

Chapter 2

Decarbonization Solutions



Abstract This chapter will be devoted to a description of the alternative decarbonization pathways that may help to decrease the dependency from fossil fuels in transport, which is currently the sector most strongly dependent on oil. Electricity, hydrogen, and biofuels are the main alternative sources for transport systems, and they will be analyzed and compared by considering the state of the art of the technologies of each pathway and the potential future development. Each transport segment and each mode have specific features, resulting in the need to evaluate dedicated applications based on the technical and economic conditions of each technological solution. Moreover, variable conditions across world regions may impact the sustainability of each pathway, particularly in relation to the current and expected power generation mix that varies from a country to another. Opportunities and challenges will be discussed to provide to the readers a clear vision on the strengths and weaknesses of each solution.

2.1 Introduction

The continuous increase of carbon emissions related to human activities is leading to rising greenhouse gases concentrations in the atmosphere, causing an increase of average world temperature. Since 1992, an international effort to “stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” has been declared by the United Nations Framework Convention on Climate Change (UNFCCC). In this framework, the Paris Agreement signed in 2016 aims to keep the increase in global average temperature to well below 2 °C above pre-industrial levels. Although these efforts may not be enough to effectively tackling the risks of climate change, there seems to be an increasing awareness both in governments and in public opinion of the importance of decreasing carbon emissions. Global energy-related carbon emissions peaked to an historic high of 33.1 Gt of CO₂ in 2018, with a 1.7% rise over the previous year (IEA, 2019a).

Around one quarter of the total emissions are related to transport, which remains heavily dependent on oil products (accounting for more than 90% of its final energy

consumption). Moreover, transport is among the sectors that are most difficult to decarbonize, especially for some segments including international shipping and long-haul flights. Different technologies may play a role in transport decarbonization, including renewable electricity, green hydrogen, biofuels, and synthetic fuels. While some solutions are already mature, their costs are often higher than the traditional oil-based technologies, and dedicated policies may be required to trigger a decrease of costs driven by economies of scale.

Carbon emissions generated by the transport of passengers or goods show a high variation depending on the mode, the technology, the age of the vehicle, the fuel, the number of passengers or the load factor, the driving cycle, etc. Table 2.1 reports some average values and ranges of variation for different countries, to compare the effectiveness of various transport modes. Since all the aspects mentioned above have an impact on emissions, it is important to highlight that these average values should only be considered as a reference for current transport modes, but they are significantly dependent on the vehicle fleets and the way people use them.

Today, CO₂ emissions related to the transport sector are around 8.2 Gt, including the emissions caused by the generation of the electricity consumed in transport (IEA, 2019a). The future evolution of these emissions will result from the combination of a strong expected increase of the demand of mobility of both people and goods, a foreseeable increase in energy efficiency of different transport modes (including the potential for higher load factors, especially for cars), and a possible shift toward low-carbon energy sources for vehicles. Based on the most up-to-date scenarios published by the International Energy Agency (IEA, 2019f), the CO₂ emissions caused by transport may increase up to 10.2–11.5 Gt by 2040 (authors' calculation

Table 2.1 Average specific CO₂ emissions for different transport modes and variation ranges

	Average	Range of variation ^a
<i>Passenger (gCO₂/pkm)</i>		
Large cars	196	74–262
Aviation	130	75–221
Cars	130	60–221
Buses and minibuses	44	26–85
Two- and three-wheelers	31	24–54
Rail	18	6–81
<i>Freight (gCO₂/tkm)</i>		
Medium trucks	96	48–152
Heavy trucks	80	58–117
Rail	15	9–52
Shipping	8	6–13

Authors' calculation from IEA (2019e)

^aThe variation is to be intended on a country basis, while stronger variations may be expected when considering a single vehicle or trip

based on the outcomes of Stated Policies and Current Policies scenarios) or they may decrease to 5.8 Gt in the best case (Sustainable Development Scenario). Transport will remain responsible of 28–37% of the total emissions in 2040, and it will remain among the most difficult sectors to decarbonize, together with heavy industry.

While there is a strong policy push toward decarbonization in multiple countries worldwide, low-carbon transport technologies alone are not the solution, but they should come together with significant energy efficiency measures, multimodal transport optimization, and mobility demand control. Sustainable mobility planning strategies with the integration of different governance levels are unavoidable, to ensure a development of the sector characterized by lower impacts related to both energy consumption and carbon emissions. Reaching the challenging decarbonization targets that are required to limit climate change may need a combination of different solutions, since there is no single silver bullet to supply all the mobility demand related to passenger and freight transport at different scales and with different modes.

2.2 Electricity—The Main Option

Electricity is already seen as a clean energy source due to the absence of local pollution emissions, although its generation in power plants may include the use of fossil fuels combustion, with consequent centralized pollutants emissions, which are usually monitored and limited by dedicated abatement systems. However, as long as GHG emissions are concerned, from a well-to-wheel (WTW) perspective, i.e., considering the entire energy supply chain, the use of electricity may not guarantee a lower impact than traditional oil-based fuels such as gasoline and diesel oil.

For this reason, the push toward electrification of transport and other final uses needs to come along with a decarbonization of the power generation mix, by supporting low-carbon sources such as renewables or nuclear, or alternatively by coupling fossil-powered plants with carbon capture, utilization, and storage (CCUS) systems. A strong penetration of non-dispatchable renewable energy sources (RES), such as solar or wind, may require the support of proper flexibility solutions to match energy demand and supply. Although the discussion of such aspects goes beyond the scope of this book, some insights will be given when dealing with specific technologies, and the reader may find additional information on dedicated literature works (Koltsaklis, Dagoumas, & Panapakidis, 2017; Sinsel, Riemke, & Hoffmann, 2020).

At global scale, the carbon emissions caused by the generation of a unit of electricity are showing a slightly decreasing trend, and currently, the global average carbon emissions intensity is equal to 518 g CO₂-eq/kWh (IEA, 2019b), but large differences remain across countries. This decrease is happening both thanks to an increase of conversion efficiency and a growing share of RES in the generation mix, although new fossil-based capacity is still being installed worldwide. Figure 2.1 reports the historical evolution of the national carbon intensity of electricity generation for the ten largest countries for power production in 2015 (most recent data available). As

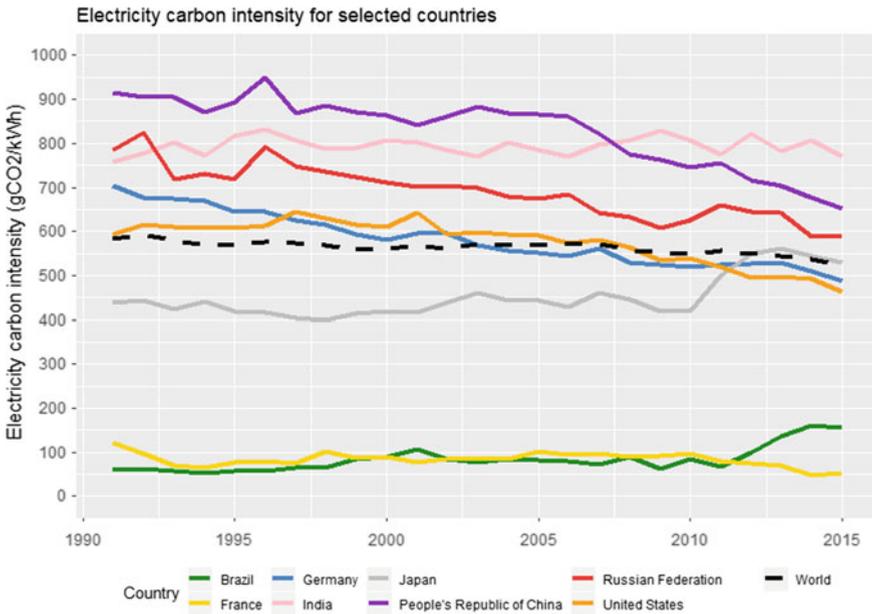


Fig. 2.1 Carbon intensity for electricity generation in selected countries. *Source* Authors' elaboration from IEA (2019c)

already noticed, strong differences exist, and while a decrease is noticeable for China and the USA, most countries have a relatively constant carbon intensity, and Brazil and Japan have even had an increase in the very last years on record.

However, the specific emissions are only one side of the story, since the total emissions are consistently rising, driven by a strong expansion of electricity demand worldwide, due to the electrification of different final uses and to the increasing electricity access rates and consumption in developing countries. It is not clear if the increasing deployment of RES plants will keep the pace with the rising demand without a supportive regulatory framework, and therefore, dedicated decarbonization policies are of utmost importance to limit the current trend of climate change.

Electricity has been widely adopted for a wide range of applications, being a flexible, efficient, and clean energy vector. However, one of the toughest barriers to electricity use is the difficulty of storing it with efficient and inexpensive solutions, since supply and demand need a continuous matching to ensure the stability of the power networks. Electricity storage has wide applications at small and medium sizes, from portable electronics to some appliances, but medium- and large-scale batteries have not yet been proven to be economically affordable nor environmentally sustainable, mainly due to the high energy consumption and impacts in the manufacturing and decommissioning stages. Currently, the only option available for large-scale electricity storage is pumped hydropower, which is however limited to sites with proper geographical conformation.

Nevertheless, electric transport is seeing a considerable boost in last years, supported by the double aim of decarbonizing the transport sector and decreasing the severe local pollution that is affecting most urban centers worldwide. The following sections will present the characteristics of the main technologies available for different transport modes, as well as the aspects related to the energy supply chain and infrastructure, together with some insights on current case studies that reflect some highlights of this opportunity.

2.2.1 Electric Transport Technologies

Electricity has already a long history in transporting passengers and goods, notably in electrified railways that can power both extra-urban trains and urban rapid mass transit systems underground or at ground level. In some cases, network-powered trolley buses have been used for urban public transport. However, all these systems required to be constantly connected to a power source, resulting in higher investment costs and a limited flexibility. Although these systems are still successful and gaining interest worldwide, the current electrification trend is oriented toward the use of electric batteries to store the energy required by the vehicle and provide the user with the flexibility that is usually available with oil-based cars or trucks.

The use of battery electric vehicles (BEVs) is still at an early stage, but some countries are developing policies and regulations to boost the adoption of these technologies, especially for light-duty vehicles (LDVs). BEVs are often providing limited ranges, and given the low availability of charging infrastructure in many countries, together with the longer charging times in comparison with oil-products refueling stations, the rate of adoption is still limited. On the other hand, the market share of plug-in hybrid vehicles is already reaching interesting values and different countries, thanks to the possibility of exploiting the electricity use where it is available and relying on a safe gasoline backup in the other cases.

The electric car sales are expanding at a rapid pace, and in 2018, the global electric car fleet, considering both BEVs and plug-in hybrids, reached a record of 5.1 million, up 2 million from the previous year (IEA, 2019b). At this stage, specific policies are critical in supporting the development of EVs market, leading to large differences across countries. The positive response of the private sector to these policy signals is encouraging, and the positive momentum for electric mobility is confirmed by increasingly ambitious targets from automotive manufacturers, followed by boosting investments in the battery development as well as in the charging infrastructure.

Electric cars provide several advantages, ranging from more efficient and silent engines, to no tailpipe emissions and a better driving experience and performance. The use of regenerative braking allows recovering energy during the deceleration phases, increasing the overall energy balance of the vehicle. However, the need of carrying the batteries, which are still lacking in both volumetric and gravimetric energy density, increases the weight of the vehicle, and the higher resistance required by all the structural components is adding up additional weight. Moreover, the very

high efficiency of the electric engine leaves limited energy to be dissipated as heat, and this aspect becomes critical in cold climates, since the dissipation heat traditionally used in cars to guarantee an acceptable indoor temperature is no longer available. As a result, the energy consumption of BEVs in cold climates may strongly increase, leading to lower ranges and additional costs in comparison with nominal conditions (Liu, Wang, Yamamoto, & Morikawa, 2018). Ambient cooling in hot climates is also impacting the specific energy consumption, but just as it happens in fossil-powered vehicles, although this should be considered when evaluating consumption figures.

The comparison between the life cycle energy consumption of an electric car with a traditional gasoline car is mostly dependent on the electricity mix. The largest impact of traditional cars happens during the operation phase, caused by fuel combustion, while electric cars have a larger impact during the manufacturing and end-of-life phases, mainly caused by the batteries. With the current world average electricity mix, both BEVs and plug-in hybrid show lower carbon emissions over their lifetime in comparison with an average traditional gasoline car (IEA, 2019b). However, while in countries with low-carbon electricity mixes the emissions savings are considerable, traditional cars still remain a better alternative to EVs in power systems dominated by coal generation, as long as carbon emissions are concerned. This aspect reflects the importance of developing policies that support EVs deployment together with low-carbon electricity sources, since EVs alone are not enough to ensure the decarbonization of the energy system.

The limited range of the vehicles, together with the weight of the batteries, becomes even more impactful for buses and trucks. In some cases, the autonomy of urban buses is currently lower than the one that would be required by their daily schedule, resulting in the need of using more vehicles to guarantee the same level of service of traditional diesel buses (Levy, 2019). This adds up to the already higher cost of electric buses, together with the charging infrastructure. Electric trucks have similar concerns, although their operation usually deals with longer travels, usually across countries, resulting in the need of additional flexibility. The current limited availability of charging infrastructure is hindering the development of such technologies, but some manufacturers are already testing electric trucks with acceptable ranges (Hanley, 2019).

An alternative solution for freight road transport electrification is the installation of catenaries in some highway networks (Barnstone & Barnstone, 2018), to be coupled with full-electric trucks with smaller batteries, or with the capacity to recharge during the travel. An alternative option is the possibility of using hybrid trucks, which can operate with higher flexibility thanks to the backup generation with traditional fuels allowing longer ranges outside of the electricity-powered infrastructure.

The challenges related to the electrification of land transport increase their magnitude when considering the potential of electrification in shipping and aviation. These transport modes are mainly relevant for passenger and freight transport over long distances, which is not compatible with the potential ranges of the current batteries nor with the reasonable expectations for new battery developments. Moreover, the charging during the travel is obviously not an option, and therefore, the electrification potential is limited to short- and medium-haul flights (although with strong challenges) and to coastal and inland navigation for water transport.

Short-haul flights may benefit from an indirect electrification: a modal shift toward high-speed trains in some national and international connections. This trend is already happening in key routes in Asia and Europe, where high-speed trains are already providing comparable performances in both prices and speed (Bachman, Fan, & Cannon, 2018). The current trade-off travel distance is around 1000 km, but future policies aiming at decarbonization may further increase the profitability of electricity-driven high-speed trains and increase this distance. Moreover, future technologies such as Hyperloop may provide additional alternatives to planes: a magnetic levitation train operated in an evacuated tube to reduce air resistance may be operated at very high speeds with little energy consumption. However, the technology is still at a very early stage, and effective demonstration systems are needed to verify the potential benefits for transport systems.

2.2.2 Electricity Supply Chain and Infrastructure

The penetration of electric vehicles involves additional aspects related to the available infrastructure, since the installation of charging stations will have an impact on the electricity supply chain. The energy consumption of electric vehicles is usually much lower than for oil-based vehicles, thanks to the higher efficiency of electric engines. However, electricity needs to be generated, distributed, and stored to be available to recharge vehicles when they need it.

Let us start from the end of the chain: the charging station. Considering electric cars, the basic possibility is to recharge it overnight using the existing low-voltage network at home or during the day at the office. A quicker option is given by chargers installed in parking lots, which are usually equipped with higher output power and allow the users to partially or fully charge their car while parked, generally at a higher price than for residential charging. A third option is given by fast-charging stations: with installed powers higher than 40 kW (and up to 150 kW in some cases), they can provide very fast recharging solutions, especially needed for long trips. While lower recharging times are more attractive for the users, although the higher economic price may be a deterrent, the impact on the power network is more challenging, since the power grid needs to guarantee a simultaneous balance between generation and demand. High penetration of fast-charging stations may require additional investments to guarantee the grid stability, including dedicated measures for distribution grids and flexibility options, including demand response and electricity storage systems.

However, while fast charging may lead to issues in specific days of high demand (e.g., when leaving for holidays), the large majority of the trips are related to short and medium distances, and thus, EVs can be recharged at lower speeds when they are not in use. The efficiency of the power system can be maximized by performing smart charging strategies, i.e., by timing the electricity supply to vehicles based on available generation from low-carbon sources. However, this results in the need of having each vehicle connected to the network for a longer time, causing a larger

number of charging points for the same electric fleet. A further evolution may be the possibility of using each vehicle as an energy storage system, not only by delaying charging but also as an electricity source to provide additional flexibility to the grid when needed (often called vehicle-to-grid, V2G). However, this possibility requires that the vehicles are equipped with specific tools to allow a bi-directional power flow (which is rarely the case in current vehicles), and there are some doubts on the potential faster degradation of the battery over time. Moreover, the economic remuneration of flexibility services may reach very high values to be attractive for electric cars' users. The installation of charging stations is facing a chicken-and-egg issue during the early adoption of electric vehicles. While customers are afraid of choosing an electric car due to the lack of a proper charging infrastructure, especially for long trips, private and public investors are reluctant to deploy charging stations for the fear of overestimating the future evolution of electric cars fleets.

While charging stations are becoming the standard for electric cars power supply, other solutions are being proposed to face the problems related to range anxiety and to the duration of the charging process. A totally different model is relying on battery swapping, i.e., the idea of substituting depleted batteries instead of charging them. This model had been used in the very beginning of electric vehicles history, at the beginning of 1900 in the USA. The main advantage is related to the very quick operation, since the swap process can require even less than a gasoline refill (Tesla managed to complete a swap operation on a Model S in just 90 s during a test event), and without the need for the driver to exit the car. Moreover, the idea of a third-party company which owns and operate the batteries, selling the service to the users at a reasonable price, may decrease the cost of the electric cars making them competitive with the traditional ones. However, this new business model may require a very high degree of battery standardization, eventually over different car models, which appears rather difficult in the current market. An additional advantage of a significant number of batteries in a swap station may be its potential to participate to V2G programs. Some pilot plants have been in operation in the last decade in different countries, and although some of them have been successful especially for scooters and electric bikes, none of them has yet proven to be an effective alternative to charging stations for electric cars. However, some battery swapping programs are being evaluated in China, with particular focus on specific fleets, such as municipal taxis or buses.

2.2.3 The EV Momentum in Different World Regions

Electric vehicles, especially passenger cars, are showing increasing penetration rates, and the first three markets in 2018 were China, Europe, and the USA, with car stocks at the end of the year reaching 2.3, 1.2, and 1.1 million vehicles, respectively (IEA, 2019b). However, the market share of new electric vehicles sales remained under 5% in all countries but four (Norway 46%, Iceland 17%, Sweden 8%, Netherlands 7%). While electric light-duty vehicles show significant increase year-over-year, the large

majority of electric vehicles worldwide remain two/three-wheelers: they exceeded 300 million at the end of 2018, the large majority being in China. Two-wheelers still account for the largest share of the 58 TWh of estimated consumption of global electric vehicles fleet in 2018, of which 80% is related to China. On a well-to-wheel basis, the (IEA, 2019b) estimates a total emission of the global EV stock in 2018 at 38 Mt of CO_{2-eq}, to be compared with 78 Mt CO_{2-eq} emissions that an equivalent internal combustion engine fleet would have emitted.

The adoption of EVs is strongly driven by dedicated policies that aim at supporting low-carbon solutions as well as decreasing the tailpipe emissions in urban environments. This latter target is especially important in Chinese cities, which have implemented strong regulations in different sectors to limit the pollutants emissions. The central government of the country has proven to be effective in deploying large fleets of EVs, including a significant number of electric buses in several cities. China accounts for 99% of the global electric buses stock, which reached around 460,000 units at the end of 2018. The country had also pursued an industrial strategy aiming at becoming the world leader in manufacturing electric vehicles, especially on the batteries and the supply chains of the required materials (investing on refining plants for lithium, cobalt, and graphite).

Other countries are generally supporting EVs as a solution to lower their carbon emissions, from European Union to South Korea, Japan, New Zealand, and some states of the USA, where California is accounting for the large majority of EV sales in the country. In the USA, policy packages are being developed by states, cities, and utilities, with different measures related both to incentives for EV purchase and operation and to deploy networks of charging points at workplaces or other public places. In 2018, the higher success of EVs in the country has been on the West Coast, with San Jose reaching 21% of EVs market share, and other major cities in California, together with Seattle and Portland, in the range 4–13% (Slowik & Lutsey, 2019).

In Europe, the deployment of electric vehicles shows large differences from a country to another, due to the different policies that are set in place to reach the broader decarbonization targets, especially in the member states of the European Union. Norway represents by far the world country with the highest market share for EVs, thanks to generous incentives for the switch to low-emission cars for their citizens. The country can exploit one of the most renewable electricity mixes in the world, with 95% of the total generation from hydropower and 2.6% from wind power in 2018 (Statistics Norway, 2019). The monthly EV market share has surpassed 50% for the first time in March (reaching 58.4%), and the forecast for 2019 is to remain near 50% as an annual figure. The parliament has voted an aim stating that by 2025 only zero-emissions cars (powered by electricity or hydrogen) should be sold in the country. In parallel, while the market is becoming more mature, the generous incentives are being gradually removed (although the main ones will stand till the end of 2021), and this aspect may slow down EV adoption for future users. While strong policy actions are proving to be effective in Norway, some of them may have rebound effects in the effort of promoting a modal shift from private cars to public transport, including the free access to bus lanes and the free parking for electric cars.

Moreover, Norway is a small country with a low population density and a very high average income, and thus, this success story may be harder to replicate in countries with different conditions.

2.2.4 Hydrogen—An Alternative or a Complement?

Vehicles powered by hydrogen may become a promising alternative to battery electric vehicles, thanks to the possibility of providing longer ranges and shorter refueling times. At the same time, they can become a complement to electric vehicles by addressing specific transport segments for which electrification may not prove to be effective. However, hydrogen technologies have still higher costs, especially considering the supply chain to produce, store, and transport this energy carrier. Just like electricity, hydrogen needs to be generated, and while it holds the potential of being produced by low-carbon sources, the current world hydrogen demand is almost totally fulfilled by using either natural gas or coal as primary source. Low-carbon alternatives include the use of electrolysis supplied by low-carbon electricity or coupling the current fossil-based solutions with effective carbon capture utilization and storage (CCUS) technologies. The success of hydrogen will depend of the advantages against electric vehicles, especially in sectors that are harder to electrify (such as trucks and ships), but there is the need of a significant cost decrease for the different steps of the supply chain and the transport technologies that are involved. Moreover, the implementation of an effective network of refueling stations may significantly increase the initial investment, slowing down the adoption of vehicles, especially for private users.

2.2.5 Transport Technologies Based on Hydrogen

Hydrogen-based powertrains may have an important role in different segments, including passenger cars, trucks, buses, and rail (for non-electrified lines). Hydrogen vehicles are lighter in comparison with electric ones thanks to the absence of a large battery, and they can generally provide longer ranges and shorter refueling times. They are particularly attractive for high-duty vehicles, such as trucks and buses, that would require very large batteries for their operation. Hydrogen vehicles are powered by fuel cells, which are the most expensive component, coupled to electric engines. The hydrogen is stored as a compressed gas at very high pressures (350 bar in HDVs and 700 bar in LDVs), which may lead to potential safety risks and thus require dedicated procedures and infrastructures.

Figure 2.2 reports a timeline of the expected commercial availability of hydrogen technologies in different transport segments, proposed by (Hydrogen Council, 2017). The chart highlights both the start of commercialization and the mass market acceptability, showing the different time required to penetrate each market. While

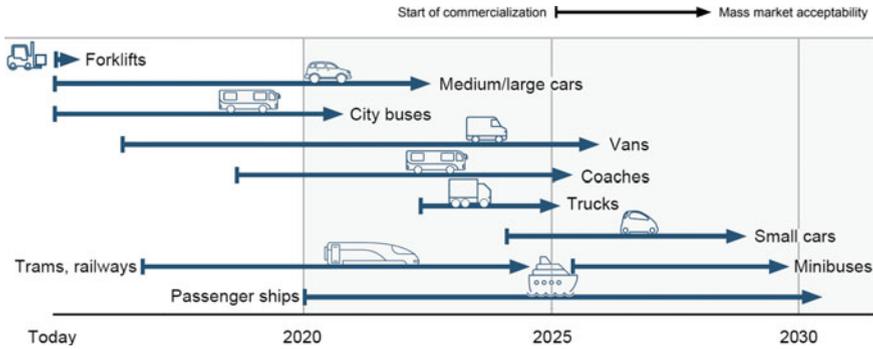


Fig. 2.2 Expected commercial availability of selected hydrogen transport technologies. Authors’ elaboration on Hydrogen Council (2017)

some technologies are already available, most of the others are expected to appear in the next five to ten years, although their penetration will likely be related to external factors including an effective deployment of a clean hydrogen supply chain and a competitive price with other powertrains.

Besides passenger cars, hydrogen-powered fuel cells are already being considered for other transport segments. Hydrogen buses are being tested in different locations, in particular in Europe, Japan, South Korea, and China, with fuel cells supporting larger buses over longer distances and with fewer interruptions than electric battery solutions. Coaches and intercity buses travelling for long distances are among the most profitable applications for hydrogen powertrains. The lack of infrastructure is less problematic, since municipal buses often rely on dedicated refueling stations. An even larger potential lies in trucks, especially considering the expected increase in road freight transport in the next decades. Some manufacturers are already testing hydrogen trucks (Toyota, Hyundai, and Nikola) that should be commercially available in the next few years, but parallel investments in hydrogen supply infrastructure will be fundamental. Also, Chinese firms and municipalities are investing in hydrogen trucks and buses, with the aim of decreasing their cost thanks to economies of scale (Liu, Kendall, & Yan, 2019).

Other applications include the substitution of diesel-powered trains on non-electrified tracks, which are already being tested in Germany and China, and the passenger ships such as river boats, ferries, and cruise ships. The main driver for the success of recreational activities will be the lower local emissions, water pollution as well as the decreased noise. Some projects are already under development in Germany, France, and Norway. Finally, more than 15,000 hydrogen-powered forklifts are already operating in warehouses today, including large projects in the USA by Amazon and Walmart (Hydrogen Council, 2017), thanks to their lower costs than electric solutions when high uptime is required.

To give some numbers on hydrogen-powered road transport, as of the end of 2018, the global hydrogen vehicles stock exceeded 12,900 vehicles, with a 80% increase over the previous year (AFC TCP, 2019). Almost half of the vehicles (46%) are in the

USA, followed by Japan (23%) and China (14%), the latter being the only country in which commercial vehicles have a larger share than passenger cars. Several countries are fixing challenging targets for the next decades, including South Korea, Japan, the USA (mainly California), China, and Europe.

2.2.6 Hydrogen Supply Chain and Infrastructure

The success of hydrogen transport will require the development of a proper infrastructure or refueling stations, together with a supply chain that is able to fulfill the demand by relying on low-carbon sources. This will require significant investments, and just like for electric charging stations with EVs, this infrastructure will probably need to be built before hydrogen vehicles reach interesting diffusion. This will likely require investors to wait a long time before seeing eventual returns, and while EVs could also benefit from existing infrastructure (e.g., home chargers), today's hydrogen demand is mostly concentrated in industrial facilities. In an early stage of development, transport applications with regular schedules (e.g., buses) may allow higher utilization rates for refueling stations, in the case of a careful planning and sizing of the expected demand.

The deployment of filling stations is a fundamental aspect to support a wide adoption of hydrogen vehicles in different segments. By the end of 2018, around 375 refueling stations were in operation worldwide (AFC TCP, 2019), with the three countries with most publicly available stations being Japan (100), Germany (60, and the USA (44). National plans to support the deployment of refueling stations aim at reaching 1000 stations by 2030 (in China and Germany) or by 2028 in France, while South Korea aims at 1200 stations by 2040. In a first phase, the development of hydrogen trucks may require fewer stations than for passenger cars, thanks to the limited number of routes and the more regular frequency of operation (Heid, Linder, Orthofer, & Wilthner, 2017).

In parallel to the final supply of hydrogen to vehicles, an upscale of the current hydrogen generation capacity from low-carbon sources will be necessary to deliver the benefits related to the shift from current oil-based technologies. While electrolyzers are already mature technologies, their cost is still higher than hydrogen production from fossil fuels (mostly natural gas and coal). While coupling natural gas with CCUS may prove to be less expensive, attention must be paid on methane losses to avoid rebound effects. On the other hand, current electrolyzers have generally high investment costs, which need to be compensated by high utilization factors, which is not always the case when using dedicated renewable sources such as solar or wind power. An additional key parameter for the competitiveness of electrolyzers is the electricity cost. Any technology will need to be able to deliver clean hydrogen at an acceptable cost, either green hydrogen (from RES) or blue hydrogen (from fossil coupled with CCUS), to support competitive solutions for different transport segments.

An additional cost in the supply chain is related to storage and transport of hydrogen, since it will not be possible to generate where and when it is required by the user. The two main solutions are to store it as a compressed gas or either in liquid form, but while the former requires pressures up to 900 bar, the latter requires temperatures as low as 20 K (which means—253 °C). Both processes—compression and liquefaction—require a significant amount of additional energy and dedicated facilities, resulting in additional costs. The choice of the best solution should be done on a case-by-case basis, due to the multiple parameters involved, and the main aspects are usually the time span of the storage (liquid hydrogen involves a fraction of losses due to boil-off) and the distance over which it will need to be transported.

For short transport distances, the main alternatives include trucks, both for compressed or liquefied hydrogen, and pipelines. In some cases, existing natural gas assets may be directly used for hydrogen, if some technical requirements on the quality of material are met. Some countries are already testing a blend of hydrogen and natural gas, but this would not be an acceptable solution for vehicles powered by fuel cells, unless pure hydrogen could be separated again from natural gas. For long-haul international maritime transport, some companies are focusing on liquid hydrogen, although other solutions include the synthesis of other chemical components that can be kept almost at ambient temperature and pressure in a liquid form, such as ammonia or other liquid organic hydrogen carriers (LOH). In this latter case, an additional process is needed to reconvert these chemicals to pure hydrogen, unless ammonia can be used directly (e.g., as a propellant for ships, either with internal combustion engines or fuel cells).

2.2.7 Case Studies and Applications

While in different places around the world, hydrogen has already been used for testing different transport systems, some countries are now developing broader policy strategies to support a coherent and wider development of hydrogen use in their energy systems. A large vision based on multiple sectors is essential in order to guarantee that the hydrogen demand would be matched by a supply of clean hydrogen, to ensure lower carbon emissions and pollution in comparison with the traditional oil-based technologies.

The first country ever to envision the possibility of developing a hydrogen economy has been Iceland. Back in 1998, the government signed an official document proclaiming its intention to reduce Iceland's fossil fuel consumption in transport and fishing by developing hydrogen-based alternatives. In 1999, Icelandic New Energy was formed, a public-private company with the aim of supporting the transition toward a Hydrogen Society by 2050. The company was a joint venture of Daimler, Shell, Norsk Hydro, Iceland National Power Co., Reykjavik Energy, and the University of Iceland (ClimateWire, 2009). Iceland was already producing hydrogen from electrolysis for fertilizers, thanks to the abundance of clean and cheap electricity from hydropower and geothermal resources. The annual production of 2000 tons of

hydrogen would have been scaled up to 80–90,000 to supply the entire transportation and fishing sectors, reducing by 66% the carbon emissions of the country. In the following years, the company tested three hydrogen buses in Reykjavik and a commercial hydrogen refueling station, and 16 passenger vehicles were in operation in the capital. But after an interesting start, this experiment has strongly slowed down and finally stopped, also because of the strong economic turmoil that invested the country in 2008. Other problems were related to the low interest from manufacturers to produce hydrogen cars, since Iceland was a limited market and there was no significant interest from other countries, resulting in high costs related to limited production scale. Today, Iceland is still considering the possibility of using hydrogen, but in parallel to other available technologies, and Icelanders recently showed a great interest in electric vehicles, which are an effective alternative to fossil fuels imports, given the abundance of clean electricity generation on the island.

Today, another country that is showing a significant interest in hydrogen is Japan, which is committed to pioneer the world's first "Hydrogen Society," through a Basic Hydrogen Strategy released at the end of 2017. The country is aiming at becoming the world leader in innovative hydrogen technologies, with the aim of developing overseas hydrogen supply chains to diversify its primary energy supply, which is currently mostly relying on imported fossil fuels. Moreover, Japan considers the development of an international hydrogen supply chain as a significant opportunity to decrease the carbon emissions of multiple sectors, including power generation, industry, and mobility. Japan's state-backed approach is ambitious, as it involves domestic and overseas industry and government stakeholders on several cross-sectoral pilot projects (Nagashima, 2018), and international cooperation will be a crucial step for the success of the entire strategy. As long as transport is concerned, the country has set increasing targets for fuel cell vehicles, up to 800,000 units by 2030, which compares with a current passenger cars stock in the country of around 69 million (Statistics Japan, 2019). Other goals are set on hydrogen buses, trucks, and forklifts.

Other countries are declaring interest for hydrogen at different levels. Australia has recently published a "National Hydrogen Strategy" (with official translations in Korean and Japanese), with the aim of positioning the national industry among the world leaders by 2030 (COAG Energy Council, 2019). Germany is currently working on a hydrogen strategy, to support the role of national industries and utilities in securing a global leadership in hydrogen technologies. Other countries are gradually showing interest and testing applications in different sectors, and transport is among the most promising.

2.3 Biofuels—A Possible Complement?

Biofuels represent today the largest share of low-carbon energy use in the transport sector, and their production has seen an increasing trend in the last decade, thanks to dedicated supporting policies, especially in the European Union, in the USA, and in Brazil. Biofuels are usually blended with traditional oil products for road transport,

and thus they do not need a dedicated distribution infrastructure, since they can exploit the existing network of gasoline and diesel refueling stations. Concerns have been raised in the last years about the sustainability of biofuel production, considering the energy consumption during the production and transportation phases, as well as the effect of direct and indirect land use changes. For this reason, new policies are focusing on supporting advanced biofuels, whose feedstocks are not in competition with products used for food or feed.

While the role of biofuels blends is expected to gradually decrease due to the phase out of oil products in the long-term, in the short- and medium-term, they represent a very important tool to decarbonize transport. Moreover, bioenergy may remain the easier solution to decarbonize specific sectors such as aviation and international shipping, since alternative technologies are not yet matching the specific requirements in terms of fuel energy density. On a global basis, the IEA Sustainable Development Scenario estimates that biofuel production needs to triple to 280 Mtoe per year by 2030, representing 10% of final transport demand, compared to 3.5% today (IEA, 2019f).

2.3.1 Liquid Biofuels—Conventional and Advanced

The distinction between conventional and advanced biofuels, often referred as first and second generation, respectively, lies in the type of feedstock required for their production. While conventional biofuels rely on crops that are often in competition with production for food or feed, the aim of advanced biofuels is to exploit residues and wastes (including vegetable oils or animal fats) or energy crops that are cultivated on less productive and marginal areas, thus with a lower probability of land-use change impacts. Currently, the advanced biofuels represent only 1% of the total liquid biofuel production at global level, due to the higher costs caused by less mature technologies and supply chains, but their development is being supported by different policies in the main biofuel markets, including Europe, the USA, and Brazil (IRENA, 2019).

Conventional biofuels are generally divided into ethanol and biodiesel, which are blended at different levels with gasoline and petroleum diesel respectively. Global ethanol production reached 61.5 Mtoe in 2018, representing roughly two-thirds of total biofuel production for transportation (IEA, 2019d). The largest producer remains in the USA, which produced more than half of the world's output (33.5 Mtoe) using mostly corn as feedstock. Ethanol generation from sugarcane in Brazil reached a record of 18 Mtoe in 2018, while the rest of the world totaled 10 Mtoe only (mainly in EU, China and India). Ethanol is mainly blended to gasoline in different world countries, to reach policy mandates that are often set on specific blending targets. The share of ethanol in the fuel supplied to final users is generally limited to 5% (named E5) to 10% (E10) in Europe and the USA, to maximize the compatibility for existing vehicles running on gasoline, but in Brazil the proportion of ethanol can be as high as 25%. In the USA, ethanol is also available as E85, called also flex

fuel, but it can be used only on vehicles that are specially designed to be operated with it (which total to around 20 million vehicles in the USA, i.e., 8% of the total fleet), and the current infrastructure of refueling stations remains limited. Flex fuels vehicles represent the majority of vehicles sales in Brazil, while it remains marginal in Europe, although E85 is widely available in Sweden, France, and Germany.

In addition to ethanol, one-third of transport biofuels is represented by biodiesel and hydrogenated vegetable oil (HVO), the latter remaining limited to a marginal share. Biodiesel can be extracted by different oilseed crops, although the most popular feedstocks are rapeseed in Europe, soybean in the USA and Brazil, while Asian countries generally use palm, coconut, and jathropa oils. Biodiesel and HVO production reached a global 33 Mtoe in 2018, mostly in Europe (11.6 Mtoe), the USA (6.1 Mtoe), and Brazil (4.0 Mtoe). As for ethanol, biodiesel is usually blended with petroleum diesel, with shares limited to 5% (B5) or 20% (B20) without noticeable differences with traditional oil-based diesel fuel.

Among advanced biofuels, HVO is the only one that is showing an interesting potential, although it still remains marginal in comparison with traditional biodiesel. However, the hydrogenation process that is used for its generation has the advantage of producing a fuel with very high quality, potentially better than the equivalent oil-based diesel. Moreover, the output can be further processed to produce bio-jet, a very interesting solution to decarbonize the growing energy demand of aviation. In addition to HVO, other advanced biofuels include ethanol from lignocellulosic biomass, sustainable sourced biodiesel, and various drop-in fuels refined through thermochemical processes. These processes are generally characterized by early technological maturity, and regulatory uncertainty appears to be the most critical issue in limiting the investments (IRENA, 2019). However, different countries are setting specific targets for advanced biofuels in the next years, and thus an increase in production is expected.

2.3.2 Alternative Biofuels—Renewable Natural Gas

While liquid biofuels are currently representing most of the bioenergy in transport, some countries are evaluating the possibility of exploiting renewable methane, obtained through the upgrading of biogas produced by anaerobic digestion of agricultural or landfill wastes. Biogas plants are already a mature technology, applied in different countries to generate electricity and heat. Since biogas is generally a mix of methane and carbon dioxide, the upgrading to renewable methane would involve a process to separate the carbon dioxide and possibly store it or use it in other applications. One of the advantages of renewable methane is the possibility of exploiting existing natural gas infrastructure for transport, as well as natural gas vehicles that are already in operation in different countries worldwide, including China, Iran, India, Pakistan, Argentina, and Italy.

Biomethane is seeing a continuous increase in Europe, where its generation reached 19.4 TWh in 2017, up from 2.3 TWh five years earlier (EBA, 2019). The

number of plants reached 540 in 2017, although with a lower increase, due to the operation of larger plants in the last years. The countries with most plants are Germany, Sweden, the UK, and France, although considering the number of plants per inhabitant Sweden, Iceland, Denmark, and Switzerland take the lead. The potential remains very large, since there are currently almost 18,000 biogas plants in Europe, mostly used for power generation. A shift toward biomethane plants is generally seen as an opportunity to substitute the significant use of imported natural gas in different countries, although in some cases (e.g., Italy) dedicated policies are supporting the use of biomethane in the transport sector.

On the other hand, like every use of methane, attention is needed to avoid any gas leakage, which would have severe consequences on climate change issues. The emission of 1 kg of methane is equivalent to 28 kg of CO₂ under the common assumption of considering 100 years of time frame, but this figure rises to 84 kg of CO₂ if we consider only 20 years, meaning that CH₄ emissions will have a more significant impact in the short term (due to their average lifetime in the atmosphere).

2.4 Emissions of Available Technologies

In the previous section, we highlighted the main advantages and limitations of each decarbonization solution that needs to be evaluated by considering several aspects. On the other hand, to assess the potential benefits of each solution, it is important to compare the specific GHG emissions of the different sources, considering all the phases of the supply chain. Figure 2.3 shows the specific CO_{2-eq} emissions of different technologies for cars, based on a Life Cycle Assessment (LCA) approach. The plot is based on a literature review of multiple research works published recently, and each point represents a specific value for each technology. The limits of the boxes represent the first and third quartile of each distribution (i.e., they are representing the 25% and the 75% of the values), while the line in between represents the median value. The colors of the points represent the reference year that has been used for the study, which has an impact of the energy mix and the performance of the available technologies.

The strong variability of the points is due to the multiple aspects that are associated to the manufacturing and operation of the vehicles, as well as to the supply chain of each energy carrier. The variability is particularly high for electricity- and hydrogen-powered cars, due to the different sources that can be used for the energy generation. While they have both the potential to reach very low emission levels, the current electricity mixes and the hydrogen production from fossil fuels are still limiting the benefits that can be reached. For this reason, it is important to highlight that the deployment of such technologies needs to be coupled to an increase of low-carbon options for both electricity and hydrogen production.

Similar patterns are expected for other vehicles (buses, trucks, etc.), although the research works are mostly focused on cars, due to their higher impact in most countries and to the availability of a wider range of technological options. High-duty

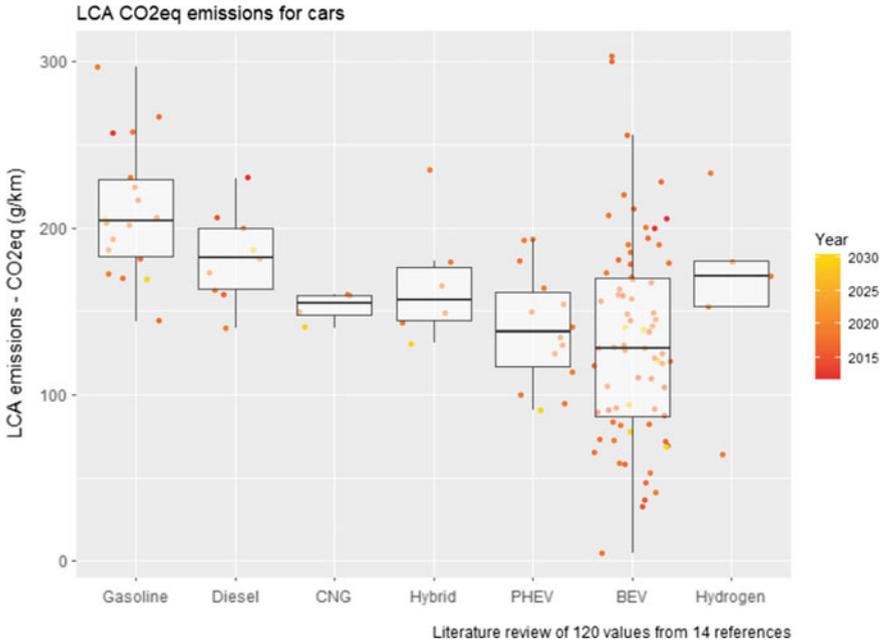


Fig. 2.3 Comparison of specific LCA emissions for cars based on different energy sources (CNG: compressed natural gas, PHEV: plug-in electric vehicle, BEV: battery electric vehicle)

vehicles are generally less suitable to use battery, especially for long-haul operations, due to their weight and space. The use of hydrogen may be a better option, although its efficiency on the entire value chain may remain lower than the direct use of electricity.

2.5 Other Decarbonization Measures

In parallel to alternative powertrain technologies, it is important to remind that other actions are needed toward a better use of vehicles, by optimizing their operation and increasing the average number of passengers. Private cars are often used by a driver without any passenger, especially when commuting for work. The implementation of carpooling services or an increased use of public transport may lead to strong emission savings without the need of investing in new technologies and supply chain. Effective sustainable mobility planning could play a strong role in transport decarbonization, just like energy efficiency is crucial in supporting the current transition toward a low-carbon energy system.

In the short-term, the adoption of more efficient vehicles can play a strong role in decreasing energy consumption in different transport segments. The continuous

technological development leads to significant improvements for new vehicles both for fuel consumption (and thus carbon emissions) as well as for pollutants abatement systems. This happens for cars, trucks, buses, and planes. Regulations and standards are continuously pushing manufacturers to improve their products, especially in developed countries. Unfortunately, the lack of regulations in most African and Asian countries is creating a large re-use of old vehicles that are no longer allowed in their country of origin. While re-use may save primary resources for manufacturing new vehicles, the additional fuel consumption and local environmental impacts may offset this advantage.

Significant savings for energy consumption and carbon emissions can be obtained through modal shifts from private cars, especially in urban environments. In particular, first- and last-mile trips can happen by walking or cycling, provided that separate bike lanes and walking paths are available to ensure the safety of the citizens. Active modes can be coupled with public transport to increase the efficiency of the mobility system, especially where electricity-powered solutions are available (e.g., light rail or subway systems).

Moreover, cars can be used more efficiently by increasing their average occupancy, which currently stands around 1.5–1.6 passengers per vehicle (including the driver) but drops to 1.1–1.2 for work trips. Carpooling schemes may help increasing these figures, when properly supported by sustainable mobility policies. Digital technologies may unlock successful business models by helping matching demand and supply of carpooling through dedicated web platforms (see Chap. 3).

2.6 Conclusions and Key Take-Aways

Transport remains among the most carbon-intensive sectors, due to its strong dependency on oil products, currently representing around 92% of final energy consumption in transport worldwide. Moreover, mobility demand is expected to increase significantly in the next decades, especially in Asia and Africa, leading to a huge rise of energy consumption and carbon emissions if no action is performed. Different technological options are available to help decarbonize the sector, and while many of them have already demonstrated a technical maturity, their cost is still higher than conventional fossil-based alternatives.

Electric vehicles are being seen as the most promising solution by many countries and car manufacturers, and thanks to specific policies EVs sales are showing promising trends in China, the USA, and Europe. Western countries are mostly focused on passenger cars, while in China electrification is affecting also buses and two-wheelers. However, to unlock the full decarbonization potential of EVs, proper measures are needed to increase the share of low-carbon sources in the electricity generation mix. While electricity may be a convenient source for light vehicles that need limited ranges, it may not be suitable for other sectors such as trucks, long-haul flights, and international shipping.

A potential complement to electrification may be the use of fuel cell vehicles powered by hydrogen, which can guarantee longer ranges and shorter refueling times. Just like electricity, hydrogen needs to be produced in a sustainable way from low-carbon sources, such as electrolysis powered by low-carbon electricity (green hydrogen) or natural gas reforming coupled to carbon capture use and storage systems (blue hydrogen). Current costs for hydrogen are not yet competitive, both for vehicles and supply chain, but manufacturing upscale may bring them down at the level of other transport solutions.

A third solution that is already commercialized since decades is represented by biofuels, although they are currently blended with traditional oil products. Biofuels, when produced in a sustainable way, will play a crucial role in the decarbonization of particular transport segments, especially aviation and shipping. Some challenges remain for the development of advanced biofuel pathways, which are not based on crops in competition with food or feed applications.

Finally, while there are different solutions being evaluated for the supply side, proper actions need to be taken on the demand side to use the available vehicle fleets in the most efficient way possible. Public transport and active modes should be preferred when available, especially in urban environments, and shared mobility options should be supported to increase the average vehicle occupancy and utilization rate.

While decarbonization policies will be crucial for tackling climate change, other aspects are involved in sustainable transport, including local pollution, congestions, noise, equitable access to mobility options, land use and safety of citizens. For this reason, it is important that policies are coordinated and discussed at multiple governance levels, as well as correctly communicated to citizens, to maximize their effectiveness and support a more efficient and sustainable transport system.

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