Chapter 2
Sustainable Transportation

Carl Hergart

Abstract The past century has seen a remarkable rise in personal mobility and heavy goods transport. The development of the internal combustion engine has played a pivotal role in this development. Significant progress has been made in improving engine efficiency and reducing emissions. However, further improvements are necessary in order to meet local zero emission regulation as well as global climate goals. A rapid transition to renewable energy sources is key, enabling clean electricity generation and widespread deployment of sustainable fuels. Every country has a role to play. Developing nations must learn to become less dependent on fossil fuels as they grow their economies and industrialized nations must continue their sustainability journey and quickly transfer critical knowledge and lessons learned. Technologies should be assessed in terms of their life cycle impact and not simply their tailpipe emissions. As we consider the wide range of disparate applications across the transportation sector, we would be wise to embrace a fact-driven approach, keeping multiple options open and to build on past successes. Rather that betting it all on a single technology, a diverse mix of low-carbon technologies should be pursued.

Keywords Sustainability · Life cycle assessment · Internal combustion engines · Battery electric vehicles · Fuel cells · Hybrids

2.1 Setting the Scene

This book discusses a range of technologies relevant to transportation, including recent developments in combustion, alternative fuels and electrification. The purpose of this chapter is to provide some background and context for these topics and offer a perspective on sustainable transportation.

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2.1.1 Brief History

The history of transportation is as old as our need to explore the world around us. Early human migration some 100,000 years ago prompted the need for a robust means of transportation. Shoes, rafts, dugout canoes and the domestication of the horse were all important early developments prior to the groundbreaking invention of the wheel around 3500–4000 years BC (Anthony 2010). As we learned to master transportation on land and over the seas, doing so quickly and conveniently became important. Instead of pulling carts and wagons by hand or using horses and oxen, we started looking for some sort of machine. Such a contraption emerged in 1712 when Thomas Newcomen successfully demonstrated continuous power transmission of his atmospheric (steam) engine (Morris 2012). The subsequent improvement by James Watt in 1776 laid the foundation for the industrial revolution. Steam engines were initially adopted by ships and became fundamental to the birth of the railways.

Towards the latter half of the nineteenth century, as means to motorize coaches and carriages were explored, the steam engine and the electric motor were obvious candidates. However, by then another interesting technology had started to gain momentum: the internal combustion engine. It offered higher power density and efficiency than steam and better range than electric. While the new technology relied on a fuel less abundant at the time than coal and electricity, it was ultimately deemed the best choice to power the rapidly growing automotive industry.

Mass industrialization quickly followed when Henry Ford brought together the concepts of the moving assembly line, overhead conveyers and a unified production plant. From its introduction in 1908 until 1927, over 15 million Model T's were sold and significantly increased the mobility of society as a whole (Floyd 1955). As the market matured, customers started to place increasing emphasis on form to go along with the function, demanding variety and annual model updates. With Ford initially being reluctant to broaden its portfolio beyond the Model T, General Motors, with their slogan "a car for every purse and purpose" rapidly gained market share. In his excellent book (Sloan 1980) Alfred Sloan gives a first-hand detailed account of the early growth of the automotive industry, establishing many of the foundational pillars we take for granted today, such as financing, trade-ins, dealer networks, overseas operations and organized research and development.

The growing number of vehicles drove the need for a supporting infrastructure, including roads, fueling stations and a service network. The early cars drove almost exclusively on dirt or gravel roads. Today, there are about 250 million vehicles just in the United States, supported by over 4 million miles of paved road and about 150,000 fueling stations (U.S. 2020; Outlet and Survey 2018). Of the roughly 1.5 billion vehicles on the roads today worldwide, 99% of them are powered by internal combustion engines consuming around 50 million barrels of oil equivalent (BOE) every day (International Energy Agency 2021).

2.1.2 Environmental Impact

The environmental impact of the early transportation solutions was not immediately apparent, but already in the 1870s concerns were raised about the noxious smoke produced by steam locomotives. The very first underground railway, the City and South London Railway, actually prohibited the use of steam power, favoring electric locomotives (Duffy 2010).

In the 1940s a phenomenon referred to as smog started appearing in Southern California and Pennsylvania, causing stinging eyes and respiratory irritation. Haagen-Smit showed that the smog resulted from a photochemical reaction of unburned hydrocarbons, ground-level ozone and nitrogen oxides (NO_x), originating from vehicle exhaust and industrial power generation (Haagen-Smit 1952). This groundbreaking discovery eventually led to the first vehicle emissions control system, positive crankcase ventilation, being introduced in 1961 in the State of California. Six years later the California Air Resources Board (CARB) was created and the Environmental Protection Agency (EPA) followed in 1970. In Europe, the European Economic Community (EEC) established rules, initially considerably less stringent than those in the United States, introduced in stages by engine displacement.

As regulations tightened, it became clear that the engine tuning required to meet the new emissions standards would incur an unacceptable fuel consumption penalty. This led to the invention of the catalytic converter, which was introduced on gasoline vehicles starting in 1975. The ensuing 35 years would see significant further emissions reduction resulting from several major developments including electronic engine control, advanced fuel injection systems, exhaust gas recirculation, sophisticated aftertreatment and combustion optimization. At the same time fuels became cleaner and better adapted to the engine. For example, gasoline fuels came to incorporate additives to inhibit engine knock and the amount of sulfur was limited in diesel fuel to ensure the durability of aftertreatment systems.

These efforts have been very effective in reducing the criteria pollutants NO_x, hydrocarbons (HC), carbon monoxide (CO) and particulate matter (PM), significantly improving the air quality in cities across the world. However, another issue has come to dominate the environmental debate: global warming.

2.1.3 Global Warming

Global warming or the 'Greenhouse effect', as it is sometimes referred to, is a naturally occurring phenomenon resulting from certain gases in the atmosphere absorbing and emitting infrared radiation. These so-called Greenhouse Gases (GHGs) include water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3), as well as manufactured halocarbons, such as chlorofluorocarbons (CFCs). Their ability to absorb and emit infrared radiation goes back to their polyatomic structure, which gives them a dipole property and a vibration spectrum in

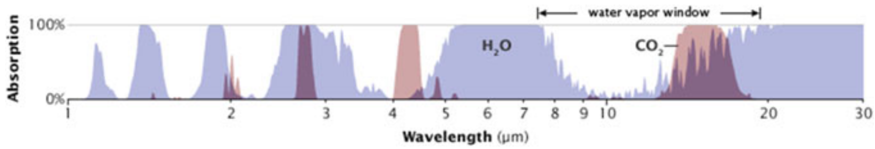

Fig. 2.1 Absorption spectrum of water vapor and carbon dioxide (Lindsay 2009)

the infrared. Diatomic molecules such as oxygen and nitrogen—while vastly more abundant than the GHGs—do not absorb radiation in the infrared and consequently do not contribute to global warming. Without the greenhouse effect, Earth would be approximately 35 degrees Celsius cooler and unable to sustain life as we know it. Hence, the GHGs can be thought of as a kind of 'thermostat' that keeps us alive. Ozone also provides the benefit of absorbing the high-energy ultraviolet radiation from the sun, thus acting as an effective and life-saving sun screen.

In order to understand the significance of carbon dioxide in the global warming discussion it is important to recognize that Earth's temperature is governed by a delicate balance between the incoming radiation from the sun, reflection by clouds and particles in the atmosphere, reflection from the surface of Earth and absorption by particles and molecules in the atmosphere (both incoming and outgoing). Any disturbance to the system, such as increased reflection through particles in the atmosphere or elevated absorption from gases in the atmosphere, will change the equilibrium and will result in a different temperature on Earth (Lindsay 2009). Figure 2.1 shows the absorption spectrum of water vapor and carbon dioxide, where 100% absorption means no radiation is getting through. Conversely, areas of low absorption are referred to as 'atmospheric windows', through which radiation can escape into space. We note that water is the dominant molecule in absorbing electromagnetic radiation in the infrared and is therefore mostly responsible for the heat being trapped in Earth's atmosphere. However, it is the 12–15 μm region in the infrared that is key to our understanding of the impact of CO_2. This is an area of the spectrum where water vapor does not absorb a lot of radiation, thus elevating the importance of CO_2. Moreover, this particular wavelength range happens to overlap with the peak of Earth's surface radiation. Hence, elevated levels of CO_2 effectively close this 'water vapor window' through which heat otherwise would escape.

Ice cores found in Vostok have allowed scientists to establish a correlation between CO_2 and temperature, dating back some 800,000 years (Lüthi et al. 2008), see Fig. 2.2. Until around 1950, through multiple ice ages and times of warmer climate, the CO_2 levels never exceeded 300 ppm. Since then, a sharp increase has been observed and as of August 2020 the atmospheric concentration of CO_2 was 410 ppm (Lindsey 2020). It is generally accepted that this recent spike in CO_2 has its origin in human activity and specifically the amount of CO_2 released into the atmosphere.

Most of the CO_2 is generated by the energy sector, whereas transportation is responsible for approximately 23% of the annual output (BP Energy Outlook 2020). When it comes to GHGs, the transportation contribution is even less, 14% (United States Environment Protection Agency (EPA) 2020). Hence, it is important to note

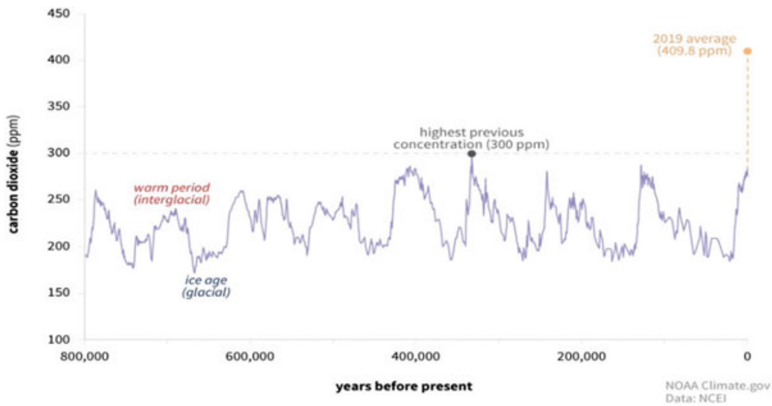

Fig. 2.2 Atmospheric CO_2 concentration measured at high resolution using preserved air samples from ice cores (Lindsey 2020)

that while CO_2 generated from vehicles indeed plays a significant role, it cannot alone solve the global warming problem. The goal of reducing CO_2 from transportation happens to be very well aligned with the objective of improving vehicle efficiency. The next section will review ways in which this can be accomplished.

2.2 Vehicle Efficiency Technologies

This book discusses a range of engine and powertrain technologies aimed at improving efficiency and sustainability. Regardless of the technology, there are a number of generic efficiency building blocks that are beneficial. This section will provide an overview of the key ones.

As seen in Fig. 2.3 (Stanton 2013), which shows the energy losses occurring in a

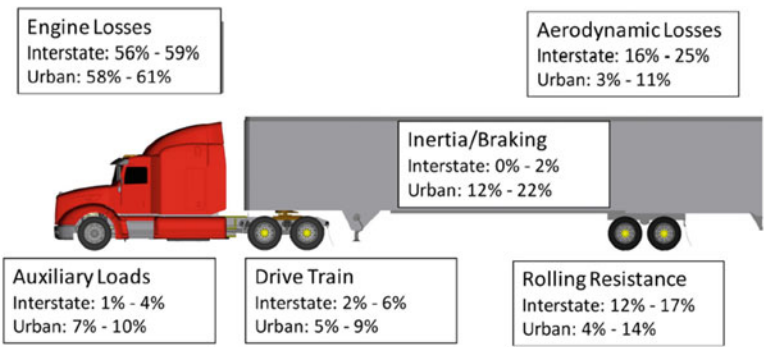

Fig. 2.3 Vehicle energy loss during long-haul and urban operation (Stanton 2013)

typical heavy-duty truck, aerodynamic losses account for 16–25% of the total energy loss during highway driving. Today's trucks have come a long way in reducing drag thanks to technologies such as cab extenders, aerodynamic bumpers, tandem fairings, vented mud flaps, chassis skirts, side fairings and wheel well covers, just to name a few.

Rolling resistance is responsible for another 12–17% during highway operation. One of the most rapidly growing technologies adopted by fuel economy minded fleets today is tire pressure monitoring or inflation systems. Auxiliary loads, responsible for up to 10% of the total energy loss during urban operation, include air conditioning, power steering, cooling and lighting. Ways of reducing these losses will be discussed later when discussing mild hybridization. The overall energy required to move the vehicle is also heavily dependent on its weight. New materials enable lighter structures, but care has to be exercised in order not to sacrifice structural integrity and durability.

Another new and interesting way to reduce the vehicle energy requirement is to leverage connectivity and automation. Current examples include predictive cruise control for heavy-duty trucks, where GPS[1]-based terrain information is used to control vehicle set speed, such that fuel consumption is minimized. Over-The-Air (OTA) software updates are also being deployed across the industry to ensure vehicles have the latest controls and calibrations updates for optimal safety, reliability and efficiency. Vehicle platooning is yet another example, where two or more trucks are connected wirelessly, enabling optimization of the following distance through synchronization of braking and steering systems.

By leveraging Vehicle-to-X (V2X) connectivity, where 'X' can include things like traffic information, weather and infrastructure information (e.g. bridge heights and weight limits), vehicles can be 'eco-routed' in a way that minimizes overall energy use. The information generated from V2X can also be used to reduce the volume of trucks carrying empty or below capacity loads, as discussed by Hvolby et al. (2019).

With increased reliance on connectivity comes more stringent requirements for cyber security. New regulation is being introduced to reflect this as part of the UN-ECE Cyber Security regulation (United Nations Economic and Social Council 2020).

Whereas many of these technologies have been commercialized and are readily available, they are not universally adopted. In their 2019 annual fleet fuel study, the North American Council for Freight Efficiency (NACFE) concluded that truck fleets adopting efficiency improving technologies and practices achieved 14% better fuel economy than a 'Business as Usual' scenario (North American Council for Freight Efficiency 2019).

Figure 2.3 also shows that most of the vehicle losses occur in the powertrain (engine and drivetrain) and we will devote the next sub-sections to an introduction of the traditional powertrain topology featuring an internal combustion engine as well as alternative ones relying on full- or partial electrification.

[1] The Global Positioning System enables localization by triangulating information from satellites.

2.2.1 *Internal Combustion Engine Powertrains*

As mentioned in the introduction, the vast majority of vehicles on the roads today are powered by Internal Combustion Engines (ICE). The task of optimizing engine performance and efficiency is one of maximizing the yield from the chemical energy stored in the fuel. This requires a fundamental understanding of where the losses occur. Figure 2.4 shows a Sankey diagram of the energy flow in a heavy-duty truck equipped with a diesel engine during highway cruising. We note that 20–25% of the energy available in the fuel goes out with the exhaust flow. Part of this energy is used to drive a turbocharger and provides heat for the aftertreatment. The remainder is oftentimes referred to as 'waste heat' and presents an interesting opportunity to improve overall efficiency as will be discussed further below.

10–15% is lost through heat transfer during the combustion process. Insulating the combustion chamber, valves, ports and exhaust pipe have all been explored with various degree of success. The vision of an adiabatic engine remains elusive in spite of extensive research, as reported in Hergart et al. (2005).

Waste Heat Recovery. Two widely explored ways of recovering waste heat energy are turbocompounding and the Rankine bottoming cycle. Turbocompounding, as the name implies, involves "compounding" the power to the crankshaft by adding turbine shaft power to the power transferred through the pistons. The compounding power can come from an independent downstream power turbine or from the turbocharger turbine (Aghaali and Ångstrom 2015). Depending on the application and load cycle, turbocompounding can provide significant fuel economy improvement. However, the technology adds complexity and cost and thus represents a challenging business case for many applications. It is important to recognize that turbocompounding is not a drop-in solution. The engine turbocharger has to be re-matched to provide the

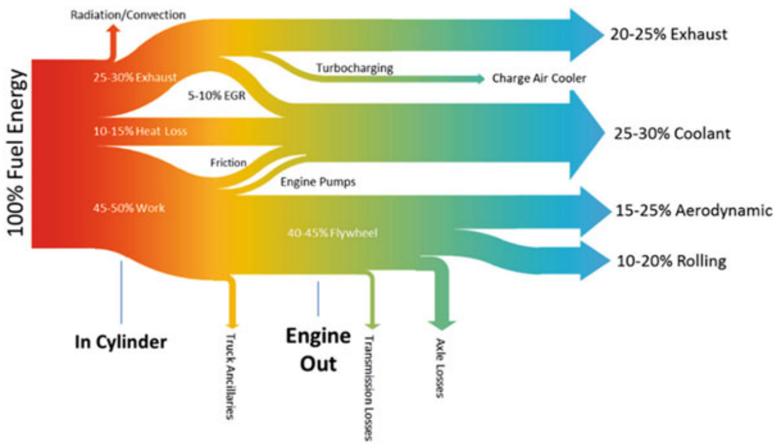

Fig. 2.4 Energy flow in a diesel engine during highway operation

required air flow and the combustion process has to be recalibrated to the new boost pressures. As the amount of energy extracted from the power turbine increases, the power of the reciprocating part of the engine typically goes down.

With the Rankine cycle, a working fluid undergoes a thermodynamic cycle, going from liquid to vapor and back to liquid, using exhaust waste heat and engine coolant. When the working fluid is an organic compound, the cycle is often referred to as the Organic Rankine Cycle (ORC), as opposed to the steam cycle used to describe the process when using water. ORC can provide up to 4% fuel economy improvement over a typical load cycle depending on how many waste sources are used.[2] Current industry developments are focused on reducing cost and complexity, providing attractive payback periods for customers adopting the technology (Xu et al. 2019).

Engine Efficiency. As shown in Fig. 2.4, 45–50% of the energy contained within the fuel can be used towards the propulsion of the vehicle. This represents the typical peak Brake Thermal Efficiency (BTE) of a modern diesel engine.[3] For gasoline engines, the BTE number is lower, primarily owing to the throttling losses associated with maintaining a stoichiometric fuel-air mixture and to a lesser extent due to the lower in-cylinder specific heat ratio and lower compression ratios required to prevent knock. Gasoline Direct Injection (GDI) has emerged as a means to increase the efficiency of gasoline engines, as discussed by Kalghatgi (2019) and Leach et al. (2020). Regardless of the fuel, increasing the brake thermal efficiency of the engine is of primary interest owing to its impact on the Total Cost of Ownership (TCO) for the vehicle operator and its direct impact on reducing CO_2 emissions.

The design of today's combustion chambers is the result of a century worth of practical experience enhanced by sophisticated high-fidelity simulations, optimizing parameters such as piston bowl shape, injector- and port geometry. Improvements in material properties have enabled friction reduction, increases in peak cylinder pressure and turbocharger speeds, ultimately increasing efficiency while complying with ever more stringent emissions standards. Figure 2.5 shows how the peak Brake Thermal Efficiency (BTE) of diesel engines in commercial trucks has evolved since 1960. The slight dip in efficiency around 2002 is attributed to the introduction of Exhaust Gas Recirculation (EGR), which required increasing the engine back pressure. Modern truck engines are almost 50% more efficient than their predecessors. Still, there is appetite for more. The U.S. Department of Energy established a goal of 55% BTE for the SuperTruck II program (Meijer and Grover 2020), which is also indicated in Fig. 2.5 with the dashed line. Focus areas for additional efficiency gains include improved combustion efficiency, e.g. through the use of Miller-cycle, increased turbocharger efficiency and reduced friction and parasitic losses.

[2] Potential energy sources for an Organic Rankine Cycle based waste heat recovery system include engine exhaust, EGR, engine coolant and charge air coolers.

[3] It is not unusual for large ship diesel engines, operating at constant speed and load, to achieve in excess of 50% BTE.

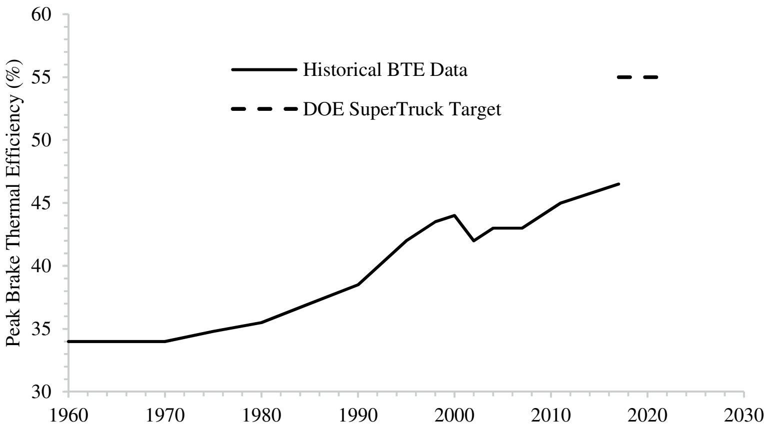

Fig. 2.5 Historical evolution of peak engine Brake Thermal Efficiency (BTE) in heavy-duty truck engines along with the Department of Energy SuperTruck II target

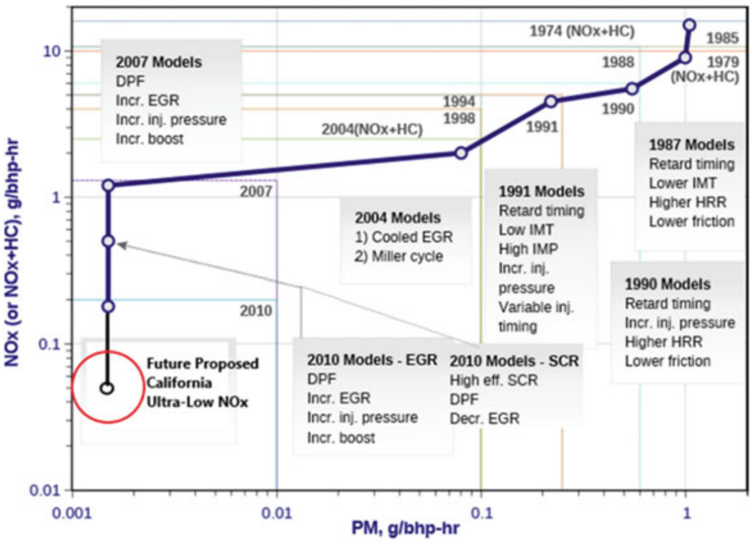

Fig. 2.6 Evolution of Heavy-Duty on-road NO_x and PM emissions in North America

ICE Emissions Reduction. The significant rise in efficiency has been accompanied by a remarkable reduction in criteria emissions.[4] Figure 2.6 shows the evolution of engine tailpipe Nitrogen Oxides (NO_x) and Particulate Matter (PM) standards for Heavy-Duty diesel engines in North America over the past 50 years, along with the major key enabling technologies. From 1985 until 2002, Heavy-Duty on-road

[4] The criteria pollutants are carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO_2), ozone (O_3), particulate matter (PM), and sulfur dioxide (SO_2).

emissions standards in North America were largely achieved by optimizing and calibrating in-cylinder performance parameters. In 2002–2004 EGR was introduced and 2007 saw the widespread adoption of aftertreatment systems. Over the last three decades NO_x and particulates have been reduced by over two orders of magnitude. The mass of particulates originating from the combustion process is now less than that produced through tire wear and in some instances the exhaust from an engine is cleaner than the air coming into the engine (Reitz et al. 2020). Meanwhile, the efforts to reduce engine emissions continue unabated. California has proposed a new Ultra-Low NO_x rule to be phased in starting in 2024 (California Air Resources Board 2020) and the European Commission is considering more stringent legislation for Euro VII in the 2025–27 timeframe (ACEA 2020a).

Advanced aftertreatment will continue to play a key role in enabling these regulations to be met without negatively impacting efficiency and CO_2. Modern diesel engines are equipped with a system consisting of a Diesel Oxidation Catalyst (DOC), a Diesel Particulate Filter (DPF), a Selective Catalytic Reduction (SCR) catalyst and an Ammonia Slip Catalyst (ASC). These components have to be designed in such a way as to optimize the overall system efficiency, while meeting prevailing emissions standards. With future emissions regulation placing an increasing emphasis on low temperature performance during warm-up and low-load duty cycles, aftertreatment thermal management will become more challenging.

Fuels. It goes without saying that the type of fuel used in the engine has a major impact on the emissions. The vast majority of ICEs on the roads today use either gasoline or diesel, both being fossil fuels and thus contributing to global CO_2 emissions. Natural gas has the potential to reduce CO_2 by about 20% compared to diesel, but typically adds cost to the vehicle and struggles to meet the performance requirements. Biofuel and e-fuels represent two interesting options to reduce the carbon footprint of ICEs. While the respective chemistries involved in making them are fundamentally different, the common denominator is that CO_2 is consumed in the production process.[5] In the case of biofuels, the CO_2 is consumed by a plant or algae, whereas e-fuels rely on carbon capture. Both classes of fuels produce CO_2 when they are burned and consequently give back the CO_2 consumed during the production, thus making them overall carbon neutral. It is of particular interest to produce fuels that are sufficiently similar in their thermodynamic properties that they can be used as a drop-in replacement for either gasoline or diesel. As such, these fuels provide a tremendous opportunity to reduce the carbon footprint of the existing vehicle fleet. Hydrotreated Vegetable Oil (HVO) represents an excellent alternative available today to reduce the carbon intensity of diesel by a factor of 10 (Emission and Factors 2021). The challenge is that cheap renewable energy is not readily available, which is limiting the supply of these fuels.

There are also fuels that do not contain any carbon, such as hydrogen and ammonia. Both are subject to active research with hydrogen getting most of the attention currently. As an ICE fuel, hydrogen has proven to be quite competitive from an

[5] Assumes renewable energy is used in the production process.

efficiency perspective (Verhelst 2014) and the NO_x produced in the combustion process can be controlled through standard aftertreatment technologies. Most of the hydrogen discussion these days, though, revolves around fuel cells, owing to their potential for higher efficiency than hydrogen-powered ICEs.

Whereas hydrogen has the highest gravimetric energy density out of any fuel, its volumetric energy density is orders of magnitudes lower than gasoline and diesel. Because of this, fuel tanks need to store the hydrogen compressed, cryogenically or through the use of chemical or adsorptive bonds to solids or liquids—all very expensive methods.

It is also relevant to consider how the hydrogen is made. The three main production methods are coal gasification, steam methane reforming (SMR) and water electrolysis. Different "colors" are used as a terminology to distinguish between these methods (Senecal and Leach 2021). Brown or grey hydrogen is the result of coal gasification or SMR[6] and represents the vast majority (around 95%) of current global production, whereas green hydrogen is generated through water electrolysis using renewable energy. The color designation of the hydrogen is highly relevant when assessing the overall life cycle impact of hydrogen-based technologies. Regardless of the production method, the hydrogen itself is effectively the same, although certain methods may introduce undesired impurities.

ICE powertrain integration. In order to obtain optimum performance and efficiency, the internal combustion engine has to be properly integrated with the overall powertrain. Transmission and axle ratios have to be selected in such a way that overall performance requirements are met while maximizing the amount of time the engine spends operating in its most efficient region.

Powertrain downspeeding is an effective means to improving efficiency. However, whereas both axles and transmission clearly benefit from downspeeding, the situation is a bit more complicated in an engine. In a downspeed engine, the combustion takes place within a shorter crank angle window, which gets the overall process closer to the ideal thermodynamic constant volume cycle. The turbocharger also tends to operate more efficiently at reduced speeds. On the other hand, in order to maintain power output, a downspeed engine has to develop higher torque, which is typically accompanied by increased cylinder pressures and thermal loads. The core engine design and overall powertrain configuration become very important in the ability to benefit from downspeeding.

2.2.2 Electric Powertrains

A range of powertrains involving some level of electrification are receiving plenty of attention in recent years partly driven by the need to operate vehicles in zero emission

[6] SMR production of hydrogen can be made carbon neutral by capturing the CO_2 produced. Hydrogen obtained this way is referred to as 'blue hydrogen'.

mode within geofenced areas (Bannon 2030). In the following we will provide a brief overview of the following technologies:

- Mild hybrid
- Full hybrid
- Battery Electric
- Fuel Cell.

With regards to hybrids, the discussion will revolve around combinations of electric motors and internal combustion engines.

Mild Hybrid. A mild hybrid offers an interesting intermediate step between the conventional ICE powertrains and all-electric ones. A key attribute of the mild hybrid is the ability to power accessories, such as power steering, air conditioning compressor and water pump more efficiently by decoupling their operation from the engine. As electric propulsion is not the chief purpose of a mild hybrid, the motor can be kept small and compact and there is no need for a large battery pack. A key design decision for the mild hybrid is the position of the electric motor. Figure 2.7 shows the five major configurations in which to place the electric motor/generator.

The choice of configuration becomes a trade-off between cost, efficiency and feature capabilities. Table 2.1 summarizes some of the key attributes associated with

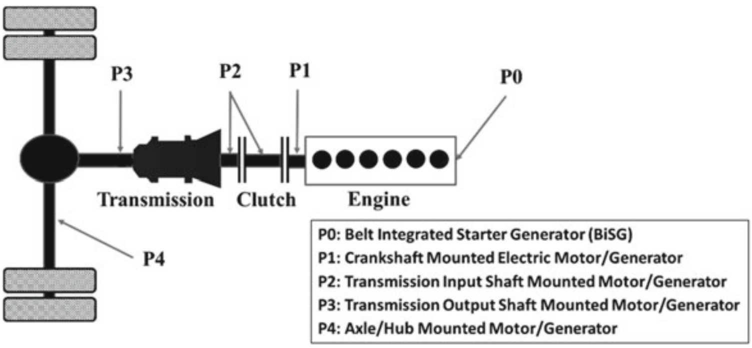

Fig. 2.7 Mild hybrid powertrain topologies

Table 2.1 Mild hybrid configurations and features

Topology	Stop/Start	Accessory electrification	Regen. braking	Torque assist	Engine-off coasting	All-electric propulsion	Torque vectoring
P0	●	●	●	●			
P1	●	●	●	●			
P2	●	●	●	●	●	●	
P3	●	●	●	●	●	●	●
P4	●	●	●	●	●	●	●

each concept. A P0 Belt integrated Starter Generator (BiSG) is a common and cost effective mild hybrid topology owing to its relatively minor impact on the existing vehicle architecture. However, it has limitations in the amount of fuel savings it offers and is not capable of engine-off coasting or all-electric propulsion.

Another attractive feature of a mild hybrid is the potential to provide thermal management to engine aftertreatment devices, which has become a highly relevant topic in light of the stringent regulation being imposed in Europe and North America, as discussed previously.

Full Hybrid. In a full hybrid, the electric motor takes on a more prominent role in the vehicle system by serving as tractive power source in addition to fulfilling all the tasks of the mild hybrid. As a consequence, full hybrids require much larger battery packs and electric motors. There are three main architectures: series, parallel and power-split, as shown in Fig. 2.8. All architectures are shown with an ICE below, but this can in principle be replaced by any type of primary energy converter. The choice of architecture depends on the application and comes with its own set of attributes. In a series hybrid the ICE is not directly connected to the drivetrain, but its output power is converted to electrical power used to charge the batteries via a generator. The energy in the batteries is used to power the electric motor, providing tractive power to turn the wheels. The decoupling of the ICE from the driveline allows the engine to operate at a more constant speed and load, which is beneficial from an efficiency and emissions standpoint and also avoids load transients. Furthermore, the engine can be switched off entirely, enabling all-electric operation. A series hybrid is sometimes referred to as a range-extender, since the ICE is effectively used to replenish the energy used by the batteries to power the electric motor. Because all traction power is provided by the batteries and the electric motor, these have to be sized accordingly, typically leading to a fairly large and expensive design. Furthermore, there is obviously an energy loss associated with converting mechanical energy into electrical and back to mechanical.

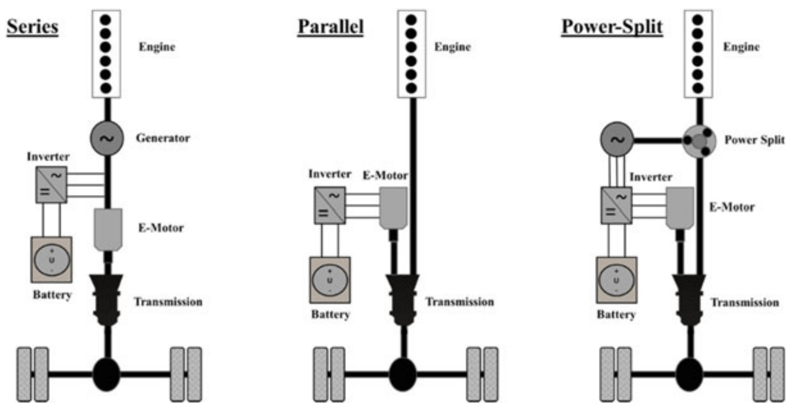

Fig. 2.8 Full hybrid architectures (left to right): Series, parallel and power-split

In a parallel hybrid, both the ICE and the electric motor are directly connected to the drivetrain and combine to provide the necessary traction power. This allows a level of powertrain optimization, such that, for example, the ICE is the primary power source during sustained highway driving, whereas the electric motor provides power during stop-and-go situations at low speeds. By splitting the duties of providing traction power, the power sources can be downsized. A smaller battery pack and electric motor typically translate into reduced overall cost and weight for a parallel hybrid than its series counterpart.

It is also possible to combine the two architectures into a series-parallel, or power-split hybrid, which aims to capitalize on the respective benefits of the series and the parallel. During low-speed, highly transient operation, the vehicle acts like a series hybrid, gradually transitioning to a parallel configuration during highway operation. This leads to increased complexity in the design and powertrain control and also requires a larger battery pack than the parallel hybrid.

A vehicle featuring the ability to charge the batteries from an external power source is called a Plug-In Hybrid Electric Vehicle (PHEV).

Battery Electric Vehicle. A battery electric vehicle relies solely on the electric power source for tractive power. The key components of an all-electric powertrain are the battery pack, electric motor, inverter and potentially a transmission depending on the application. The battery pack has to be sized to provide the desired range and have proper controls and thermal management to achieve adequate cycle life.

The voltage level is primarily dictated by the amount of power required, since the maximum current is effectively limited by the cost and weight of connectors and wires as well as the ability to route the cables. Higher current levels are also associated with winding losses.

A key architectural decision relative to all-electric powertrains is where to place the electric motor. There are broadly speaking three possibilities: Central Drive, e-axle and hub motors, as shown in Fig. 2.9. There are pros and cons associated with each. The central drive configuration retains the conventional driveline and axles and provides easy transmission packaging. An integrated e-axle benefits from a direct connection between motor, transmission and wheel ends, not requiring a bevel gear to connect a driveline to the rear axle. Consequently, e-axles have the potential of being

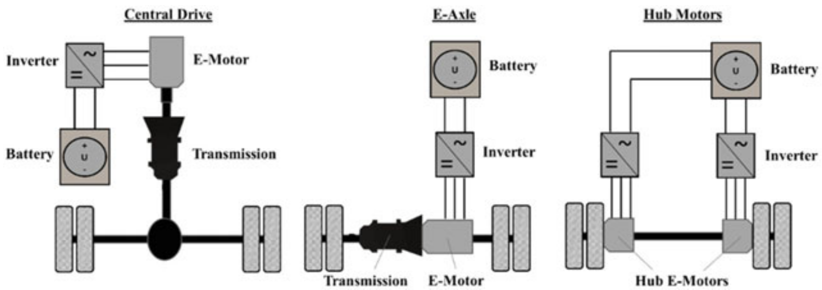

Fig. 2.9 Battery electric powertrain topologies (left to right): Central drive, e-axle and hub motors

a little bit more efficient than the central drive topology. However, challenges include un-sprung masses, vibration, hose- and wire flexing and packaging (especially when a gearbox is necessary). Hub motors are advantageous in terms of efficiency and also allow torque vectoring, but typically add cost.

Another key design decision is whether or not to connect a transmission to the electric motor. While less speed sensitive than diesel engines, the efficiency of electric motors does vary with speed and there are limits to their operation. The e-motor ratio defines the ratio between maximum and nominal motor speed. Depending on this ratio and the application requirements, a 1–4 speed transmission may be necessary. The most common motor types are Permanent Magnet Synchronous Machines (PMSM), Induction Magnet (IM), Synchro Reluctance (SynRel), and External Excited Synchro Machine (EESM). Of these the PMSM and the EESM typically offer the highest efficiency and power density, whereas the other types are more attractive in terms of cost.

Battery Technology. Choosing a battery starts with a clear understanding of the application. The amount of packaging space available determines the amount of capacity that can be accommodated for a given cell chemistry and form factor. The mission and duty cycle govern the necessary charge and discharge rates, which in turn have an impact on the amount of cooling required. The rate at which a battery is charged or discharged is characterized by the C-rate, defined as the battery power delivered divided by its energy capacity. Hence, a 10 kWh battery delivering 20 kW is being discharged at a C-rate of $2h^{-1}$. High C-rate capability (~10) is important in mild hybrid applications featuring stop-start. The need for high power density is also the reason for lead acid batteries being used in conventional vehicles to power e.g. the starter motor and the ignition system. Conversely, battery electric vehicle batteries are typically designed for C-rates between 0.5 and 1.

The lithium-ion battery has established itself as the dominant cell chemistry in battery electric vehicles. There is a wide range of different types, distinguished primarily by the type of material used for the cathode.[7] Figure 2.10 shows the trade-off between power and energy density for a range of different Li-ion battery types (Thelen and Bubna 2018). Nickel-Cobalt-Aluminum (NCA) and Nickel-Manganese-Cobalt Oxide (NMC) batteries have the highest energy density and are most common among battery electric passenger cars. Lithium-Titanate-Oxide (LTO) and Lithium-Manganese-Oxide (LMO) with their relatively high specific power are better suited for hybrid applications. There are several active efforts to increase the energy density, e.g. the Battery-500 consortium managed by PNNL, which aims to achieve 500 Wh/kg (Pacific Northwest National Laboratories 2021). Future chemistries (Li-Air, Al-Air, Zinc-Air) are expected to significantly improve specific energy and help the BEV/PHEV adoption, but currently suffer from limitations of the air cathode cycle life. Sodium-ion batteries are also being explored given concerns about the availability and cost of lithium (Fang et al. 2020). The use of solid-state electrolytes offers the potential for improved safety, energy density and faster charging capability.

[7] There are exceptions, such as the Lithium Titanate Oxide (LTO) battery, which is named after its anode material.

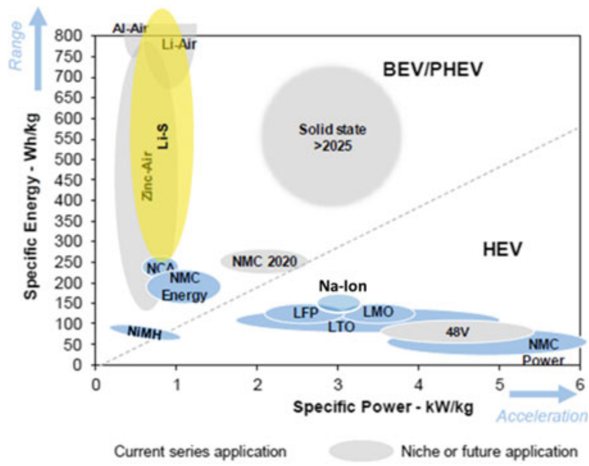

Fig. 2.10 Battery power vs. energy trade-off (Thelen and Bubna 2018)

However, the manufacturing is more complex and involve more hazardous materials (Advanced Propulsion Centre 2021a).

Battery cells, which typically have a voltage of 2–4 V each, are combined into modules and subsequently to packs. There are three main ways in which the cells are combined into modules: cylindrical, prismatic and pouch types. The choice effectively comes down to a trade-off between space utilization and thermal management. Cylindrical cells provides poor space utilization, but lend themselves to relatively straightforward thermal management. Prismatic cells make optimal use of the available space, but are more challenging to cool and are also less forgiving to cell swelling. Pouch cells are very flexible and provide excellent cell space utilization. However, they typically require some sort of support structure. Of the three types, pouch cells also suffer from the highest amount of swelling, which has to be taken into account in the thermal management and cell packaging.

Battery cost remains a major challenge. However, as seen in Fig. 2.11, significant progress has been made in recent years with further improvements expected as the installed capacity continues to grow.

Fuel Cell Electric Vehicle (FCEV). Similar to Battery Electric Vehicles (BEVs), Fuel Cell Electric Vehicles (FCEVs) rely on electricity to drive a motor, which provides propulsion power to the wheels. In that sense, the prior discussion on powertrain topology for BEVs applies here as well. However, unlike BEVs, FCEVs generate the electricity on-board and requires a continuous flow of reactants to sustain

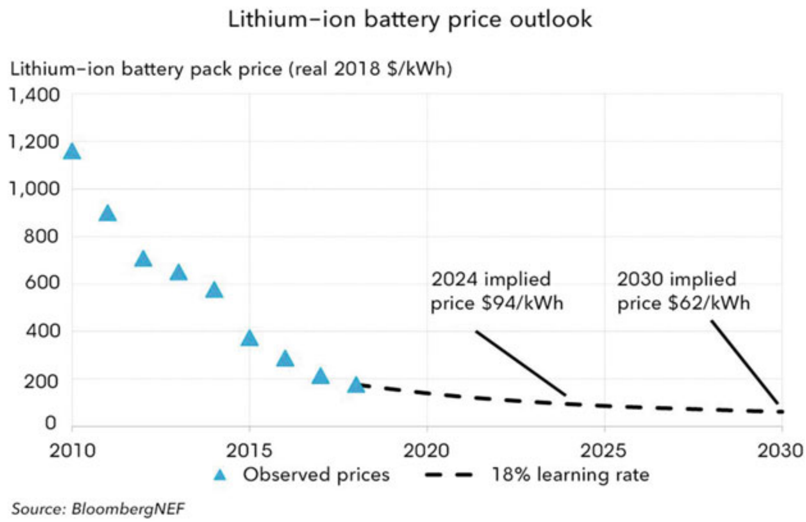

Fig. 2.11 Li-ion battery pack price outlook (BloombergNEF 2018)

the operation. FCEVs therefore do not need nearly the amount of battery capacity that BEVs do.[8] This gives them an advantage in weight and fueling times.[9]

There are a number of different types of fuel cells, but they all feature an anode, a cathode and an electrolyte allowing charged ions to flow between the electrodes. In all but one (the solid oxide fuel cell), an oxidation reaction—assisted by a catalyst—occurs at the anode, generating positively charged ions and negatively charged electrons. The positively charged ions travel through the electrolyte, which is a semipermeable membrane that acts as an electrical insulator (O'Hayre et al. 2016). The electrolyte does not allow the electrons to go through, instead routing them through an electrical circuit from anode to cathode, thereby producing electricity. The type of electrolyte is used to classify the different kinds of fuel cells. The most commonly used fuel cell for automotive applications is the Polymer Electrolyte Membrane (PEM), also referred to as the Proton Exchange Membrane (PEM) type. Figure 2.12 shows a schematic of a PEM Fuel Cell (PEMFC) system. The heart of the fuel cell is the Membrane Electrode Assembly (MEA), which includes the membrane (electrolyte), the catalyst layers (electrodes), and Gas Diffusion Layers (GDLs). The latter facilitate transport of the reactants, i.e. hydrogen for the anode and oxygen for the cathode, into the catalyst layers. Because each MEA only produces a rather modest voltage, typically less than 1 V, several MEAs are connected in series to produce a fuel cell stack. Each MEA is separated by so-called Bipolar Plates (BPP) made of metal, carbon or composites, providing electrical conduction between cells and

[8] The presence of a battery is important in providing adequate transient response for the FCEV, since the fuel cell itself is limited in this respect.

[9] The time it takes to fill up a FCEV is comparable to that of an ICEV, whereas BEVs are an order of magnitude higher. However, proper pre-cooling of the hydrogen is required.

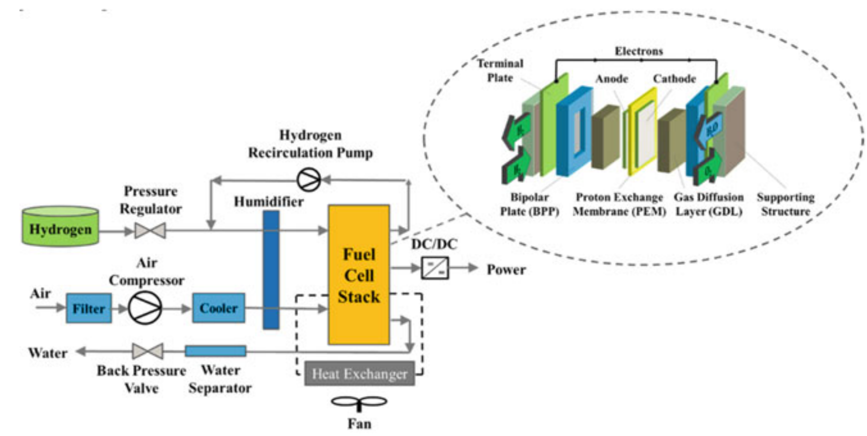

Fig. 2.12 Fuel cell system and stack schematic

strengthening the stack structure. Gaskets are also important parts of a fuel cell in order to prevent gas leaks.

In order to make the system work several other components are required, as shown in Fig. 2.12. These include, filters, valves, pumps, fans, compressors, humidifiers, controllers and DC/DC converters. Of the energy present in the hydrogen, roughly a third is lost to heat, which highlights the need for proper stack cooling. Another 5% or so is lost through membrane purging and leakage, such that the average stack efficiency is typically around 60%. The coolant pump and the air compressor consume about 5% of this, resulting in an overall system efficiency of around 55% (Sens et al. 2021). Efforts to improve the efficiency include reducing the electrochemical losses through optimized BPPs and GDLs and lowering power consumption of the system components. Increasing the operating temperature also have the potential to boost efficiency.[10] As a result of these developments, the efficiency is likely to improve in the future with some sources predicting 70% overall system efficiency in the next 15 years (Advanced Propulsion Centre 2021b).

Other major focus areas in the fuel cell research and development is to reduce cost and improve durability. The stack accounts for approximately 2/3 of the fuel cell system cost (excluding the hydrogen storage system) and efforts are underway to reduce the amount of Platinum Group Metals (PGM) used in the catalyst layers, finding cheaper materials for the BPPs and innovative GDL designs. However, the biggest potential lies in achieving economies of scale and optimized manufacturing. The worldwide number of fuel cell vehicles was about 23,000 in 2019, triple the figure in 2017 (International Energy Agency 2020). Continued growth will be necessary in order to sustain the cost reduction trend. This is of course also predicated by the

[10] Temperature control is very important for the fuel cell stack. The operating temperature for a PEMFC is the range of 50–100 °C, whereas it can be up to 1000 °C for a solid oxide fuel cell.

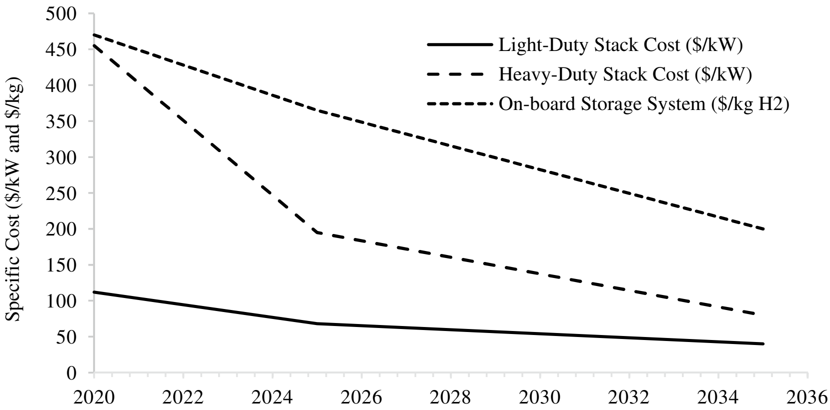

Fig. 2.13 Key fuel cell component cost projections (Advanced Propulsion Centre 2021b)

availability of extensive hydrogen fueling infrastructure and competitive fuel prices ($2/kg desirable vs. today's ~ $14–16/kg).

Figure 2.13 shows the cost trends for light- and heavy-duty fuel cell costs along with the on-board storage. Hitting these targets will be essential in order to begin to rival the Total Cost of Ownership (TCO) of a vehicle powered by an internal combustion engine.

The durability of a fuel cell is impacted by the duty cycle, the thermal management and the design of the stack. In particular, catalyst aging leading to a reduction in active surface area can result in voltage loss over time. Impurities in the hydrogen may also impact catalyst performance and work is ongoing to reduce the sensitivity of the catalysts to such mechanisms. The current stack durability of 5,000 and 15,000 h, respectively for light- and heavy-duty applications will need to be further improved in order for the technology to gain widespread adoption.

2.3 The Way Forward

As the previous sections have shown, the history of transportation has been marked by significant progress, but also unintended consequences. Time and again, the transportation industry has responded to the challenges put forth by coming up with innovative solutions to further improve efficiency and reduce the environmental impact. As humanity faces its perhaps biggest challenge yet, posed by climate change, it is more important than ever for scientists and engineers across multiple disciplines to develop sustainable transport solutions and for policies to be guided by hard facts. Before entering into a discussion on potential solutions, it is useful to first clearly state the problem we are trying to solve. It can broadly be summarized as follows:

> The amount of greenhouse gases added to the atmosphere needs to be reduced and eventually eliminated, such that we limit the temperature rise in the atmosphere and thus prevent anthropogenic climate change. Preferred transport solutions minimize greenhouse gases over the entire product life cycle and provide intermittent zero vehicle emission capability as required in geofenced areas while sustaining continued economic growth.

As a problem statement, it serves the purpose, but it lacks specificity. In order to be able to develop an effective strategy, we need to know the answers to questions like:

- By how much do we need to reduce GHGs? What areas need zero emission operation?
- How do we assess technologies in light of their GHG impact?
- How should the responsibility be divided among industry sectors and countries?
- Are the solutions we propose realistic, i.e. do they support continued economic growth and can they be achieved in time?
- By when do we need to have the solutions in place?

The objective of this section is to provide suggestions to these questions, positioning us to make some recommendations on the way forward towards a more sustainable future.

2.3.1 The Carbon Budget

To date 195 nations have signed onto the Paris Agreement (United Nations 2015), setting out a goal to limit global warming in this century to well below 2, preferably 1.5 degrees Celsius, compared to pre-industrial levels. The 1.5 degree figure was derived by the Intergovernmental Panel on Climate Change (IPCC), which stated that "with global warming of 1.5 degrees Celsius there would be increased risks to health, livelihood, food security, water supply, human security, and economic growth" (IPCC 2018). As we have seen from the opening section of this chapter, atmospheric temperature is intimately linked to the amount of GHGs. Specifically, the amount of additional CO_2 we can allow to go into the atmosphere prior to exceeding the previously discussed temperature target is referred to as the *carbon budget*. Estimates vary in the literature, but generally range between 200 and 600 billion tons of CO_2 equivalent. At the current rate of about 35 Billion tons of CO_2 being emitted annually, along with another 15 Billion tons coming from other GHG emissions (Ritchie and Roser 2020), it is clear that the carbon budget will be exhausted in the relative near term unless the global output is quickly reduced. This is confirmed by various atmospheric models, taking into account things like deforestation as well as biological and anthropogenic CO_2 emissions. Even the most optimistic scenarios only predict another 20 years until the carbon budget is exhausted (Hausfather 2018).

2.3.2 *Carbon Intensity and Life Cycle Analysis*

Any climate policy must be based on a good understanding of the sources of greenhouse gas emissions and what their relative contributions are. Carbon footprint is a commonly used term to characterize the amount of CO_2 directly or indirectly produced from human activities. As it pertains to transportation, carbon intensity is a good measure, defined as:

$$Carbon\ Intensity = \frac{Carbon\ Dioxide\ Produced\ (\mathrm{g})}{Energy\ Consumed\ (\mathrm{kWh})} \tag{2.1}$$

When considering the carbon intensity resulting from the various technologies we have discussed previously, it is important to look beyond the emissions generated during the use phase and consider the impact over the entire life cycle of the vehicle. Such a concept is referred to as a Life Cycle Assessment (LCA), and represents an ISO 14040/44 method to calculate the environmental impacts of products, covering the entire life cycle from cradle to grave, starting at the extracting and refining of raw materials and ending with the recycling of components and material. Figure 2.14 illustrates the different phases of LCA.

The amount of CO_2 generated in each stage varies significantly depending on the specific technology. Unfortunately, most of the debate today tends to revolve around the energy production, Well-To-Tank (WTW) and product use phase, Tank-To-Wheel (TTW). This is also reflected in the tailpipe focused CO_2 regulations being introduced in Europe and North America. And while the emissions originating from these phases are significant, dominant in many cases, disregarding the contributions from other stages of the life cycle results in a skewed picture and may in fact lead to the wrong conclusions. In a study commissioned by FVV, the German Research Association for Internal Combustion Engines, Bothe and Steinfort reviewed over 80 publications on LCA and concluded that there were not enough comprehensive studies that take all stages of the product life cycle into account (Bothe and

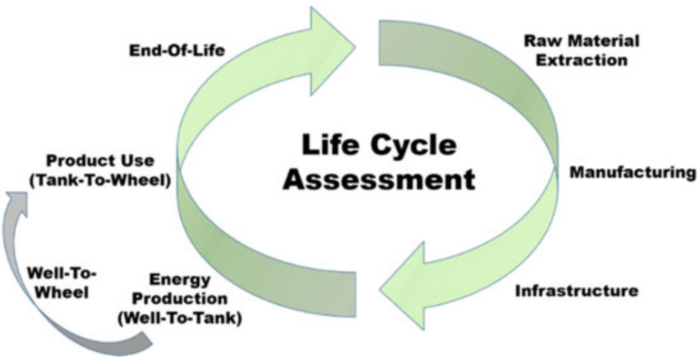

Fig. 2.14 Vehicle Life Cycle Assessment (LCA)

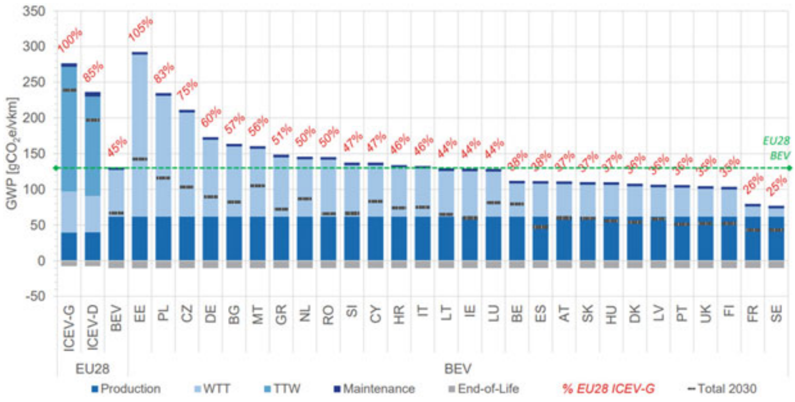

Fig. 2.15 Ricardo LCA analysis for European Commission (Ricardo 2020)

Steinfort 2020). Most of the literature reviewed centers around the 'Well-to-Wheel' (WTW) phases, which as discussed is only a subset of LCA. In particular, few studies focus on end-of-life emissions, and scarcer still are papers discussing the emissions related to the expanded infrastructure needs associated with new technologies. The FVV report compared a conventional diesel Internal Combustion Engine Vehicle (ICEV), a Battery Electric Vehicle (BEV), and a Fuel Cell Electric Vehicle (FCEV), concluding that lifecycle CO_2 emissions are similar across the three technologies. In a Ricardo report commissioned by the European Commission, Hill et al. (Ricardo 2020) noted that most studies tend to focus on passenger cars with relatively few covering commercial truck applications. Figure 2.15 compares the respective life cycle CO_2 emissions[11] from ICEVs burning gasoline and diesel against Battery Electric Vehicles (BEVs) using electricity from the various EU28 countries. The study suggests that in general, the BEV produces the lowest lifecycle CO_2 emissions, as a result of the considerably lower TTW contribution. However, in Poland the BEV is only marginally better than diesel and in Estonia it is worse. We also note that the BEVs are generally associated with the highest production stage CO_2 emissions. In fact, half of the BEV lifecycle CO_2 emissions may occur in the production phase. This contribution obviously grows with reduced vehicle Full Useful Life (FUL), as the emissions get spread across a lower mileage. Approximately half of the CO_2 generated during the BEV production phase is associated with the battery (Ricardo 2020). As noted by Amarakoon et al. (2013), the production of the cathode and electrolyte are particularly resource and manufacturing intensive. In an extensive Life Cycle-Impact Assessment (LCIA), they also concluded that the upstream materials extraction, processing and production of lithium-ion battery production has a non-negligible impact in terms of eutrophication potential (fertilization of surface waters through ammonia), ozone depletion (through production of aluminum for cathode material), ecological toxicity (freshwater contamination through use of steel

[11] Lifetime vehicle mileage of 225,000 km was assumed in this study.

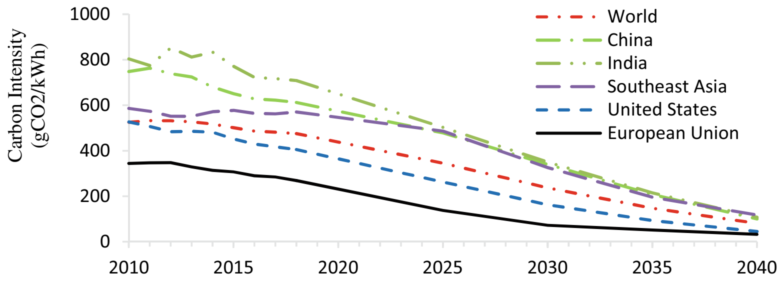

Fig. 2.16 Electricity grid average carbon intensity projections for various regions in the world (data compiled from Ritchie and Roser (2020))

in battery housing), and cancer and non-cancer hazard impact categories. End-of-Life material recovery is essential, since the extraction and processing of virgin materials are key contributors to these life cycle impacts. In particular, the extraction of lithium from salars[12] in Chile has received some attention in light of the potential impact on water supply and drought. Furthermore, mining of cobalt has raised ethical concerns, as more than half of the world's supply is extracted in the Democratic Republic of Congo, where child labor is still an issue (Posner 2020). The annual global production of cobalt increased by 60% over the last 10 years (U.S. 2020) and is destined for further growth as a result of accelerated adoption of BEVs.

With regards to fuel cells, the manufacturing process of the Membrane Electrode Assembly (MEA) is highly energy intensive and difficult to manage environmentally. Other focus areas for fuel cells from an LCA perspective is to reduce the amount of PGM required in the catalyst layers and the need for materials such as Carbon Fiber Reinforced Polymer (CFRP) composite for the tank (Advanced Propulsion Centre 2021b).

Regulation centered around Tank-to-Wheel or Well-To-Wheel contributions fail to capture circular economy aspects, not drawing sufficient focus to the importance of making battery and fuel cell production more sustainable. It is also clear that more studies are needed to adequately assess the contributions from supporting infrastructure, such as the electric vehicle charging and hydrogen fueling stations.

With increasing decarbonization of the electricity grid, the case for the BEV improves—all other things being equal. Figure 2.16 shows the carbon intensity electricity grid average in different regions of the world, including future projections. As already apparent from Fig. 2.15, there is significant stratification across individual countries. Li et al. (2020) notes that the carbon intensity varies between 200 and 1,200 g CO_2/kWh across the different provinces of China. Actual carbon intensities associated with BEV charging may be considerably higher than the grid average in cases of coal power being used to generate the margin electricity. Weis et al. (2016) employ a consequential life cycle approach when comparing the emissions generated

[12] A salar is a salt desert resulting from raw material extraction from salt water.

by different technologies in order to capture the change in power plant operations due to charging of electric and plug-in vehicles.

Disregarding any infrastructure and End-of-Life (EOL) contributions, we may express the benefit of a BEV relative to a diesel ICEV as:

$$\Delta_{CO_2} = \left[\left(\frac{M_{CO_2}^{ICE}}{D_{FUL}} + CI_{Diesel}^{WTW} \cdot \frac{37.85}{FE_{ICEV}} \right) - \left(\frac{M_{CO_2}^{BEP}}{D_{FUL}} + CI_{EV}^{WTW} \cdot W_{EV} \right) \right] \tag{2.2}$$

where Δ_{CO_2} is the difference in grams of CO_2/mile, $M_{CO_2}^{ICE}$ and $M_{CO_2}^{BEP}$ are the respective amounts (grams) of CO_2 generated in the production of a BEV and an ICEV, CI_{Diesel}^{WTW} (g CO_2/kWh) is the WTW carbon intensity of conventional diesel, CI_{EV}^{WTW} (g CO_2/kWh) is the grid carbon intensity, D_{FUL} (miles) is the distance associated with vehicle Full Useful Life, FE_{ICEV} is the ICEV fuel economy (miles per U.S. gallon) and W_{EV} is the energy consumption of the BEV (kWh per mile). Table 2.2 provides some representative values to enable the BEV CO_2 benefit over a diesel ICEV to be calculated.

The passenger car diesel fuel economy used in this example is equivalent to 129 g CO_2/km, which is consistent with the data from the European Environmental Agency for newly registered vehicles (European Environment Agency 2021). The CO_2 resulting from the production phase is assumed constant here, but could be expected to reduce for both the diesel ICEV as well as the BEV, as a result of energy decarbonization. Figure 2.17 uses Eq. (2.2) along with the data from Fig. 2.16 and plots the CO_2 benefit of the BEV relative to a diesel ICEV as a function of time and region of the world. We note that the CO_2 emissions of the BEV actually exceed those of a diesel ICEV in many regions of the world until at least 2025. As previously mentioned, this is based on *average* grid densities and neglects consequential charging effects. This study emphasizes the need to decarbonize the energy supply, including the electricity grid. Only then do Battery Electric Vehicles and Fuel Cell Electric Vehicles truly offer a sustainable solution. With widespread access to renewable energy and increased availability of climate-neutral fuels, such as biodiesel and e-fuels, the ICEV baseline will also improve. As an example, an ICEV running on

Table 2.2 Carbon intensity and energy comparison between a diesel ICEV and a BEV

	Diesel ICEV	BEV
Carbon Intensity (gCO_2/kWh)	330 (Ricardo 2020)	See Fig. 2.16
Fuel Economy (mpg)	60	N/A
Energy Consumption (kWh/mile)	0.63	0.29 (Electric Vehicle and Database 2021)
Production Phase CO_2 (kg)	8,000 (Ricardo 2020)	16,000 (Ricardo 2020)
Vehicle Full Useful Life (miles)	120,000	120,000

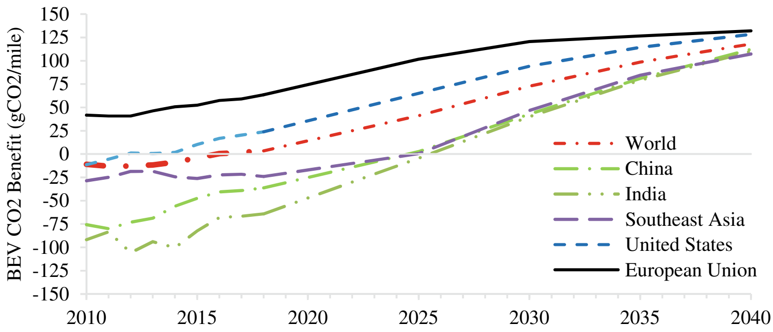

Fig. 2.17 CO_2 advantage of battery electric vehicles over diesel internal combustion engines as a function of the average electricity grid carbon intensity based on Eq. (2.2)

Hydrotreated Vegetable Oil (HVO) has a carbon intensity of 31.5 g/kWh (Emission and Factors 2021), roughly one tenth of current fossil fuel based diesel.

2.3.3 A Global Solution to a Global Problem

As the name implies, global warming is an issue that transcends national borders. While every country has an important role to play, this does not mean the same solution will work universally. It is important to take a careful, nuanced approach that accounts for regional differences in energy supply, infrastructure and economic conditions.

It might be tempting to look to the countries primarily responsible for today's CO_2 emissions and argue that the lion share of the responsibility lies with them. For example, Fig. 2.18 shows that China is by far the highest emitter today with roughly 10 billion tons of CO_2, representing 27% of the total global output (Ritchie and Roser 2020). However, if we instead consider cumulative emissions, the United States is by far the highest emitter (400 billion tons), followed by Europe (350 billion tons). Together, these two regions are responsible for almost 50% of the cumulative CO_2 emissions, historically. Clearly, the countries currently generating the bulk of the emissions do need to reduce their carbon footprint, but the developed nations have a critical role to play in transferring proven solutions, knowledge and applying lessons learned. The tremendous economic growth of the developed nations was powered by energy sources that historically produced high amounts of GHG emissions. With the threat of climate change coming into focus in these countries, important steps towards sustainability have already been taken, causing the annual CO_2 emissions to plateau and even decrease in the United States and Europe. While China will continue to play a key role, it is also important to recognize that over the coming decades an increasing share of the CO_2 emissions will come from other developing countries, as they embark on a journey towards economic prosperity.

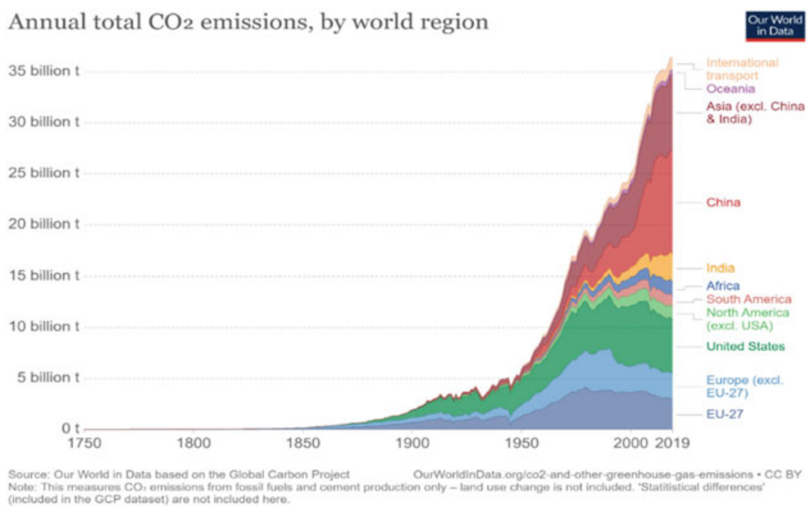

Fig. 2.18 CO_2 emissions by world region (Ritchie and Roser 2020)

Figure 2.19 reveals a strong correlation between CO_2 emissions and economic growth (Our World in Data 2021). Going forward, it is of vital importance that the developing world is able to build wealth without incurring the associated CO_2 emissions that accompanied economic growth in the developed nations. This is where careful consideration has to be given to prevailing local circumstances. As

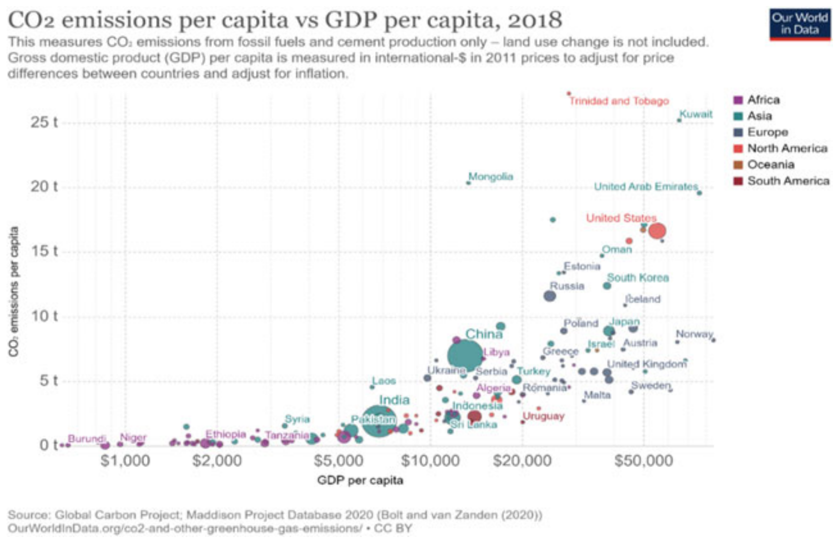

Fig. 2.19 CO_2 emissions per capita versus GDP per capita (2021)

an example, Africa today contributes less than 5% of total CO_2 output to the atmosphere. However, this number is likely to grow sharply in the future as an increasing number of people come out of poverty. The energy supply in Africa largely comes from fossil sources and biofuels (Ayompe et al. 2020). With an under developed and unreliable electricity grid, the right solution for Africa at this point in time is not widespread deployment of electric cars. A better first step would be to tighten the exhaust emissions regulations and ensure the cleanest and most efficient transport solutions are implemented in all segments of the market, removing high-polluting vehicles from the roads. This would have an immediate positive impact on carbon dioxide emissions while limiting disruption to local economies. In parallel, there needs to be a clear focus on decarbonizing the energy and electricity production. The investments associated with this are significant. Kalghatgi estimates that the world would need the equivalent of 3,100 nuclear power plants, each with an output of 3 GW, in order to replace 60% of the current fossil fuel use (Kalghatgi 2020). With the average age of vehicles being relatively high (>15 years) in many of the African countries, by far the least disruptive near-term option to reducing CO_2 would be drop-in biofuel and/or e-fuel replacements for regular gasoline and diesel. Incidentally, the Middle East and North Africa (MENA) region is very well suited to e-fuel production.

2.3.4 One Size Doesn't Fit All

Transportation covers a huge variety of applications which do not lend themselves equally to all technologies. Apart from the CO_2 emission aspects just discussed, the technologies obviously have to be economically viable. This is especially critical in commercial applications where the vehicle is a revenue generator. The reliability and durability requirements associated with commercial applications also differ significantly from automotive ones.

Using representative numbers for energy consumption, energy density and pack cost, it is straightforward to calculate the required battery capacity, weight, cost, and associated charge times for BEVs. The results of such an analysis are summarized in Table 2.3 for three different applications. For a battery electric passenger car with a range of 200 miles, the battery pack costs roughly $8,000 and weighs about 460 kg. For many people this is considered acceptable, both from a range and cost perspective, especially when taking available incentives into account. Range/fueling anxiety, does become an issue when taking longer trips, but the majority of trips are less than 30 miles. However, let us consider a BEV that matches the range of a diesel-powered heavy-duty (HD) line-haul truck equipped with two 80-gallon (U.S.) tanks of diesel. Assuming 8 mpg, such a truck has a range of 1,280 miles. The equivalent battery electric truck would have to carry approximately 20 tons of batteries, far offsetting the weight benefit of removing the conventional powertrain, and sacrificing precious payload. Furthermore, the cost of the batteries would be around $450,000

Table 2.3 Battery comparison between passenger car and commercial applications

	Passenger car	MD truck	HD truck
Energy density (kg/kWh)	8	8	8
Battery cost ($/kWh)	137	175	175
Energy Cons. (kWh/mile)	0.29	1	2
Charge rate (kW)	22	150	350
Battery capacity (kWh)	58	300	2,560
Battery cost ($)	$7,946	$52,500	$448,000
Range (miles)	200	300	1,280
Battery weight (kg)	464	2400	20,480
Charge time (h)	3	2	7

and would take around 7 hours to charge. This makes for a very challenging business proposition for heavy-duty line-haul applications to say the least.

For Medium-Duty (MD) applications with their more limited range and power requirements, there is a more attractive and nearer term business case. Depending on the assumptions made (e.g. electricity cost, annual mileage, fuel consumption and service), the medium-duty battery electric truck has the potential for a more reasonable payback.

With regards to fuel cells, a passenger car with a fuel economy of 70 miles per kg of hydrogen, achieves a range of 350 miles on a tank carrying 5 kg of hydrogen. Using the 2020 costs provided in Fig. 2.13, this results in about $2,300 and $14,000 for the tank and stack, respectively. Again, the heavy-duty case is very different. Using the range assumptions of Table 2.3, the hydrogen tank and stack costs would be $75,000 and $160,000, respectively, for a 350 kW heavy-duty truck getting 8 miles per kg of hydrogen.

Andersson and Börjesson (2021) identify a Plug-In Hybrid Electric Vehicle operating on HVO as an attractive alternative for automotive applications. The relatively small battery pack provides necessary range to comply with local zero emission regulation without generating significant CO_2 in the production phase.

2.3.5 Cause for Optimism

The task of reducing the carbon dioxide emissions in line with the Paris Agreement without stifling economic growth may seem daunting. However, as the preceding sections have shown, it is a well-defined problem for which we are looking to apply—to some extent—known solutions. The sources of the emissions are understood and we possess the tools to assess the impact of different technical solutions. Perhaps most importantly, we have a good grasp of the technologies to accomplish the task.

That said, progress relies on continued investment in research and development in all the technologies described in this chapter.

In parallel to deploying known technologies to reduce vehicle energy consumption, such as those discussed in Sect. 2.2, efforts to decarbonize the energy and electricity supply need to be aggressively pursued. Furthermore, it is important to focus on reducing the energy intensity associated with the production of batteries and hydrogen. Ample supply of renewable energy will substantially reduce the environmental impact from both conventional and electrified powertrains.

Optimized conventional powertrains are favored in developing countries, timing the introduction of battery electric and fuel cell vehicles to when coal and oil have been phased out as energy sources. The industrialized nations have a great responsibility—and opportunity—to transfer known technologies that will have an immediate impact.

CO_2 regulation is in place for both automotive and commercial applications in both Europe and North America. Europe's major truck manufacturers have pledged that all new trucks sold will be fossil free by 2040 with the goal of reaching carbon-neutrality by 2050 (ACEA 2020b). It also looks increasingly certain that a system will be created for emissions trading in European road transport. It is critical that the regulation be amended to capture the environmental impact over the entire product lifecycle.

There are past examples of effective global action to address environmental hazards. The agreement to curb emissions of chlorofluorocarbons[13] (CFCs) depleting the ozone layer is an example of swift global action. At its worst, in the late 1990s about 10% of the upper ozone layer was depleted. However, following the agreement to ban CFCs, signed by all nations in 1987, the ozone layer is expected to be fully restored by 2060. The consistent reduction in criteria pollutants from internal combustion engines over the last several decades (see Fig. 2.6), significantly contributing to reduce the smog in many major cities, is another success story demonstrating that green technologies do not have to compromise performance and economic growth.

The actions taken by the industrialized nations to curb CO_2 emissions have been effective and annual output is now decreasing in Europe and North America, as seen in Fig. 2.18. Global CO_2 emissions are expected to peak in 2035 (ExxonMobil Outlook for Energy 2019), but by quickly transferring lessons learned, we have an opportunity to accelerate the downward trend and help the developing world on their journey towards sustainable prosperity.

As we look ahead to our biggest environmental challenge yet, we would be wise to embrace a fact-driven, decisive approach, keeping multiple options open and build on past successes. Rather that betting it all on a single technology, we need to pursue a diverse mix of low-carbon technologies. In the words of Senecal and Leach (2021),

[13] Chlorofluorocarbons is a family of chemicals that has seen widespread use in refrigeration and as propellants in aerosol cans. Their role in destroying the ozone layer became widely known in the 1980s.

“the future is eclectic”. It is hard to imagine a more interesting time to be working in the transport industry.

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