Impact of Zero Emission Vehicle Adoption on the Fuel Cycle and the Vehicle Cycle

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Abstract

The adoption of electric cars is considered a necessary step in the transition towards achieving net zero CO_2 emissions in the energy system. In this article, the shift to electric cars in road transport is discussed, focusing on the impact of Zero Emission Vehicle (ZEV) adoption on the fuel and vehicle cycles. Adopting ZEVs will shift fuel consumption in road transport from gasoline to hydrogen and electricity, affecting parts and services required for fuel production, transportation, and storage. Additionally, adopting ZEVs will shift the demand for services and part manufacturing from those required by internal combustion engines to those required by batteries, motors/generators, controllers/inverters, and fuel cells. Furthermore, if car mass reduction is targeted, material consumption for lightweight materials such as carbon fiber-reinforced polymers and glass fiber-reinforced polymers will increase, affecting services and parts required for manufacturing, maintaining, disposing, and recycling cars.

Introduction

Combustion of fossil fuels constitutes the main source of greenhouse gases (GHG), such as CO_2, CH_4, and N_2O. The transport sector relies heavily on fossil fuels and contributes significantly to global GHG emissions. According to the International Energy Agency (IEA) (IEA/OECD, 2021), the transport sector accounted for 24% of the 33,622 Mt-CO_2 emitted in the world from fossil fuel combustion in 2021, with the road transport sector representing around three-quarters of the transport sector CO_2 emissions. In particular, cars represent a significant share of energy consumption and CO_2 emissions from the transport sector. For instance, cars consume 52% of the energy and emit 41% of the CO_2 emissions from the transport sector in the world (WEC, 2011). In the future, the situation tends to be more critical as the number of cars worldwide increases. For instance, the Global Fuel Economy Initiative (GFEI) (GFEI, 2016) predicts the number of cars in the world to increase from 850 million in 2013 to more than 2 Billion vehicles by 2050.

The contribution of cars to global CO_2 emissions is explained by the widespread use of gasoline- and diesel-fueled internal combustion engine cars (ICEVs). For instance, more than 99% of the approximately 1.1 billion road vehicles (including cars, trucks, and buses) in the world in 2015 corresponded to ICEVs (IEA/OECD, 2017). Replacing the internal combustion engine with electric powertrains and shifting from fossil fuels to alternative fuels such as hydrogen or electricity can contribute to achieving net zero CO_2 emissions in the road transport sector. With the shift to electric powertrains, cars are experiencing a shift towards connectedness, automation, and sharing. These changes constitute a once-in-a-century revolution, and future cars are expected to be Connected Autonomous, Shared, and Electric (CASE). Despite the simultaneity of these changes, this article focuses only on the shift to electric powertrains, known as powertrain electrification.

Cars using electric powertrains include Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), Battery Electric Vehicles (BEVs), and Fuel Cell Electric Vehicles (FCEVs). The latter two types of cars, BEVs and FCEVs, have zero tailpipe CO_2 emissions. For that reason, they are often called Zero-Emission Vehicles (ZEVs). ZEVs are fundamental in achieving zero CO_2 emissions in the road transport sector. Despite ICEVs dominating the global car fleet, the number of electric cars in the world has been increasing steadily, reaching 16.5 Million cars in 2021 (IEA/OECD and EVI, 2022). Furthermore, with more ambitious goals for CO_2 emissions reductions related to achieving net zero CO_2 emissions in the energy system, global ZEV sales are expected to increase in the future, affecting the fuels, materials, parts, and services consumed by cars in the world. In this article, the shift to electric cars in road transport is discussed, focusing on the impact of ZEV adoption on the fuel and vehicle cycles.

Adoption of electric cars in the car fleet

A shift to electric cars is necessary to achieve zero CO_2 emissions in the road transport sector. However, the potential of electric cars to reduce CO_2 emissions in road transport depends not only on the CO_2 emissions reductions achievable by each powertrain but is also affected by the share of electric cars in the car fleet. For example, there are approximately 62 Million cars in Japan (AIRIA, 2022); if few BEVs enter the car fleet, the impact on road transport CO_2 emissions will be negligible despite BEVs having zero CO_2 emissions. The more BEVs enter the car fleet, the larger the CO2 emissions reductions. Eventually, if all the approximately 62 million cars in the Japanese fleet become BEVs, then zero CO_2 emissions in the car fleet will be possible.

However, the adoption of electric cars in the car fleet is a process that takes time, as the time lag effect of the car service life influences it. The service life of a car is in the order of decades. For example, in the case of Japan, the average service life of a car is 13 years for compact and normal cars and 15 years for mini-sized cars (Nishimura, 2011). In the case of developing countries, the average service life of the car is longer; such is the case of 26 years for cars in Colombia (González Palencia et al., 2012). When a car is manufactured, it enters the car fleet as a new car when the vehicle is purchased. The owner uses the car for several years and then sells it. Then other owner buys the car, uses the car for several years and sells the car. The process is repeated until the car is disposed of at the end of the car service life of. Therefore, it takes several years from when a new car enters the fleet until the car is disposed of at the end of the service life. This aspect must be considered when setting targets for CO_2 emissions reduction in the road transport sector. For instance, in the European Union (EU), gasoline car sales will be banned starting from 2035, considering that the average service life of a car in the EU is 15 years, and it is aimed to have zero CO_2 emissions by 2050 (Kottasová, 2023). In that sense, by 2050, the average gasoline car sold in 2035 will no longer be used.

The number of cars in a given country for a given year is determined by the number of cars in the previous years, the new car sales during that year, and the number of cars disposed of during that year. The resulting behavior shows that a country's number of cars is driven mainly by income. As income increases, people can afford a car causing the number of cars to increase until reaching a saturation value that varies from country to country depending on circumstances such as existing infrastructure and consumer preferences. New car sales can be classified into two types: new purchases and replacement purchases. New purchases correspond to cars purchased by people who did not own a car, while replacement purchases correspond to cars purchased by people who previously owned a car.

In developed countries, replacement purchases account for the majority of new car sales, causing the number of cars in the future to experience few variations. In the case of developing countries, it is expected that new purchases will account for the vast majority of new vehicle sales. As the number of cars in the world keeps growing, the majority of the increase in the number of new cars is expected to occur in developing countries, where new purchases account for the majority of new car sales.

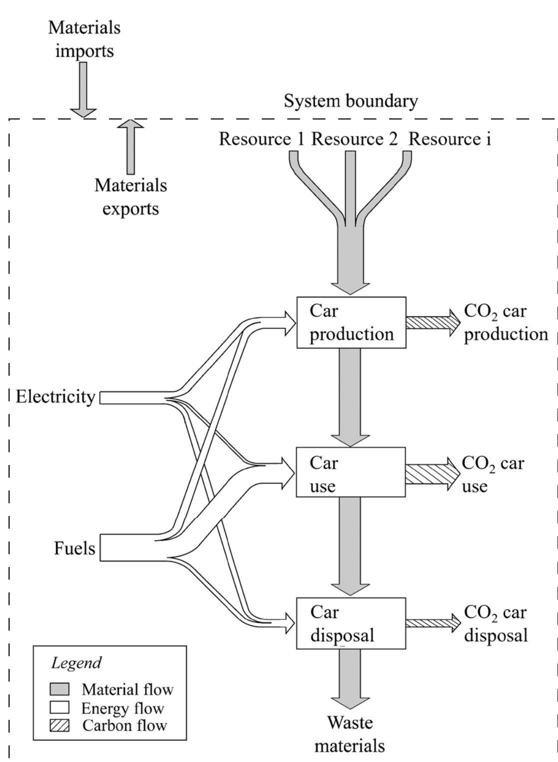

Figure 1. Energy and material flows associated with cars. Built using data from (González Palencia et al., 2012).

The adoption of new technology in any sector of the energy system usually takes place in an incremental manner. For example, in the case of telecommunications, telephones were adopted first, which were replaced by cellphones, which were replaced by smartphones. In the same way, an incremental way for the adoption of electric cars will be the shift from ICEVs to HEVs, later to PHEVs, to shift to BEVs or FCEVs finally. Based on data for the adoption of other technologies in the automotive sector, it has been estimated that it takes around 24 years for new technology to increase its market share from 10 to 90% (Hollinshead et al., 2005) (Grübler, 2003). In developed countries, the incremental pattern for the adopting electric cars is observed, with the number of HEVs, PHEVs, and BEVs gradually increasing. In the case of developing countries, the adoption of electric cars is at a very early stage, with new car sales for HEVs at very low levels and sales for PHEVs, BEVs, and FCEVs almost inexistent.

Similar to the adoption of cellphones and smartphones in developing countries where people went from not having a fixed telephone to having a cellphone or a smartphone without a fixed telephone, people can go from not having a car to purchasing a BEV or a FCEV directly. This leap-frogging approach can be very effective in adopting ZEVs and curbing the increase of CO_2 emissions from road transport. However, several economic barriers prevent the adoption of ZEVs. For instance, ZEVs have higher capital costs than ICEVs. Additionally, infrastructure development is required to charge BEVs and refuel FCEVs with hydrogen. The development of infrastructure to use electricity and hydrogen in road transport requires large investments. Since developing countries have lower incomes than developed countries, the primary option for consumers when purchasing a car will be the cheapest one, which is usually the gasoline-fueled ICEV. In that sense, leap-frogging to ZEVs in developing countries requires international cooperation to subsidize the cost differences between gasoline-fueled ICEVs and ZEVs using electricity and hydrogen.

The energy flows and material flows associated with cars used in road transport are shown in Figure 1. Shift from gasoline-fueled ICEVs to ZEVs will affect the demand for fuels in road transport, shifting from gasoline to electricity and hydrogen. Simultaneously, it will also affect the demand for materials and parts for car manufacturing. The impact of the adoption of electric cars on the fuel cycle and the vehicle cycle is discussed in the next sections.

Impact of the adoption of electric cars on the fuel cycle

ICEVs use fossil fuels such as gasoline, diesel, natural gas, and liquified petroleum gas as energy sources. Fossil fuels enter the engine mixed with air and are ignited to produce heat through combustion, emitting CO_2. Gasoline is the main fossil fuel used in cars. The main motivation for shifting to ZEVs is to replace gasoline with another fuel that does not produce CO_2 emissions during car use. However, replacing gasoline with electricity or hydrogen in road transport has significant implications for the fuel cycle.

To use gasoline in a car, oil is extracted from an oil well and transported to an oil refinery. Oil is processed at the oil refinery, obtaining gasoline and other products such as diesel and kerosene. Gasoline is then transported to the gas stations, where it is fueled into the tank of ICEVs. As shown in Figure 2, the fuel cycles for gasoline, electricity, and hydrogen used as fuels in road transport are very different.

In the case of electricity, energy resources are transported to the power plant, where electricity is generated. After that, electricity is transmitted and distributed using transmission and distribution lines. BEVs are charged using an electrical outlet. Electricity generation may produce CO_2 emissions depending on the energy resource used. Fossil fuels such as coal and natural gas are the main energy resources used in electricity production, and their combustion emits CO_2. In the case of renewable energy sources such as solar, wind, and hydro, electricity is produced with zero CO_2 emissions. Achieving net zero CO_2 emissions in the energy system requires a drastic reduction of CO_2 emissions across all sectors. If gasoline-fueled ICEVs are replaced with BEVs and electricity is produced using fossil fuels, CO_2 emissions will be shifted from road transport to electricity generation. In that sense, to boost the benefits of ZEV adoption in road transport, it is necessary to simultaneously promote the use of renewable energy resources for electricity generation.

In the case of hydrogen, there are several technologies for hydrogen production. 96% of the hydrogen in the world is produced from fossil fuels using technologies such as steam methane reforming (SMR), oil/NAFTA reforming, and coal gasification (Weger et al., 2017). SMR is probably the most common technology to produce hydrogen. Hydrogen production using SMR uses methane and water as feedstock and methane and electricity as energy resources. Hydrogen production using SMR emits 9 to 10 kg-CO_2/kg-H_2 during the process (Parkinson et al., 2018). Electrolysis using water as feedstock has been considered an option to produce hydrogen without emitting CO_2. In the case of electrolysis, electricity separates hydrogen and oxygen from the water molecule. CO_2 is not emitted directly from the electrolysis process. However, as mentioned above, electricity generation emits CO_2 if fossil fuels are used; and when assessed on a cradle-to-gate basis, electrolysis using electricity produced using fossil fuels emits more CO_2 than hydrogen production using SMR. For instance, using data from (González Palencia et al., 2022), it is estimated that hydrogen production using SMR emits 15.1 kg-CO_2/kg-H_2 on a cradle-to-gate basis, which is lower than CO_2 emissions for hydrogen production using electrolysis with electricity from the grid in Japan that emits 27.7 kg-CO_2/kg-H_2. In that sense, similar to BEVs, it is necessary to promote hydrogen production using electricity generated using renewable energy resources to boost the potential of ZEVs to reduce CO_2 emissions in the energy system.

Renewable energy use for electricity generation offers the advantage of zero CO_2 emissions. However, it has high variability and low availability, requiring large installed capacities to satisfy the demand. For example, Japan's solar photovoltaic electricity generation capacity factor is 0.12 (METI, 2014). This means that electricity can only be generated during 1,051 hours of the 8,760 hours in one year. In addition, electricity generation requires large capital investments and time to build power plants. For this reason, retrofitting current thermal power plants that use fossil fuels to prevent them from emitting CO_2 into the atmosphere is an attractive option for achieving carbon neutrality. This can be achieved using carbon capture and sequestration (CCS). In this case, CO_2 is separated from the exhaust gases after combustion, compressed, and stored in former oil or natural gas wells or other geological formations. Additionally, captured CO_2 can be used to cultivate microalgae that can be processed to produce biodiesel. In this case, CO_2 is used after capture, and the process is

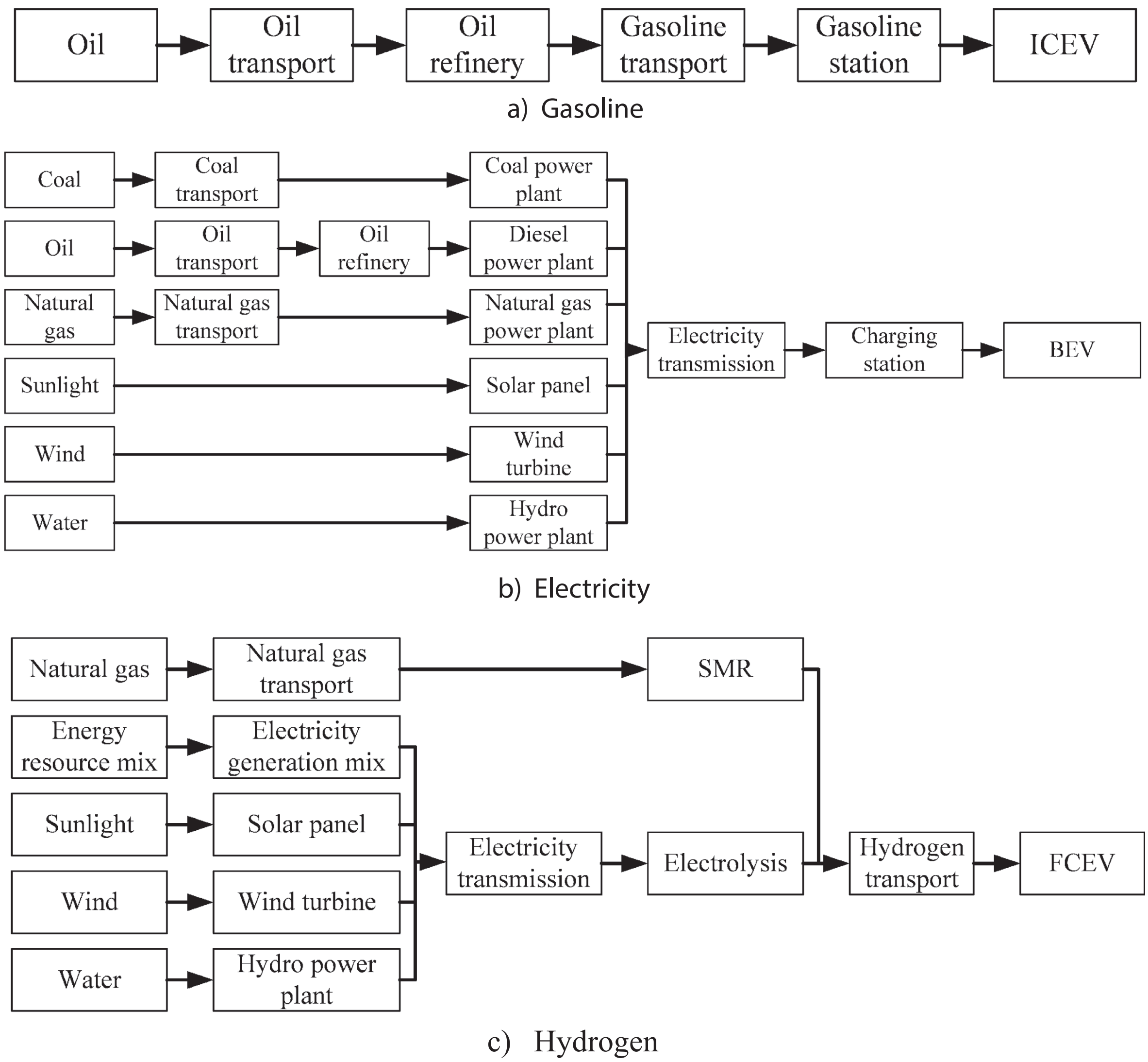

Figure 2. Fuel cycle for a) gasoline, b) electricity, and c) hydrogen

named carbon capture use and sequestration (CCUS). CO_2 can be used in different industrial processes and is not limited to fuel production.

Gasoline, electricity, and hydrogen production are processes intensive in the capital. For that reason, they are controlled mainly by large-scale enterprises. In contrast, small and medium-scale enterprises (SMEs) are part of the supply chain for fuel production for the transport sector as suppliers of services and parts for the technologies used in the energy conversion processes. In order to achieve net zero CO_2 emissions in the energy system, replacing gasoline with electricity and hydrogen will require a shift from oil refining to electricity generation using renewable energy and electrolysis. Services and parts for technologies required for fuel production will shift from those related to oil refining to those related to electricity generation using energy conversion technologies such as solar panels, wind turbines, and hydraulic turbines. Additionally, services and parts related to electrolysis will be required for using hydrogen in the road transport sector. In the case of CCS and CCUS adoption, there will be a demand for services and parts associated with the capture, use, and sequestration of CO_2.

Impact of the adoption of electric cars on the vehicle cycle

Fuel storage and energy conversion processes in cars vary significantly depending on the type of powertrain used. For this reason, the components and materials utilized also vary depending on the powertrain and the fuel used. The schematics of the main components of the powertrains for ICEVs, HEVs, BEVs, and FCEVs are shown in Figure 3.

In the case of gasoline-fueled ICEVs, gasoline is stored in the fuel tank and then injected into the engine cylinder using a fuel injector. Gasoline mixes with air,

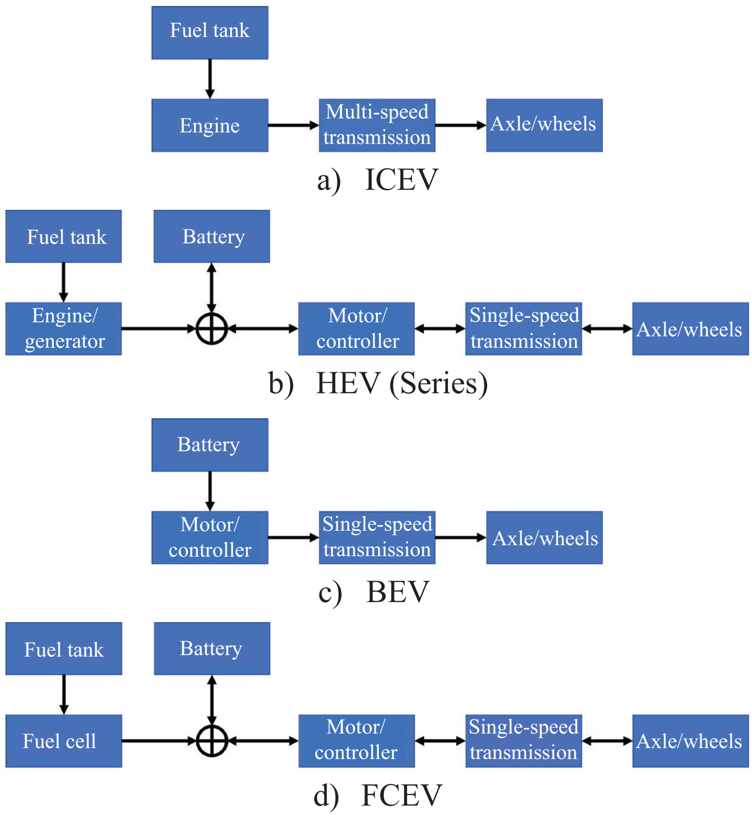

Figure 3. Schematic of the main components of the powertrain for a) ICEVs; b) HEVs (series configuration); c) BEVs; d) FCEVs. Based on data from (Simpson, 2005)

and it is ignited using a spark plug. The gasoline-air premix burns, generating heat that is transformed into work by the internal combustion engine, making the crankshaft rotate. Crankshaft movement is transmitted to the transmission, and it is connected to the axle that makes the tires rotate. In the case of HEVs, kinetic energy is regenerated during braking using a generator that produces electricity. Electricity is stored onboard using a battery, and converted to work in a motor. The motor shaft rotates, and movement is transmitted to the axle using a transmission, making the tires rotate.

In the case of BEVs, electricity is stored onboard using a battery. The electricity is converted to work in a motor, causing the shaft to rotate. Shaft movement is transmitted to the transmission connected to the axle, making the tires rotate. Similar to HEVs, kinetic energy is used to generate electricity using a generator, and electricity is stored in the battery during braking. Regarding FCEVs, hydrogen is stored at high pressure in a hydrogen tank onboard. Hydrogen is used to generate electricity in the fuel cell. Electricity is converted to work in a motor, causing the shaft to rotate. Shaft movement is transmitted to the transmission connected to the axle, making the tires rotate. Like HEVs and BEVs, in FCEVs, kinetic energy is used to generate electricity during braking using a generator, and electricity is stored in the battery.

Components and materials used in car manufacturing vary depending on the powertrain utilized. The main components of cars using different types of powertrains are presented in Table 1. At the same time, materials used in car manufacturing also change according to the powertrain used. Furthermore, to reduce vehicle mass, the use of lightweight materials has been gaining attention in recent years. Conventionally, steel is used for manufacturing the vehicle glider. Vehicle mass can be reduced by replacing steel with lightweight materials such as high-strength steel, carbon fiber reinforced polymers, and glass fiber reinforced polymers. The same strategy can be applied to other components in the car. As a result, the material breakdown of cars tends to change in the future, as shown in Figure 4.

Additional to lightweight materials used, car mass reduction can be achieved by reducing the size of the car. The main motivation behind car mass reduction is to reduce energy consumption. For instance, for gasoline-fueled ICEVs, every 100 kg mass reduction improves energy consumption by 7% (Cheah, 2010). In the case of electric cars, reducing car mass also

	ICEV	HEV	BEV	FCEV
Glider	✓	✓	✓	✓
Internal combustion engine	✓	✓		
Fuel cell stack				✓
Fuel tank	✓	✓		
Emission control electronics	✓	✓		
Transmission multi-speed	✓	✓		
Transmission single speed			✓	✓
Motor/generator		✓	✓	✓
Controller/inverter		✓	✓	✓
Fuel cell auxiliaries (including hydrogen storage)				✓
Li-ion battery		✓	✓	✓
Charger			✓	

Table 1. Main components for cars using different powertrains.

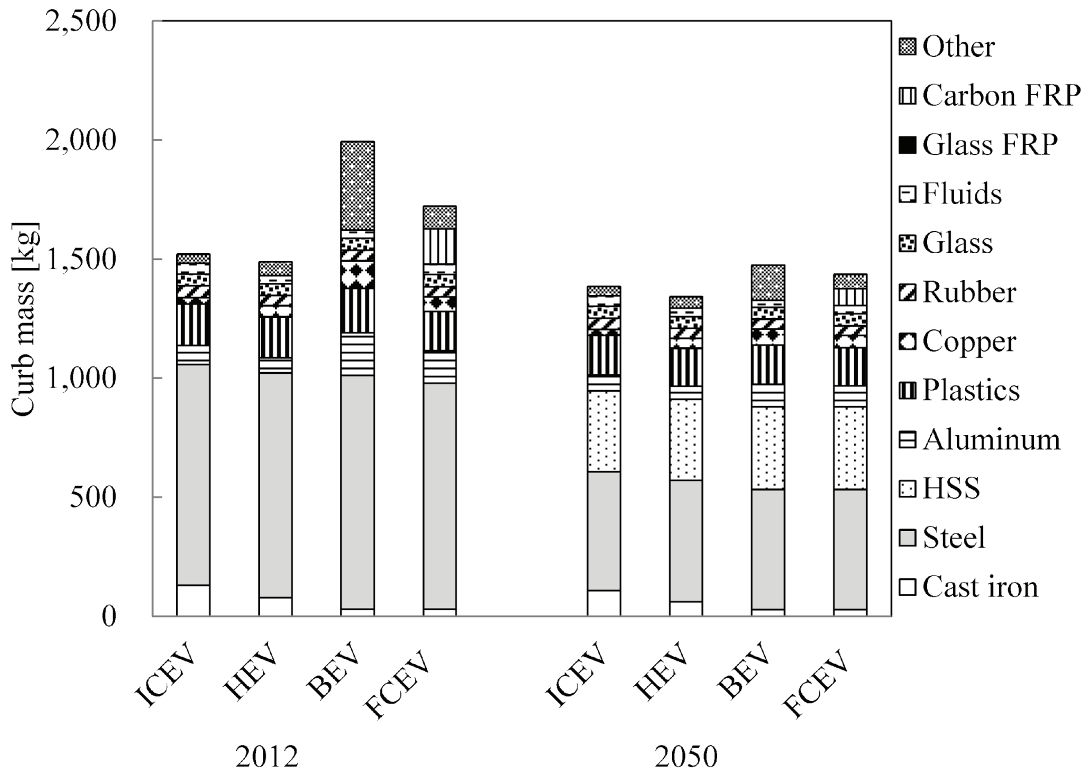

Figure 4. Change in material composition for normal cars in Japan between 2012 and 2050. Using data from (González Palencia et al., 2016)

contributes to reducing energy consumption. However, the impact of car mass on energy consumption is lower for electric cars than for ICEVs due to the increase in the energy conversion efficiency of the powertrain (Pagerit et al., 2006). Nevertheless, energy consumption reduction due to car mass reduction lowers the demand for electricity and hydrogen in road transport, requiring less infrastructure for adopting ZEVs.

SMEs are an important part of the car supply chain. SMEs engage in a large range of activities such as supplying parts and services for car manufacturing, supplying parts and services for material manufacturing, maintenance service during the car service life, recycling, and final disposal of parts and materials at the end of the car service life. Switching from gasoline-fueled ICEVs to electric cars will significantly impact the services and products that SMEs supply to the automotive sector. For example, in the case of the powertrain, demand for services and parts will shift from those required by internal combustion engines to those required by batteries, motors/generators, controllers/inverters, and fuel cells. In the case of lightweight materials used, shifting from steel to composite materials such as carbon fiber-reinforced polymers and glass fiber-reinforced polymers will change the process for material manufacturing and the process for parts manufacturing. Furthermore, the process for recycling and final disposal of parts made using lightweight materials will likely differ from the process for parts made of steel.

Conclusions

Replacing gasoline-fueled ICEVs with electric cars is considered a necessary step in achieving net zero CO_2 emissions in the energy system. In this article, the shift to electric cars in road transport is discussed, focusing on the impact of ZEV adoption on the fuel cycle and vehicle cycles. The main conclusions are as follows:

1. The adoption of electric cars in the car fleet is a process that takes time, as the time lag effect of the car service life influences it. Based on historical data for the adoption of other technologies in the automotive sector, it takes about 24 years for the market share of a new technology to increase from 10 to 90%. The share of electric cars in the car fleet affects the CO_2 emissions reduction potential.
2. Adoption of ZEVs will shift fuel consumption in road transport from gasoline to hydrogen and electricity. To boost the benefits of ZEV adoption for CO_2 emissions reduction, it is likely the simultaneous adoption of electricity using renewable energy and electrolysis. This will affect the parts and services required for fuel production, transportation, and storage.
3. Adopting ZEVs will shift the demand for services and parts manufacturing from those required by internal combustion engines to those required by batteries, motors/generators, controller/inverters, and fuel cells.

Furthermore, if vehicle mass reduction is targeted, material consumption for lightweight materials such as carbon fiber-reinforced polymers and glass fiber-reinforced polymers will increase, affecting services and parts required for manufacturing, maintaining, and disposing of cars.

References

- ✓ AIRIA, 2022. 2022 Vehicle Stock (in Japanese). Automobile Inspection & Registration Association. [online] available at: https://www.airia.or.jp/publish/statistics/ub83el00000000wo-att/01.pdf. Last accessed in March 2023.
- ✓ Cheah, L., 2010. Cars on a diet: The material and energy impacts of passenger vehicle weight reduction in the U.S. Doctor of Philosophy in Engineering Thesis, Engineering Systems Division. Massachusetts Institute of Technology, Cambridge, Mass.
- ✓ GFEI, 2016. Fuel Economy State of the World 2016; Time for global action. Global Fuel Economy Initiative, London.
- ✓ González Palencia, J.C., Araki, M., Shiga, S., 2016. Energy, environmental and economic impact of mini-sized and zero-emission vehicle diffusion on a light-duty vehicle fleet. Appl. Energy 181, 96–109. https://doi.org/10.1016/j.apenergy.2016.08.045
- ✓ González Palencia, J.C., Furubayashi, T., Nakata, T., 2012. Energy use and CO2 emissions reduction potential in passenger car fleet using zero emission vehicles and lightweight materials. Energy 48, 548–565. https://doi.org/10.1016/j.energy.2012.09.041
- ✓ González Palencia, J.C., Itoi, Y., Araki, M., 2022. Design of a Hydrogen Production System Considering Energy Consumption , Water Consumption , CO 2 Emissions and Cost. Energies 15, 7938. https://doi.org/https://doi.org/10.3390/en15217938
- ✓ Grübler, A., 2003. Technology and global change. Cambridge University Press, Cambridge, U.K.
- ✓ Hollinshead, M.J., Eastman, C.D., Etsell, T.H., 2005. Forecasting performance and market penetration of fuel cells in transportation. Fuel Cells Bull. 2005, 10–17.
- ✓ IEA/OECD, 2021. Greenhous Gas Emissions from Energy Highlights. International Energy Agency and Organization for Economic Cooperation and Development, [online] available at: https://www.iea.org/data-and-statistics/data-product/greenhouse-gas-emissions-from-energy-highlights#. Last accessed in November 2021, Paris.
- ✓ IEA/OECD, 2017. Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations. International Energy Agency and Organization for Economic Cooperation and Development, Paris.
- ✓ IEA/OECD, EVI, 2022. Global EV Outlook 2022: Securing supplies for an electric future. International Energy Agency/Organization for Economic Cooperation and Development and Electric Vehicles Initiative of the Clean Energy Ministerial.
- ✓ Kottasová, I., 2023. EU Was Set to Ban Internal Combustion Engine Cars. Then Germany Suddenly Changed Its Mind. Automobile Inspection & Registration Association. [online] available at: https://edition.cnn.com/2023/03/24/cars/eu-combustion-engine-debate-climate-intl/index.html. Last accessed in March 2023.
- ✓ METI, 2014. Significance of Introducing Renewable Energy and Characteristics of Each Source (in Japanese). Ministry of Economy, Trade and Industry. [online] available at: https://www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/mitoshi/004/pdf/004_05.pdf. Last accessed in May 2021.
- ✓ Nishimura, E., 2011. Assessing the fuel use and greenhouse gas emissions of future light-duty vehicles in Japan. Master of Science in Technology and Policy Thesis, Engineering System Division. Massachusetts Institute of Technology, Cambridge, Mass.
- ✓ Pagerit, S., Sharer, P., Rousseau, A., 2006. Fuel Economy Sensitivity to Vehicle Mass for Advanced Vehicle Powertrains, in: SAE World Congress & Exhibition, SAE Paper 2006-01-0665. Society of Automotive Engineers, Detroit, MI.
- ✓ Parkinson, B., Tabatabaei, M., Upham, D.C., Ballinger, B., Greig, C., Smart, S., McFarland, E., 2018. Hydrogen production using methane: Techno-economics of decarbonizing fuels and chemicals. Int. J. Hydrogen Energy 43, 2540–2555. https://doi.org/10.1016/j.ijhydene.2017.12.081
- ✓ Simpson, A.G., 2005. Parametric Modelling Of Energy Consumption In Road Vehicles. Doctor of Philosophy in Engineering Thesis, School of Information Technology and Electrical Engineering. The University of Queensland.
- ✓ WEC, 2011. Global Transport Scenarios 2050. World Energy Council, London.
- ✓ Weger, L., Abánades, A., Butler, T., 2017. Methane cracking as a bridge technology to the hydrogen economy. Int. J. Hydrogen Energy 42, 720–731. https://doi.org/10.1016/j.ijhydene.2016.11.029