]. It requires both vehicles and charging stations to be equipped with the necessary capabilities to feedback energy to the grid in moments of high demand and then be charged again when the electricity demand is low. The idea aims to use BEVs staying for a long time at parking lots like those at transport hubs (airports or train stations) or those at workplaces where employees would not leave the office for long hours [90]. The concept is already being tested by some manufacturers like Volkswagen with a pilot program in Berlin and BMW in the United States [32]. Nevertheless, this brings up other challenges like the associated costs of the additional requirements of the charging stations, or the will of the drivers to leave their vehicles connected to the grid while adding further charging-discharging cycles to their batteries [90].

3.3. *Internal combustion engine vehicles*

The ICE possesses a series of advantages in contrast to the alternative powertrains that will probably keep it relevant for some additional decades [91]. For starters, it is state-of-the-art technology with over 100 years of research and development background; this means that manufacturers can produce them fast and cheap. Furthermore, the petrol infrastructure is highly developed and globally widespread, making it more convenient for drivers. Finally, despite the relative success of alternative powertrains in recent years, their market penetration has been mostly focused on the passenger car segment; no alternative powertrain technology is currently capable of fully tackling the sectors of aviation, freight, rail or even heavy-duty trucks.

In 2020, there were around 1,500 million ICEVs (light-duty plus heavy-duty) worldwide and stand-alone ICEs are globally pervasive in power generation plants [92]. ICEVs are significantly cheaper than alternative powertrain vehicles and the availability of affordable energy in many places is linked to the use of fossil fuels paired with the ICE. For many countries, electricity generation alternatives like wind and solar are still expensive and their adoption would hinder their perspectives for growth and for taking their population out of poverty [92].

Government pleas of highly industrialised nations in the EU* and the US to completely replace the vehicle market offer to 100 % electric vehicles before 2035 and 2040 respectively [93] have been accompanied by similar pleas in other states like India (no new ICEV after 2030), Egypt (no new ICEV after 2040) or Taiwan (phase-out of all ICEVs by 2040) [94]. Whether they are fully implemented or not, a complete replacement of the current global vehicle fleet may take decades. Therefore, it may be relevant to consider that further improvements in the reduction of ICEs-related emissions are still possible.

Fuel consumption improvements and reduction of emissions can be realised in the short term by switching fuels from petrol to diesel (11 % emission reductions) [92], hybridising the power train with electric motors (16 % emission reductions) [92], using properly-sized turbochargers [95], implementing variable valve actuation control [96] or introducing pre-chamber ignition systems [97]. Likewise, in the long term, further improvements could be achieved by introducing flexible-fuel engines that take advantage of synthetic fuels or biofuels [98] or by co-designing fuel-engine systems for optimal performance [92]. On top of this, the use of hybridised powertrains combined with synthetic fuels may even achieve higher reductions of CO_2-eq emissions than using BEVs when the whole life cycle emissions are considered [93].

4. Cost analysis of the different powertrains.

When looking at the market in retrospect, the ICE has been omnipresent across all vehicle sectors and sizes. This situation has changed gradually during the last couple of decades and the sector of passenger vehicles starts displaying a heterogeneous mix of powertrain technologies competing for market share (see Section 2).

The technologies of ICEVs, BEVs and FCEVs, are significantly different from each other and each of them is currently placed in a very different state of maturity. This affects directly the production costs (related to retail price) and indirectly the operational costs (related to services, fuel and infrastructure). Moreover, even when the same vehicle model is offered with different powertrains as an option, the cost differences cannot be exclusively associated with the powertrain technology. This is, because even small changes in the dimensions for different parts may require different moulds for manufacturing, directly affecting the costs of individual components [44].

The place of origin of the vehicles also influences their costs; local regulations, labour costs, raw materials accessibility, currency value fluctuations and many other factors can play a significant role in the final cost of a vehicle. An example of this situation is displayed in Fig. 9, where the purchase price of a bus is presented for different powertrains and different regions [44]. The powertrain alone represents a significant part of the final vehicle cost and fuel cell technology is currently the most expensive powertrain to produce (see Fig. 10) [99]. Fuel cell prices are mostly driven by high technological production requirements, while battery prices are mostly driven by commodity-type raw materials [44].

Lithium-ion batteries have been gradually reducing their price per kWh. They have gone from 834.42 USD/kWh in 2010 to 170 USD/kWh in 2019 and they are expected to cross the 100 USD/kWh mark at some point after 2024 [100]. On the other hand, projections of the US Department of Energy estimate that the price of fuel cell systems can decrease from over 150 USD/kW to roughly 45 USD/kW if production scales up from less than 1,000 units/year to 500,000 units/year [99]. Meanwhile, the amount of platinum required for fuel cell manufacturing has been reduced by approximately 80 % since 2005 [99] and its content accounts now for less than 1 % of the whole cost of the powertrain [44].

The costs of BEVs and FCEVs are expected to keep decreasing while their market share increases during the upcoming years. Their prices are expected to get closer to those of the ICEVs with differences of less than 10K USD for vehicles of the same segment [101].

5. Alternative powertrains beyond passenger vehicles

The previous sections analysed the alternative powertrains solely from the point of view of passenger vehicles and their infrastructure. Nevertheless, other areas of the transportation sector exist where alternative powertrains can play a significant role in diminishing CO_2-eq emissions. Heavy-Duty Vehicles, maritime cargo ships and aeroplanes are transportation sub-sectors that together represent ~51 % of the CO2-eq transport-related emissions worldwide [11] and approximately 54 % within the EU-28 [12]. A brief analysis of the status quo for these transportation sectors is given in Appendix F.

6. Synthetic fuels

Synthetic fuels are an alternative to counterbalance emissions of current and future generations of ICEs. Their chances for massive adoption may be tied to the transportation sectors of freight and aviation since such sectors represent a steep challenge for alternative powertrains to overcome (see Appendix F). Because of their potential relevance for the future of transportation, a brief analysis of synthetic fuels is presented in Appendix G.

7. Conclusions

The current trends of renewable electricity generation demonstrate growth and a positive change towards an environmentally responsible energy paradigm. Nonetheless, the transportation sector is still lagging and the penetration of alternative powertrain technologies in the sector is slow.

The number of charging stations and HRS is key regarding BEVs and FCEVs adoption. However, charging stations are more numerous and BEVs can even be charged at home, making them more convenient than FCEVs.

Both BEVs and FCEVs have inherent strengths that compensate for the deficiencies of each other. The discussion should not be seen as a dichotomy. On the contrary, both technologies may coexist and complement each other when necessary.

There is still a place in the future of transportation for the ICE tied to various improvements related to efficiency and fuel consumption improvement. Its use will probably be restricted to freight transport and aviation.

Green hydrogen should not be framed exclusively as a mobility-related technology. Hydrogen is used across other industrial sectors that will also benefit from green-hydrogen-technologies improvement.

The cleaner the energy mix of the electrical grid, the cleaner would be the resulting future transportation sector. A 100 %-renewable electricity grid may eliminate most of the emissions in the cradle-to-gate scenario.

Current progress is mainly focused on selected regions inside the developed world. Climate change does not consider borders and the need to pursue the same progress in other nations should also be considered a priority.

The future of mobility may look like a heterogeneous mix of different vehicles taking advantage of the different strengths of each powertrain while considering regional energy resources availability and local needs. In that sense, BEVs may probably dominate the short to medium ranges within urban regions, FCEVs may dominate the long-distance range for passenger and commercial vehicles while ICEVs powered by synthetic fuels may remain driving heavy-duty vehicles and other applications outside of the urban areas. Table 2 compares briefly the different powertrains.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendices.

Appendix A: *The colour code of hydrogen.*

The different colour designations are not related at all to the actual physical colour of the gas (H_2 is colourless) but instead, they are used as a way to classify its origin and how environmentally friendly its production was. This colour coding does not find its basis in any official documentation or standard, it arises from partial consensus among industry and media, who recognise unanimously just a handful of colours while several others may carry a different meaning for different institutions and sources.

a) **Grey, brown or black hydrogen:** According to the German Government and its National Hydrogen Strategy [28], grey H_2 is produced by the use of fossil Hydrocarbons, specifically through the steam reforming of natural gas. Other sources identify it as H_2 coming exclusively from the steam reforming process and assign different colours to different fossil fuel sources. That is, for example, the case of the North American Council for Freight Efficiency (NACFE); which classifies hydrogen from fossil fuels as brown and that from steam-methane reforming as either black or grey [102]. At the same time, the Commonwealth Scientific and Industrial Research Organization (CSIRO), considers brown and black H_2 as that made from the gasification of brown or black coal correspondingly [103]. While there seems to be no consensus about these three colour codes for H_2, one thing is certain, any of these three different colours refers to a process that releases a significant amount of CO_2-eq as a by-product into the atmosphere.

b) **Blue hydrogen:** Similarly to the previous case, Blue H_2 is defined differently among different entities. In this way, the definition for the German Government and the NACFE is that this hydrogen is obtained through the transformation of fossil fuels but it uses carbon capture storage technology (CSS) to significantly reduce the releasing of CO_2-eq into the atmosphere (see [28;102]). On the other hand, CSIRO defines blue hydrogen as that coming from the steam reforming process of natural gas [103].

c) **Turquoise hydrogen:** Unlike the previous two cases, the different cited sources ([28,102;103]) define this type of H_2 as the one produced through the process of thermal splitting methane, a process known as methane pyrolysis. This process has the particularity of producing solid carbon as its only by-product. In theory, the process does not emit any CO_2-eq, however, indirect emissions associated with the production and transporting of natural gas are still present and should be considered.

d) **Pink hydrogen:** This is another example of consensus among different sources. Pink hydrogen is produced employing electrolysis where the source of electricity is exclusively nuclear power plants. [103]

e) **Green hydrogen:** This classification refers to hydrogen that has been produced exclusively through electrolysis and the use of clean electricity from renewable energy sources [28]. Green hydrogen is considered one of the fundamental pillars to solving the climate change problem and part away from the use of fossil fuels.

Appendix B: *CO2-eq emissions for the production of 1 tonne (1,000 kg) of non-green hydrogen fuel.*

Fig. B.1 in this appendix illustrates the relevance of renewable energy sources for the production and processing of hydrogen fuel. The displayed information follows the process to produce one tonne of hydrogen fuel that is liquefied for transportation and cooled down to −40 °C to fuel vehicles with pressures of up to 700 bar at the HRS.

The values were calculated by considering the specific energy requirements and specific emissions intensity of the different processes. The value of emissions from the state-of-the-art process of Steam Methane Reforming (SMR) are 9 kg CO_2/kg H_2 and using Carbon Capture, Utilisation and Sequestration (CCUS) technology can achieve up to 90 % reduction of that amount [104]. The state-of-the-art process for Coal gasification produces around 19 kg CO_2/kg H_2 and pairing it with CCUS can reduce that amount to just 2 kg CO_2/kg H_2 [104]. The electrolyser system technologies have typical specific energy requirements in the range of 53–70 kWh/kg H_2 [105] and the values for each technology are averaged from those given by the International Renewable Energy Agency [62] —Alkaline Electrolyser: 50–78 kWh/kg H_2; Proton Exchange Membrane (PEM) Electrolyser: 50–83 kWh/kg H_2; Solid Oxide Electrolyser Cell (SOEC): 45–55 kWh/kg H_2; and Anion Exchange Membrane (AEM) electrolyser: 45–55 kWh/kg H_2) — [62].

Values for the typical specific energy of compression technology were taken from the works of the United States Department of Energy (USDOE) [106] for mechanical compression (3 kWh/kg H_2) and from the works of Sdanghi et al. [107] for electrochemical compression (2 kWh/kg H_2). The values of the specific energy for the liquefaction process (occurring at 20.15 K) are also taken from the USDOE [106] (14.4 kWh/kg H_2) and for pre-cooling to 233.15 K are taken from the works of Elgowainy et al. [108] (0.4 kWh/kg H_2). The emissions for the different processes were calculated by considering the 2021 carbon intensity of the electricity grid for three regions: China (0.549 kg CO_2/kWh), the EU* (0.263 kg CO_2/kWh) and Germany (0.364 kg CO_2/kWh) [109]. Finally, for the transportation, it was decided to consider only 500 Km since this distance fits the range of an average diesel-powered truck for making the trip back and forth without refuelling [110]. The CO_2 efficiency of the vehicle for the EU* (0.307 kg CO_2/tKm -limited here to EU27 plus the United Kingdom and Norway-) comes from the works of Ragon et al. (2021) [111], where a 4x2 Urban Delivery Truck was taken as reference. For Germany (0.111 kg CO_2/tKm), the number was taken from data given by the German *Umweltbundesamt* for a heavy duty vehicle [112]. For China, the regulations follow a different approach to measure emissions (values given in fuel-litres/100Km) [113], because of this, the value was not easily available in literature and it was decided to approximate it with the same value of the EU*.

The resulting numbers seen in Fig. B.1 hint at the importance of decarbonising the electricity grid. Hydrogen as an alternative for the decarbonisation of the transportation sector makes sense only when using 100 % green hydrogen and this can only be achieved when the electricity for electrolysis is also 100 % renewable.

Appendix C: *Charging plugs and the growth of their distribution across Germany*

Figs. C1 and C2.

Appendix D: *Comparison of price and energy requirements for obtaining different metals relevant to the automobile industry*

Table D1.

Appendix E: *Tyre wear and tear*

Table E1.

Appendix F: *Alternative powertrains beyond passenger vehicles*

Heavy-duty vehicles

It has been already pointed out in numerous studies that heavy-duty BEVs are impractical due to the poor energy density of current battery technology [110,114,115] yet several manufacturers are attempting to bring them to market as listed in the works of Liimatainen et al. [116]. The given range of those vehicles (200–800 km) [116] (tied to the size of the battery pack) is limited by the effects of mass compounding, payload capacity and the legal maximum weight of the vehicle. Further battery-size increases come to a point where the battery pack weighs more than the payload itself [115]. On the other hand, heavy-duty-FCEVs offer a range (1,062–1,776 km) and refuelling time (16.67 min) that is comparable to that of diesel trucks (1,569–3,138 km and 6–12 min respectively) [110] but it is only recently that they have attracted significant attention for commercialization [117]. The latest heavy-duty applications have been limited to the area of busses [117] but the goal of the EU-28 is to incentivise market penetration of 5,000 trains and 1.7 million trucks and busses combined by 2050 [118].

Cargo ships

Cargo ships are considered to be the transportation sector that consumes the largest amounts of fuels worldwide [119,120], therefore the International Maritime Organization is aiming to set more restrictive rules to reduce the amount of CO_2-eq emissions from cargo ships [119]. Maritime cargo ships come in many different sizes and shapes and the lengths of their journeys, combined with the amount of cargo that they are capable of transporting, limit the possibilities of using battery-powered powertrains. The overhauling of existing cargo ships by replacing their engines with electric motors powered by either batteries or hydrogen-driven fuel cells combined with liquid or highly-pressurised hydrogen storage is comprehensively studied in the report by Minnehan et al. [121]. Their study offers a clear view of how limited the use of batteries and even pressurized hydrogen is while the use of liquid hydrogen remains a suitable option for many types of ships and the only solution possible for the largest ones.

Aeroplanes

From the aviation sector perspective, emissions are expected to grow by a factor of three in the upcoming decades; that means that despite the current annual improvements in fuel efficiency of 1.5 %, expected emissions by 2050 are placed in 2,381 million tonnes of CO_2-eq [122]. Numerous challenges exist for hydrogen to be used in commercial flights, e.g. hydrogen liquefaction and storing [123,124], safety regulations [124], price of green hydrogen or green-hydrogen-based fuels [122], fuel cell power density [122], among others. Further analysis of the challenges in the design of a hydrogen-based aeroplane is explored in the works of Amy and Kunycky [123], Guynn et al. [125] and Bruce et al. [122]. On the battery-powered side of things, a few companies are attempting to bring electrified aviation to the commercial sector, however, the weight of such vehicles limits their use and scope to small aeroplanes (2–10 passengers) and short distances (300–1,000 km) [124].

Appendix G: *Synthetic fuels*

Synthetic fuels or at least a fraction of them can be manufactured using green hydrogen and CO_2 coming either from capturing gases at industrial sites or from extraction directly from the air. The details regarding the chemical processes involved are beyond the scope of the present work; however, it is important to mention that at present time it is entirely possible to manufacture artificial petrol, diesel and kerosene for the main mobility sectors (passenger cars, freight and aviation). The problem with such an approach is first cost and second efficiency. Due to the number of energy conversions necessary to manufacture, transmit and distribute the fuel, it will always be cheaper and more efficient to use electricity directly [40]. Even so, it may be possible for these types of fuels to enjoy a broad range of acceptance within the fields of maritime freight and transoceanic flights due to the limitations of alternative powertrains in such sectors.

A type of synthetic fuel with current extended adoption is the so-called biodiesel or renewable diesel. Biodiesel is an umbrella term for different types of diesel fuels derived from diverse plants or animal fats. These fuels are also referred to as HVO (Hydrogenated Vegetable Oils), following the name of the process used to obtain them. The European Union is the largest worldwide producer of biodiesel [126], followed by the United States, Indonesia, Brazil and Argentina in the top five biodiesel producers. Considering the production of individual states, Germany uses rapeseed oil as primary stock for the production of biodiesel and its share accounts for one-fourth of the total amount of such fuel coming from the European Union [127].

Rapeseed oil and used cooking oil represent most of the feedstock used for the production of biodiesel (over 60 % in total); palm oil and animal fats are the second most representative type of feedstock while animal fats, soybean oil, pine oil and other fatty acids account usually for less than 10 % of the feedstock material used for biodiesel manufacturing [126]. One of the main counterarguments against biodiesel is related to the use of arable land and food supplies for the production of fuels, nonetheless, the quantity of grains used for the production of biodiesel accounts for only 12 % of the global production [127]. Furthermore, food security and famine problems have underlying complex causes that go far beyond the quantity of food being produced [127].

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