ISSUE BRIEF Transport

COUNCIL OF ENGINEERS
FOR THE ENERGY TRANSITION

An independent advisory council to the
United Nations Secretary-General

Comprehensive Catalog on Transportation Decarbonization

Key Messages

Minimize Energy Losses and Promote Electricity as Primary Energy Vector

Current business practices sometimes dictate the use of longer routes than necessary or to carry excessive amounts of fuels. Such practices unnecessarily increase the fuel consumption for propulsion and should be avoided. Most alternative fuels require the use of massive amounts of electricity, part of which is lost during conversion to alternative fuels. Direct electrification is the most efficient way of using electricity and it should be promoted whenever the electric grid is powered by a majority of green energy. [e.g. in Poland the power is 100% old coal power stations, and until that has been changed biofuels will be a better option than EV's and electrifying railways]

Aviation

Aviation plays a crucial role in economic and social development by connecting societies and generating employment opportunities. While electrification is the most efficient solution, it would not be feasible for long-haul flights for decades. Indeed, aviation faces an additional complexity, as flying requires high energy density, especially for long-haul flights. For long-haul flights, it is necessary to rapidly upscale the production of advanced biofuels and synthetic fuels until alternative technologies become available at the 2050 horizon. Electric and hydrogen-powered aircraft hold great promise for short and medium-haul flights in the next decade. Overall, all these solutions will require a huge amount of low-carbon, clean and affordable electricity.

Rail

Rail has the potential to play a major role in the future of transportation and its decarbonization considering the advantages that it offers in terms of of energy and space efficiency,[1] time-saving, comfort, and load volumes. Today rail networks carry approximately 8% of global motorized passenger movements and 7% of freight transport. Rail infrastructure is a capital-intensive business depending on diverse factors including costs of land, labor and materials, tracks per line, track electrification, topography, and intended operation speed. Therefore high throughputs are required to minimize unit costs. Modal shift, especially from short-haul air travel to high-speed rail, is determined by the routes that lower construction costs. To be a competitive alternative, rail journeys must be time saving compared to available flight options. Finally, the demand has to be large enough to achieve the economic viability of the investments required for rail connections.

Road

With increasing CO_2 emissions, the road transport sector urgently needs to embrace clean energy solutions. Further accelerating the sector's electrification stands as a critical pathway. Electric vehicles (EVs) and fuel cell vehicles (FCVs) represent the primary pathway to zero emissions. Both leverage on clean energy like renewables energies, but EVs perform better on shorter distances, while FCVs do well on longer and heavy-duty journeys. By investing in infrastructures, renewables, storage and other leading low-carbon technologies and implementing targeted policies and regulations, the road sector can unlock sustainable mobility and economic growth. Now is the time for collaborative efforts from governments, consumers, and the private sector to overcome existing challenges and accelerate the transition to renewables in the road transport sector.

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Shipping

For millennia, ships have connected civilizations and enabled economic development. Cutting-edge technologies such as modern wind sails and batteries support the further increase of a ship's already very high energy efficiency. Abandoning fossil sources of energy in favor of renewable fuels offer opportunities for emerging economies. The International Maritime Organization (IMO) has recently mandated the gradual replacement of fossil fuels with low-carbon fuels, triggering their international demand for shipping. A few ports on international shipping routes are located in emerging economies and the IMO mandate provides an opportunity for these to establish manufacturing facilities for energy and alternative fuels. Such fuels may be then sold at the price of globally traded commodities.

Executive Summary

Transportation sectors are still heavily relying on fossil fuels and accounted for 37% of CO_2 emissions among end-use sectors in 2021. Though many regional or global decarbonization roadmaps for each transportation sector have been published, decarbonizing the most emitting transportation sectors such as aviation, road, train, and shipping is not an easy task. We all know that there is no silver bullet to get rid of our dependency on fossil fuels. For each transportation sector, this catalog provides an estimation of the decarbonized energy demand, an inventory of all decarbonization technology pathways, strategic and technical recommendations, and existing policy measures to accelerate the deployment of decarbonized solutions at an affordable cost. It has been drafted to be accessible and comprehensive for both expert and non-expert audiences with the aim to facilitate informed decisions for transportation climate action plans.

Aviation Sector

Like other transportation sectors, decarbonization of the aviation sector will require a mix of different technologies with different potential of CO_2 emissions reduction depending on the carbon intensity of the electricity used in the process. Regardless of the technological pathway to decarbonize the aviation sector, the required electricity is huge. There is an urgent need to scale up the production of renewable/clean/low-carbon electricity by 2050.

Electrification is a promising solution as it is the most energy efficient solution, with a Well to the Wake (WtW) electricity need of 7,500 TWh for a hypothetical 100% electric aircraft scenario in 2050. In comparison, other technologies such as hydrogen-powered aircraft or synthetic fuels (e-SAF) require 16,000-20,000 TWh and 17,000 TWh respectively in 2050 for a similar hypothetical 100% scenario. However, electrification of aviation faces an additional complexity, as flying requires a high energy density storage device. While addressing safety concerns with flammable electrolytes in current lithium batteries, the energy density of the battery should be drastically improved. A transition from fossil jet fuel to 100% electric aircraft would be an incredible challenge and would require nearly tripling the battery energy density every decade until 2050, especially for long-haul flights. If fuel cells are selected to power future aircraft, they would require significantly greater power density, an extended lifespan, and enhanced efficiency.

The use of Sustainable Aviation Fuels (SAF) is another promising solution to decarbonize aviation by 2050. As drop-in fuels, SAF can be used in existing aircraft by blending with Conventional Aviation Fuels with minimal modification. However, the production of SAF should not lead to negative environmental impacts, such as deforestation, land use change, or competition for food and water resources. It is necessary to implement sustainability standards and certification schemes for SAF production.

The market penetration of new technology is also an essential factor to accelerate the decarbonization of the aviation sector. Aircraft typically remain in service for about 20 years. Early investments should be incentivized to accelerate fleet renewal and development of new markets.

It is likely that a mix of aircraft technologies will co-exist by 2050. Zero-emission aircraft (electric, hydrogen, methane, ammonia…) and conventional aircraft will share the skies with their specific needs in terms of infrastructure, fuels, and energy demand. We recommend the following three principles to accelerate the decarbonization of the aviation sector:

- Prioritizing initiatives to create feasible solutions for fast and significant CO_2 emissions reduction.
- Supporting early investments through financial support and alliances.
- Earmarking revenues collected from aviation-related taxes to foster aviation innovation and increase its bankability.

The catalog also proposes a tool that could be used by any region to estimate local energy needs depending on the decarbonization strategy of the aviation sector.

Road Sector

The road transportation sector, a critical contributor accounting for 78% of the transportation industry's CO_2 emissions, stands at a pivotal juncture in the global quest for carbon neutrality by 2050.

As the urgency to mitigate climate change intensifies, the sector is increasingly focusing on renewable and clean energy solutions as the path forward. Electricity and low-carbon molecule-based fuels have become the primary energy source for road transport. This report highlights the strategic importance of key technological pathways on Electric Vehicles (EVs), Fuel Cell Vehicles (FCVs), along with hybrids and other clean energy for decarbonization by 2050. Low-carbon fuels such as electricity-based hydrogen, e-methanol, ethanol, methanol, and Hydrogenated Vegetable Oil (HVO) diesel, derived from various forms of biomass and organic wastes, also play a significant role in achieving a low-carbon future.

EVs are at the forefront of this transition, particularly suitable for short-range commutes. Their zero tailpipe emissions make them a cornerstone in reducing the carbon footprint of road transport. The 55% surge in EV sales in 2022, despite a global market contraction, signals a paradigm shift towards sustainable transportation.

FCVs offer a compelling solution for long-distance travel. Utilizing hydrogen as a fuel source, FCVs produce only water vapor as a byproduct, making them an environmentally friendly option that can significantly contribute to the decarbonization of the road transport sector. According to the Hydrogen Council, the global fleet of hydrogen-powered fuel cell electric vehicles could exceed 13 million by 2030, driven by market expansion and cost reductions.

Hybrid vehicles serve as transitional solutions, offering enhanced fuel efficiency and reduced emissions. However, their continued reliance on fossil fuels necessitates a phased blending with low-carbon fuels for a comprehensive climate-friendly transition. This approach balances economic development needs and mitigates risks of capacity shortages, avoiding the pitfalls of a single-technology focus.

In addition to introducing the technical paths of road transportation energy transformation, the road transport sector section also conducts an in-depth analysis of the obstacles encountered by different technical routes, and proposes corresponding solutions, along with comprehensive analysis on the full life cycle carbon emissions and carbon intensity assessment of different paths.

The following measures are recommended to accelerate the energy technology transition and deep decarbonization in the road transportation sector:

- Implement policies such as financial incentives and regulations to provide a stable and supportive environment for the roll-out of new energy vehicles.
- Improve infrastructure to improve the convenience of vehicle consumer use.
- Promote core technology innovation and research.
- Enhance investments in the entire new energy vehicle value chain.

The necessity of developing electricity, hydrogen and low-carbon fuel vehicles are apparent. By focusing on technology pathways, implementing targeted policies, and establishing favorable regulatory frameworks, development of renewable energies, New Energy Vehicles (NEVs) and low-carbon vehicles is not only paving the way for sustainable mobility but also fostering global economic growth through enhanced international cooperation and knowledge sharing.

Electrification and development of low-carbon emission fuel hold immense potential to revolutionize the transportation sector and drive the global energy transition. Early investments and groundbreaking technologies are setting the stage for a transformative shift towards a sustainable future. It calls for collaborative efforts among governments, consumers, and the private sector to overcome existing challenges and accelerate the transition to renewable energy in road transportation.

Train Sector

Rail has the potential to play a major role in the future of transportation and its decarbonization considering the advantages that it offers in terms of of energy and space efficiency, time-saving, comfort, and load volumes (for both passengers and freight). One railway line can carry the same load as multiple lanes of motorway, using considerably less energy. Today rail networks carry approximately 8% of global motorized passenger movements and 7% of freight transport.

Rail is also the transport sector that is most electrified: three-quarters of passenger traffic and half of freight rely on electricity and the remaining relies mostly on diesel. Europe, Japan, Republic of Korea, and Russia are the regions with the highest share of electric train activity.

Electrified rail routes fivefold the passenger-kilometers per kilometer track carry, and twice as many ton-kilometers when compared to the fuel-powered routes, so payback periods for the electrification investment costs are shorter.

Besides its intrinsic strengths, rail faces various challenges: cost, availability, congestion, and security. Rail infrastructure is a capital-intensive business depending on diverse factors including costs of land, labor and materials, tracks per line, track electrification, topography, and intended operation speed. Therefore high throughputs are required to minimize unit costs.

Rail projections show that passenger modalities nearly double their share of the total transport activity with special growth in urban and high-speed rail, contributing to the fall of emissions from 95 Mt CO_2 in 2020 to virtually zero by 2050.

Rail infrastructure is expensive. The deployment of overhead lines or third rails have been associated with high upfront costs. For a rail development project to pay off, high passenger or freight throughput is strictly necessary. Another costly process that stakeholders could find is the upgrading of the existing rolling stock, especially with assets that may not be easily retrofitted. In this context, strong policies regarding subsidies and easy access to credit with competitive conditions are required.

Battery electric trains are an alternative to electrify the rail fleet in areas where deployment of conventional overhead lines is not feasible due to capital costs.

Modal shift, especially from short-haul air travel to high-speed rail, is determined by the routes that lower construction costs. To be a competitive alternative, rail journeys must be time saving compared to available flight options. Finally, the demand has to be large enough to achieve the economic viability of the investments required for rail connections.

For travelers, price, safety, and core product offering (including convenience, reliability, and speed) are the key drivers for choosing a mode of transport. Increased reliability, new offers incentive pricing and fare structures, as well as increased capacity that is accessible to all people could increase modal share. For freight buyers the price, response time to requests, reliability and whole-journey solutions decide the mode of transport. Positive models in the airline industry, like low-cost approach and easy access for new operators, can be adapted to the rail sector.

Maritime/Shipping Sector

For millennia, ships have connected civilizations and enabled economic development to the extent that well-functioning ports and port infrastructures are key elements of a country's development. Today, maritime shipping enables global trade, transporting 11.5 billion tons of goods around the globe each year, which amounts to about 80% of the goods produced worldwide.

Despite the gigantic size of the industry and its critical importance on global trade, shipping consumes around 300 million tons of marine fuels and emits approximately 1 billion tons of CO_2 — which is roughly 2-3% of global emissions. This relatively modest impact is a testimony of the very high efficiency of maritime transport. Shipping's emissions intensity per ton of moved goods is 5-100 gCO_{2e}/km, which is comparable to rail transport and only about one tenth and one hundredth of the emission intensity of road transport and air transport, respectively.

Decarbonizing shipping is approached with a three-pronged effort: increasing energy efficiency (technological and operational measures), decarbonizing operations at ports (shore power is a strong candidate), and decarbonizing propulsion (alternative propulsion methods and alternative fuels). Efficiency improvements are expected to be countered by an increase in maritime traffic so that by 2050, the propulsion energy that must be satisfied by fuels is expected to be approximately the same as today.

For shipping, the call to eliminate emissions is a huge challenge. However, the same call offers tremendous business opportunities to the industry and opportunities for a just transition for developing countries. Some important areas of attention are described in the following points:

Dissemination of engineering-based assessments. A lifecycle climate impact label applied on every sold product informs authorities, consumers, and technology developers of the burden that each product creates, including transport. This offers strong business opportunities to shipping since this transport option has a very low energy consumption. At the same time, it forces shipping to eliminate emissions with high global warming potential, such as methane from LNG and bioLNG ships, N_2O, and black carbon, besides CO_2. In the context of assessing the climate impact of a cradle-to-supply chain, we advise against the use of "standard" emissions intensity values. Instead, we advocate for asset- and value chain-specific assessments because experience shows that the difference between standard and specific values may be large, and the practice does not incentivize emissions reduction.

Identify cutting-edge bankable technologies. The replacement of fossil fuels with alternative fuels increases the primary energy demand for almost all cases — it actually decreases primary energy demand for wind sails propulsion and batteries. At the current status of development, both technologies may support shipping, but neither is able to completely displace fossil fuels. Improvements in energy density for batteries is critical if long-haul shipping shall rely on EV propulsion.

Cross border regional scale systems. Abundance of natural resources has a regional character: the sun shines in geographies where wind may not blow and vice-versa; biomass may not be abundant in areas with high density populations that generate waste, and so on. Transporting primary energy may involve losses and transforming energy locally is often the most efficient option. There may be important opportunities in considering a cross-border approach, in which abundance of natural resources in one country can be made available to neighboring countries. For regional-scale systems to be effective, either physical infrastructure or chain of custody certification and trading schemes must be in place. Typical examples are Power Purchase Agreement (PPA) for renewable electricity or Guarantee of Origin certificates for biomethane.

Opportunities in the energy transition. The International Maritime Organization (IMO) has recently mandated the gradual replacement of fossil fuels with low-carbon fuels, triggering international demand for low-carbon fuels from shipping. A few ports on international shipping routes are located in emerging economies and the IMO mandate provides an opportunity for these to establish manufacturing facilities for energy and alternative fuels that may be sold at the price of globally traded commodities.

Common Challenges and Possible Path Forward

Though many regional or global decarbonization roadmaps for each transportation sector have been published, decarbonizing the most emitting transportation sectors such as aviation, road, train, and shipping is not an easy task. Decarbonizing the transportation sector requires a significant amount of investments in terms of energy production, infrastructure improvement, and development of new technologies. However, governments should introduce policies and incentives that encourage these investments in order to drive the transition to net-zero carbon emissions by 2050. These policies and incentives include carbon taxes, subsidies for low-carbon technologies, and regulations that mandate reductions in emissions. On the other hand, a mandate-based regulatory approach is another option and has been successfully used to expand the production of conventional biofuels (biodiesel) as it creates structural demand for these fuels and compulsory blending. Mandates also give long-term security to investors by de-risking investments. One of the main challenges of an incentive-based regulatory approach is the costs of the incentives. They need to be funded, and most of the time, funding is done via a tax mechanism affecting all citizens. On the other hand, the main challenge of a mandate-based approach is the potential additional costs, especially at the beginning of a mandate when the fuel production is still limited. Selecting the best instrument depends on a mix of factors including economic efficiency, cost-effectiveness, distribution of benefits or costs, ability to address uncertainties, and political incentives.

1. Introduction

Mobility and connectivity are essential in our society, playing a vital role in the operation of an economy, in moving people and goods, and in medical care supplies and functioning. However, transportation solutions are still relying on fossil fuels and accounted for 37% of CO_2 emissions from end-use sectors in 2021. During the COVID-19 pandemic, all transportation sectors were affected and associated emissions drastically decreased, which is represented in Figure 1, but now the demand is back and emissions are rising again, with the highest growth in developing and emerging countries.

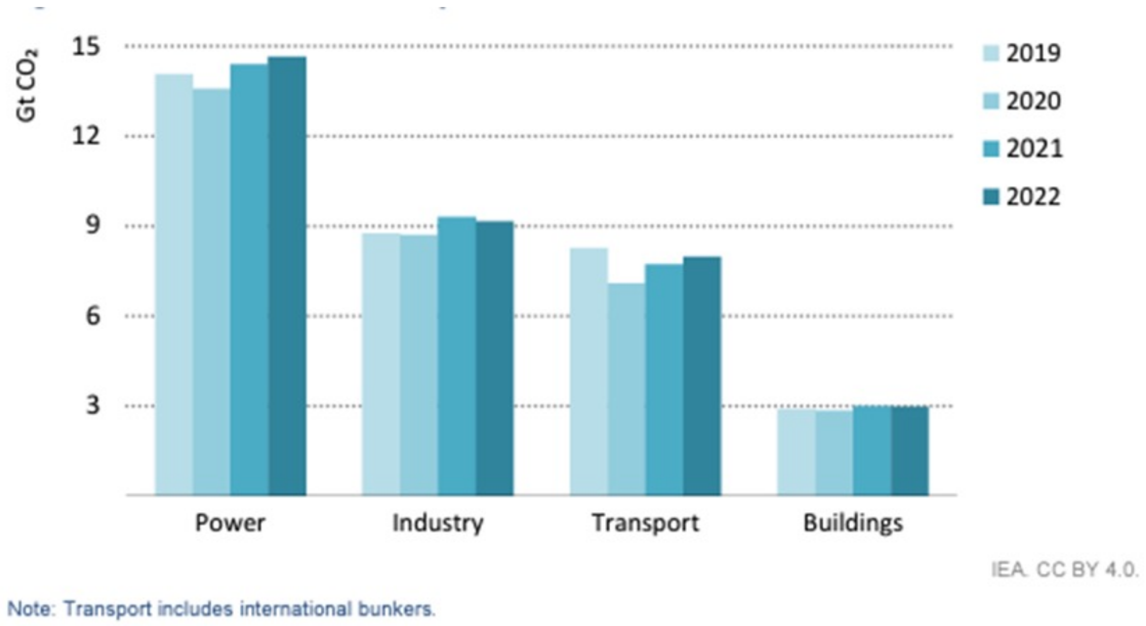


FIGURE 1: Global CO_2 emissions by sector, 2019-2022.[2] Source: International Energy Agency, "C02 Emissions in 2022." (International Energy Agency, 2023) P. 9, Figure 5.

The Paris Agreement, a legally binding international treaty, entered into force on November 4th, 2016. More than 200 States have joined this agreement, which encourages countries to take ambitious climate actions that keep warming below 1.5 degrees Celsius. To achieve this goal and to support the transition to net zero by 2050, there are many actions that need to be taken in the short, mid, and long terms by policy makers and both national and international authorities. Decarbonizing the transportation sectors should be one of top of the agenda.

Decarbonizing the most emitting transportation sectors such as aviation, road, train, and shipping is not an easy task.

Many regional or global decarbonization roadmaps for each transportation sector have been published. They all have in common that there is no silver bullet to get rid of our dependency on fossil fuels. There are many different decarbonization pathways relying on different technological solutions and energy needs, each with different levels of maturity and technological readiness.

The purpose of this catalog is to support the design of ambitious climate action plans to decarbonize the transportation sectors: namely aviation, road, train, and shipping. Each state has its own specificities and depending on the available raw material, feedstock, or energy strategy, there are different options that might be considered to support the transition to net zero.

This catalog provides for each transportation sector an estimation of the decarbonized energy demand, an inventory of all decarbonization technology pathways, strategic and technical recommendations, and existing policy measures to accelerate the deployment of decarbonized solutions at an affordable cost. It has been drafted to be accessible and comprehensive for both expert and non-expert audiences with the aim to facilitate informed decisions for transportation climate action plans.

2. The Decarbonized Energy Demand and Its Use for All Transportation Sectors

2.1. Aviation Sector

2.1.1. The Decarbonized Energy Demand in the Aviation Transport Sector Towards 2050

Aviation plays a crucial role in economic and social development by connecting societies and generating employment opportunities within and beyond the industry. As the impacts of COVID 19 recede, the aviation sector is on a growth trajectory, with the International Civil Aviation Organization (ICAO) projecting a steady increase in passenger travel until 2050. However, despite its significant social and economic benefits, the aviation industry is responsible for a substantial amount of greenhouse gas emissions, contributing over 2% to the overall emissions that cause climate change, emitting around 1036 million tons(mt) of CO_2 in 2019 according to the International Energy Agency (IEA).[3]

Although modern aircraft consume 20% less fuel than previous-generation technologies, the slow pace of fleet renewals is a result of most aircraft having a lifespan of over 20 years. Additionally, aviation operators require different types of aircraft for various purposes such as general, military, business aviation, cargo, and passengers, over different distances, namely short-haul, medium-haul, and long-haul. The fuel consumption of aircraft varies significantly depending on the distance flown and the aircraft type. For instance, according to Figure 2 below, about 9% of long-haul departing flights flying more than 3000 km per trip, which are mostly performed by heavy aircraft families, account for 50% of aviation emissions.

In contrast, about 29% of short-haul departing flights, mostly operated by small aircraft flying up to 500 km, produce only 5% of the total emissions from aviation.

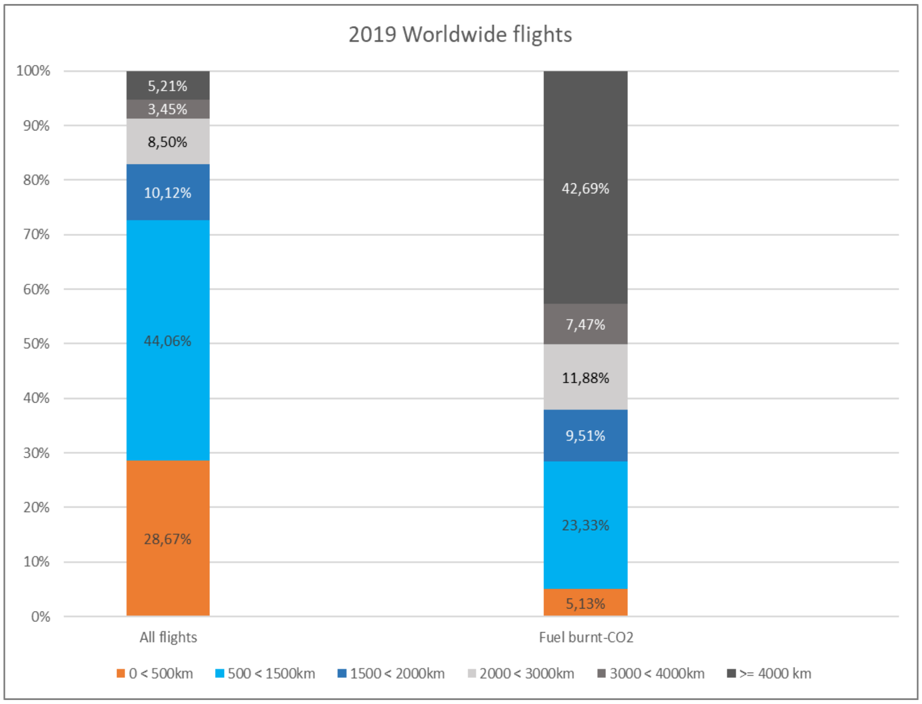


FIGURE 2: Fuel consumed and CO_2 emissions from departure world flights in 2019. Source: Figure created by the authors for the paper. [4]

The very high energy density of fuel presents a considerable challenge for the adoption of new technologies for reducing emissions, especially for long-haul flights. As a result, decarbonizing the aviation industry will mainly rely on Low Carbon Aviation Fuels or Sustainable Aviation Fuels in the first decades. In the Net Zero Emission Sce nario from International Energy Agency (IEA), emissions from heavy trucks, shipping and aviation fall by an annual average of 6% between 2020 and 2050, but still collectively amount to more than 0.5 Gt CO_2 in 2050 (Figure 3).

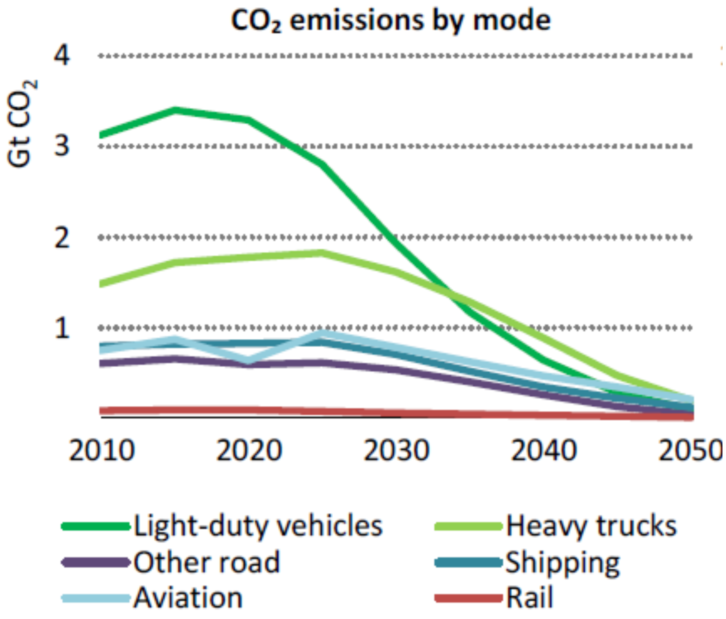


FIGURE 3: Global CO_2 transport emissions by mode and share of emissions. Source: International Energy Agency, “Net Zero by 2050.” (International Energy Agency, May 2021) P. 132, Figure 3.21.

In the ICAO LTAG report, the residual CO_2 emissions of the aviation sector are estimated between 203 $MtCO_2$ and 954 $MtCO_2$ by 2050 depending on the level of ambition of the different decarbonization scenarios that have been assessed.[5] It shows that the aviation sector could be one of the main contributors if nothing is done to accelerate its decarbonization. Scaling up the production of the different fuels (including electricity) has the best potential to reduce emissions and is therefore vital to reach net-zero emissions by 2050. Accessibility to enough clean energy is a key enabler.

In the following chapters, we will investigate the energy needs of various cutting-edge technologies, the level of decarbonization provided, and the remaining challenges that each technology must overcome.

2.1.2. The Use of Clean or Low-carbon Energy in the Aviation Sector

The use of clean energy plays an important role in reducing carbon emissions for the aviation sector. It includes a shift towards electric or hydrogen aircraft, also called zero-emission aircraft, and a shift towards higher fuel blending ratios and direct use of low-carbon fuels (bio or synthetic). Aircraft powered by methane and ammonia could also be an option, but the level of maturity is low and it is unlikely to play an essential role by 2050. The development of an optimized, hybrid aircraft which uses electricity for some of its propulsion, e.g., for taxiing or for take-off to provide additional thrust, could also lead to additional gains.

2.1.2.1. Electric Aircraft

Electric aircraft using battery power hold great potential for the aviation industry by offering the potential for zero direct emissions, considerably lowering operational and maintenance costs, providing high efficiency, and reducing noise emissions. Advances in battery technology are expected to enable the use of battery electric aircraft for regional flights, meeting up to 3% of aviation energy demand by 2050 in the Net-Zero Emission (NZE) Scenario according to IEA. Several aircraft manufacturers such as Heart Aerospace and Aura Aero aim to design a 19-seater electric aircraft using current state-of-the-art batteries by 2026.[6] Although the energy density of current Li-ion batteries is around 260 Wh/kg at the cell level, the high efficiency of electric motors associated with inverters and propfans could achieve a 77% Tank to Wake (TTW) efficiency, significantly higher than the 37% achieved by current turbofan engines. In contrast to other modes of transport, aircraft must lift not only their own weight but also the weight of passengers, luggage, cargo, engines, an additional fuselage to accommodate the volume and density of the new energy sources, and the energy required for the flight itself. These factors have a direct impact on the total energy required to complete a flight and they significantly increase the drag. Consequently, the overall energy efficiency of aircraft is adversely affected when compared to other modes of transportation. The constant weight from take-off to landing of an electric aircraft results in an additional 16% energy penalty for a heavy long-haul flight. This penalty does not exist for conventional flights as they become lighter when burning fuel during the flight. Another challenge is the design of the fuselage, which must accommodate a larger volume and the extra weight of the batteries. All these batteries-specific constraints lead to an additional 32% energy penalty compared to conventional flights.

Figure 4 shows the results from several dozen hours of simulation and experiments conducted using the BADA total energy model.[7] It shows, according to the distance flown, the minimum required energy density of the battery pack.

As an example, for an Airbus A380 to perform a 10,000 km (5,400NM) flight, a minimum battery pack energy density of 5,000 Wh/kg would be required, whereas a regional ATR76 flying 1,500 km (800 NM) would only need 1,500 Wh/kg (Figure 4).

The potential benefits of battery electric aircraft make it a promising technology for the future of aviation, but some limitations still need to be overcome to have a full electrification of the aviation sector.

2.1.2.1.1. What Would Be Required to Succeed?

- The battery's pack energy density capacity would have to increase from today's 260 Wh/kg to 500 Wh/kg (a factor 2) to allow a regional aircraft to fly 60 passengers on 500 km (270 NM) distance, 1,000 Wh/kg (a factor 3.8) for the same aircraft to fly 1500 km (810 NM), 2,000 Wh/kg (a factor 7.7) to fly 3000 km (1620 NM) with an equivalent A320/B737 carrying 144 passengers (80% load factor) and 5,000 Wh/kg (a factor 19) with an A380 on 10,000 km with 444 passengers (80% load factor).
- Landing gear needs to be reinforced to resist a higher maximum landing weight as the aircraft weight is constant all along the trajectory compared to conventional flights.
- Lifespan of batteries needs to be increased up to 50,000 flight hours.
- Ensure batteries withstand full discharge cycles without compromising their durability.
- Improve recycling of batteries to reduce the operating costs if lifespan cannot be extended.
- Address safety concerns with flammable electrolyte in current lithium batteries
- Extremely powerful electric engines and lightweight high efficiency 7.5 kW/kg would need to be available.
- Use low-carbon electricity supply.
- Deploy ultra-high-power electricity grid at airports worldwide. For example, a single 72 seat regional aircraft flying 500Km (175 NM) would require 6 MWh of electricity. During a 30-minutes turnaround, this would represent one and a half 8 MW offshore wind turbines or 24 seconds of electricity production from a 911 MW nuclear reactor. In contrast, a heavy long-haul 530 seats aircraft flying, for example from Paris to Singapore (10,000 km or 3,500 NM) during its 2 hours turnaround, would require a total of 1,577 MWh from one hundred 8 MW offshore wind turbine or 1.73 hours of electricity production from a 911 MW nuclear reactor to charge its batteries.

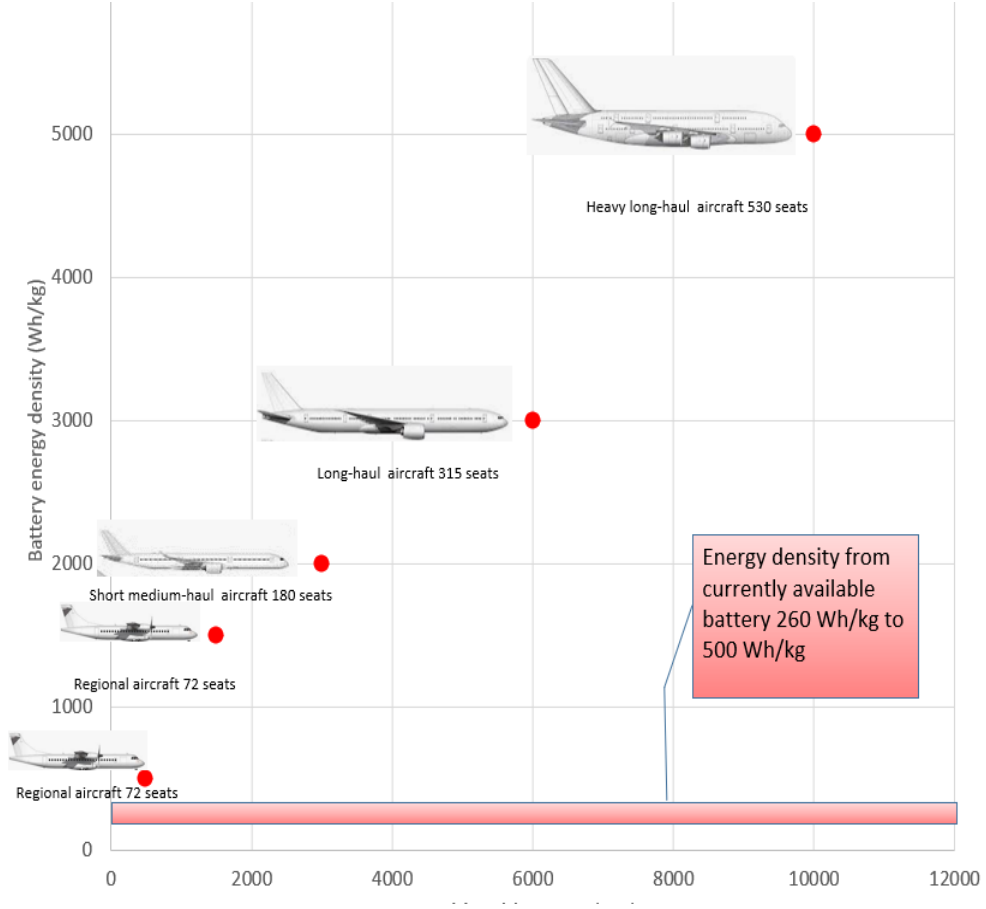


FIGURE 4: Achievable range for different types of aircraft according to minimum required energy density of the battery pack. Source: Figure created by the authors for the paper.

In conclusion, any variation in battery energy density affects aircraft's energy efficiency and its maximum achievable range, which will in turn affect the overall electrical energy needs for aviation. **A transition from fossil jet fuel to 100% electric aircraft would require nearly tripling the battery pack energy density every decade until 2050, especially for long-haul flights.** Based on 2050 worldwide forecasted aviation traffic, a 100% electric aircraft scenario (well to wake) would require about 7,500 TWh, which represents 15% of the 2050 worldwide electricity.[8]

2.1.2.2. Hydrogen Direct Combustion and Fuel Cell Aircraft

The commercialization of hydrogen aircraft is expected to begin in 2035. However, the growth of hydrogen-powered aircraft depends on advancements in storage tanks to keep liquid hydrogen at -253°C, as well as the hydrogen production, delivery systems, fuel cells price, and availability of raw materials such as platina, cost, and geopolitical dependencies. Due to the significant amount of electricity involved, investments in the production of highly decarbonized electricity and airport infrastructure will have to be considered as well. While hydrogen can be used in direct combustion or through fuel cells, it presents challenges such as the need for innovative fuel storage methods and redesigned airframes. Indeed, hydrogen requires four times larger volumes than traditional fuels, which cannot be stored aerodynamically for free in the wings of the aircraft. Using fuel cells results in similar well to the wake efficiency, but the weight of the fuel cells adds to the total energy needed for the flight, resulting in slightly higher quantities of hydrogen to be carried. Finally, although it is not a pollutant on its own, hydrogen can take part in atmospheric chemical reactions in the lower and upper atmospheres and these chemical reactions may lead to environmental damage.[9]

Airbus's ZEROe is a prominent program, developing large hydrogen aircraft for commercial operation by 2035 and collaborating with other companies to develop hydrogen-powered engines for larger and smaller jets. Other companies are designing smaller hydrogen aircraft, including retrofits and hydrogen tank-swapping concepts, with demonstrations planned for the near future.

Overall, the adoption of hydrogen-powered aircraft presents both opportunities and challenges that require ongoing technological innovation and investment.

2.1.2.2.1. What Would Be Required to Succeed?

- Designing a high gravimetric index liquid H_2 proof tank capable of maintaining temperature below -253°C for 14 hours or more, especially when the aircraft is still waiting on the ground.[10,11]
- Affordable and extremely pure hydrogen at 99.97. This hydrogen fuel quality is even exceeded in the case of liquid hydrogen, but needs to be maintained along the whole chain of distribution because of the reduction in the fuel-cell performance due to contaminants at levels of only a few nmol/mol.[12]
- For the long-haul flights, more efficient fuel-cells, and a lighter associated cooling system to achieve an efficiency of 1.6 kW/kg, which would represent an improvement factor of 2.7 over the current efficiency including cooling at 0.6 to 0.75 kW/kg.[13]
- The Maximum Landing Weight (MLW) could be exceeded especially for heavy long-haul aircraft. This would require landing gear to be reinforced to resist a higher landing weight; otherwise, a more efficient fuel cell and lighter associated cooling system should be designed.
- No fuel cells with a capacity of hundreds of MWh have been created; the most powerful ones reach 250 kW. Associated electronic DC-AC converters and circuit breakers need to be developed for managing hundreds of MW especially for heavy long-haul aircraft.
- The lifespan of the fuel-cell should be extended up to 50,000 hours.
- Resistance to vibrations, impurities, and demand in cold temperatures under which degradation makes fuel-cells less efficient over time would need to be improved.
- For a heavy aircraft, the price of the fuel-cells would be between 230M$ to 337M$ and need to be reduced.

- The refueling cost would vary depending on the source of electricity. There would be a need to reduce the cost of liquid H_2 production.
- Supply of low-carbon electricity.
- Deploy the liquid H_2 production and distribution infrastructure in all countries.

Based on 2050 worldwide forecasted aviation traffic, transitioning from fossil jet fuel to 100% liquid hydrogen in fuel cells or direct combustion and jet engines would result in an equivalent of 16,000 TWh to 20,000 TWh of electricity needs (WTW). This is equivalent to 32% to 39% of the world's projected electricity in 2050.

2.1.2.3. Sustainable Aviation Fuels

The use of Sustainable Aviation Fuels (SAF) is one of the most important solutions to decarbonize aviation by 2050. As drop-in fuels, they can be used in existing aircraft and blended with Conventional Aviation Fuels (SAF) with minimal modification. SAFs can also use existing infrastructure (pipelines) for distribution around the world. This makes it easier for airlines to transition to SAF without incurring significant costs or disruptions to their operations.

SAF can be produced by applying different pathways depending on the feedstock used, and two types of SAF can be distinguished:

- Bio-based fuel (renewable and waste derived) obtained from organic or municipal, industrial waste material.
- Synthetic-based fuel or electro-fuels obtained by using electricity to produce hydrogen and by capturing CO_2 from the atmosphere.

SAF produces the same amount of CO_2 emissions during the combustion as any conventional fuel, but the potential for emissions reduction relies on the well to wake life cycle. SAFs have little or no aromatic content, reducing their contribution to non-CO_2 warming effects, such as contrail formation.[14] To be considered as sustainable in the EU, SAF must use renewable biomass and electricity, and achieve 70% of decarbonization compared to actual jet fuel. Current SAF can be blended up to 50% with CAF, but Rolls Royce, Airbus, and Boeing have announced that their new engines and aircraft will be 100% SAF certified in 2030.

2.1.2.3.1. (Advanced) Biofuels

Sustainable Aviation Fuels (SAF) currently represent only 0.05% of worldwide aviation fuel consumption. The level of sustainability and total energy to produce 1 MJ of bio-based SAF is very dependent on the conversion pathway and the nature of the feedstock, be it waste or feed-food. Used cooking oil would require about 0.18 MJ input energy; the feedstock, however, is very limited.[15] An alternative approach involves optimizing biomass conversion through hydrogen boosting to maintain a favorable carbon-to-hydrogen ratio. While this strategy increases energy requirements, it concurrently maximizes the utilization of biomass. In the case of agricultural and forestry lignocellulosic residues, projections indicate a demand for 1.16 MJ of electricity input by 2030 and a reduced requirement of 0.5 MJ by 2050.[16] It is also important to note that biomass feedstocks are limited and would not allow to produce all the bio-SAF needed for the aviation and other transport sectors. Hydro-processed Esters and Fatty Acids (HEFA) is the most commercially SAF conversion pathway, producing SAFs from vegetable oils and waste lipids. It is also currently the cheapest, with a minimum price of $1,000 to $1,300 per ton, and costs are expected to fall further.[17]

Based on 2050 worldwide forecasted aviation traffic, moving from fossil jet fuel to 100% bio-SAF scenario would result in an equivalent of about 5,600 TWh electricity needs (11% of 2050 worldwide electricity).

2.1.2.3.1. Synthetic Fuels or E-Fuels (PTL)

Synthetic-based fuels, commonly referred to as electro fuels (E-Fuels) or Power to Liquid (PtL), can be produced from clean electricity sources such as solar, wind and low-carbon nuclear energy. The efficiency of energy production can vary depending on the transformation processes such as high or low temperature electrolysis for hydrogen production, fermentation, and CO_2 capture from air or industrial flue gasses.[18] Therefore, the total energy from the Well to the Tank to produce 1 MJ of synthetic SAF would require on average about 4.5 MJ to 1.54 MJ input energy.[19] This “1.54 MJ” value is quite challenging but should be possible by 2050 and is used as reference through the document.

Based on 2050 worldwide forecasted aviation traffic, moving from fossil jet fuel to 100% Synthetic SAF at 1.5 MJ per MJ input energy would result in an equivalent of about 17,000 TWh electricity needs which represents 34% of 2050 worldwide electricity.

Both biofuels and e-fuels are quite promising to decarbonize the aviation sector at large scale before 2050. However, some considerations need to be considered by airlines and aircraft manufacturers when suing SAF.

2.1.2.3.1. What Would Be Required to Succeed?

- While SAF can be blended with traditional jet fuel and used in existing aircraft, it is important to ensure that the fuel is compatible with the specific type of engine and fuel system used by each aircraft. This may require some minor modifications or adjustments to the fuel system.
- Before using SAF, aircraft operators need to obtain certification from the relevant aviation authorities to ensure that the fuel is safe to use. This may involve additional testing and analysis to demonstrate that the fuel meets the required safety and performance standards. SAF can be blended with conventional aviation fuel up to 50%. It is expected to go up to 100% by 2030.
- SAF may require different handling procedures compared to traditional jet fuel due to its chemical composition. For example, some types of SAF may be more prone to microbial growth, so additional precautions may be needed to prevent contamination and ensure fuel quality.
- Currently, the production of SAF from bio or synthetic sources is limited and more expensive than traditional fossil fuels. To overcome this challenge, there is a need to scale up the production of SAF, which requires significant investments in research, development, and infrastructure. This includes developing new technologies and processes to produce SAF more efficiently and at a lower cost, as well as building new production facilities and supply chains to deliver the fuel to airlines around the world.
- Another challenge is ensuring that the production of SAF is sustainable and does not lead to negative environmental impacts such as deforestation, land use change, or competition for food and water resources. This requires implementing sustainability standards and certification schemes for SAF production, as well as ensuring that feedstocks are sourced responsibly and do not have negative social or environmental impacts.

2.1.2.4. Ammonia-powered Aircraft

Liquid ammonia (NH3) produced from green hydrogen is being considered as an alternative hydrogen carrier. It emits only water, NOx, and unburned NH_3 during combustion, and does not produce CO_2. It is not explosive or corrosive, but its vapor is highly toxic. At -33.3°C temperature in liquid form, ammonia is also much easier to manage compared to the liquid hydrogen or methane. In liquid form, its volumetric and gravimetric energy content is lower than current kerosene, meaning that more ammonia would need to be used — however, its combustion could potentially be as or more efficient.[20,21] Similar to hydrogen, liquid ammonia can be used in direct combustion or through fuel-cells, and it presents challenges such as the need for innovative fuel storage methods and redesigned airframes. This is because ammonia is more than two times heavier than CAF and would require more than three times larger volumes than traditional fuels, which can no longer be stored aerodynamically for free in the wings of the aircraft.

NASA has previously used liquid ammonia on the X-15 rocket engine, and it is being studied for use on the Dassault Falcon 50 later in 2023. A group at COP26 led by Reaction Engines has also launched a design for an ammonia cracking unit for aviation use.

2.1.2.4.1. What Would Be Required to Succeed?

- Ensuring the climate-neutrality of the liquid NH_3 combustion and its non-CO_2 emissions such as contrails and NO_x. Indeed, the combustion of liquid NH_3 will still produce contrails and NO_x.
- A liquid NH_3 tank capable of maintaining a temperature below -33.3°C degrees for 14 hours or more, especially when the aircraft is still waiting on the ground.
- Adapting the fuel pump and injectors on the turbofan.
- Efficient and light, powerful cracker units would need to be developed, especially for heavy long-haul aircraft with the ability to decompose several hundred tons of ammonia into hydrogen in the space of a few hours.
- Reducing energy losses in electrolysis and liquefaction distribution.
- The cost of the electricity used to produce the ammonia, depending on the source of electricity. There would be a need to reduce the cost of liquid NH_3 production.
- Use low- carbon electricity supply.
- Deploy the liquid NH_3 production and distribution infrastructure in all countries.

Based on 2050 worldwide forecasted aviation traffic, moving from fossil jet fuel to 100% liquid ammonia scenario would result in an equivalent of about 20,200 TWh Well to the Wake electricity needs which represents 40% of 2050 worldwide electricity.

2.1.2.5. Methane-powered Aircraft

Green methane (CH_4), produced from either hydrogen and carbon capture or from feedstocks of agricultural, forest, and waste origin could be an alternative, but the former pathway will require high quantities of renewable electricity. This has already been envisaged by NASA and is now used in SpaceX Starship Raptor rocket engines.[22] It has a better tolerance of the liquid form at freezing temperatures of -161°C to -182°C compared to -253°C to -259°C for hydrogen. Its larger molecules are less likely to pass through most materials, which would make it more manageable than liquid hydrogen. Loss of methane through leakage or liquid CH_4 boiling must be avoided at all costs. Indeed, over a period of a century, CH_4 would contribute more than 30 times to global warming than CO_2 and 82.5 times over a period of twenty years.[23] The aerodynamics, the type of aircraft, and the weight of the fuselage, which changes to accommodate the large tank caused by the liquid methane (twice the volume of actual jet fuel) and the liquid methane weight itself (depending on the distance flown), could add up to 22.6% to the total energy needed for the flight. The total weight of the methane would be about 10% higher compared to the actual CAF.

2.1.2.5.1. What Would Be Required to Succeed?

- Ensuring the climate-neutrality of the liquid CH_4 combustion and its non-CO_2 emissions such as contrails and NOx. Indeed, the combustion of liquid CH_4 will still produce contrails and NOx, but certainly less than actual fossil fuel.
- A liquid CH_4 tank capable of maintaining a temperature below -161°C to -182°C degrees for 14 hours or more, especially when the aircraft is still waiting on the ground.
- Adapting the fuel pump and injectors on the turbofan.
- Reducing energy losses in electrolysis, carbon capture and liquefaction distribution.
- The refueling cost would vary depending on the source of electricity. There would be a need to reduce the cost of liquid CH_4 production especially for the hydrogen and carbon capture pathway.
- Use low-carbon electricity.
- It might be possible to perform the liquefaction at the airport, as Liquid CH_4 production and gaseous distribution pipelines infrastructure already exists.

Based on 2050 worldwide aviation traffic, moving from fossil jet fuel to 100% liquid methane scenario would result in an equivalent of about 17,500 TWh Well to the Wake electricity needs which represents 35% of 2050 worldwide electricity.

2.1.3. Readiness of the Technology and Applicability According to Flight Distance

Decarbonizing the aviation sector will require a mix of different technologies. Some technologies will be easier than others to deploy and their level of maturity is also quite variable. Table 1 provides a timeline of the technological readiness of new categories of aircraft and fuels.

The market penetration of new technology is also an essential factor for accelerating the decarbonization of the aviation sector. Aircraft typically remain in service for about 20 years. Therefore, even if there are promising disruptive technologies coming into market, it could take years before achieving a full commercial deployment. Pioneers taking the risks to invest in new technologies should be supported to support the development of new markets.

TABLE 1: Technological readiness of new types of aircraft and associated fuels. Source: Table created by the authors for the paper.

Aircraft technological Readiness	2020	2030	2040	2050
Advanced Biofuels (SAF)	All flights	All flights	All flights	All flights
Synthetic Fuels (e-SAF)		All flights	All flights	All flights
Electric aircraft		Short hauls	Short hauls	Short & Medium hauls
Hydrogen Aircraft			Short & Medium hauls	All flights
Hybrid aircraft		All flights	All flights	All flights
Ammonia aircraft		Short hauls	Short & Medium hauls	Short & Medium hauls
Methane aircraft			Short & Medium hauls	All flights

2.1.4. Summary of the CO_2-eq Saving

Like any other transport sector, the potential for CO_2 emissions reduction in the aviation sector will depend on the carbon intensity of the consumed energy. Carbon intensity measures the amount of carbon dioxide (CO_2) emissions released to produce one kilowatt hour (kWh) of electricity. Electricity generated from fossil fuels such as coal and gas have a higher carbon intensity since the production process creates CO_2 emissions. The carbon intensity of various countries around the world is illustrated in Figure 5.

Table 2 shows the percentage of decarbonization in2050 compared to current aviation fossil fuel according to the carbon intensity of the electricity needed to produce the different sources of aviation fuels required to decarbonize aviation.

Nuclear power has the best performance among non-renewable energy sources, with a carbon intensity ranging from a minimum of 3.7, median of 12 and to a maximum of 110 grams of CO_2 equivalent per kilowatt hour (IPCC[24]). This allows for a median decarbonization of between -94% and -98% depending on the “fuel” produced. Renewable energy sources, such as offshore wind, have a minimum, median, and maximum carbon intensity respectively of 8, 12, and 35 grams of CO_2 equivalent per kilowatt hour (IPCC[27]). They also have a high median decarbonization ranging from -94% to -98%. Finally, solar energy has a minimum, median, and maximum carbon intensity of 26, 48, and 180 grams of CO_2 equivalent per kilowatt hour (IPCC[27]) where only electric aircraft (batteries) and hydrogen technologies would pass the -70% threshold level of sustainability, with a decarbonization range of -71% to -89% for the solar mean carbon intensity.

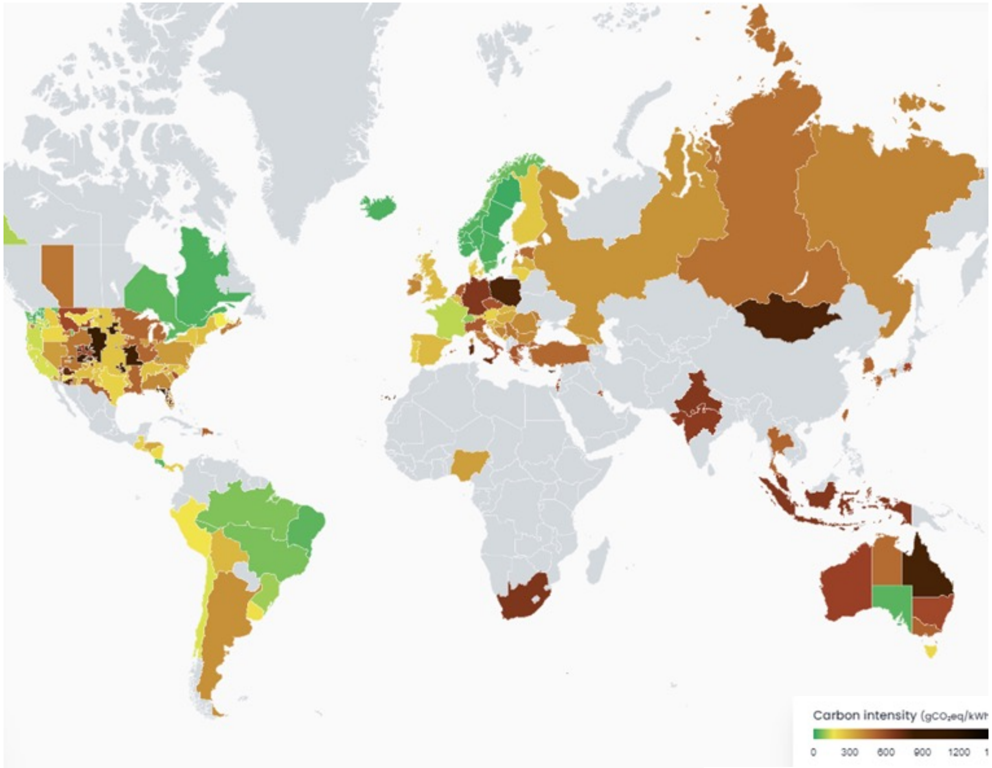
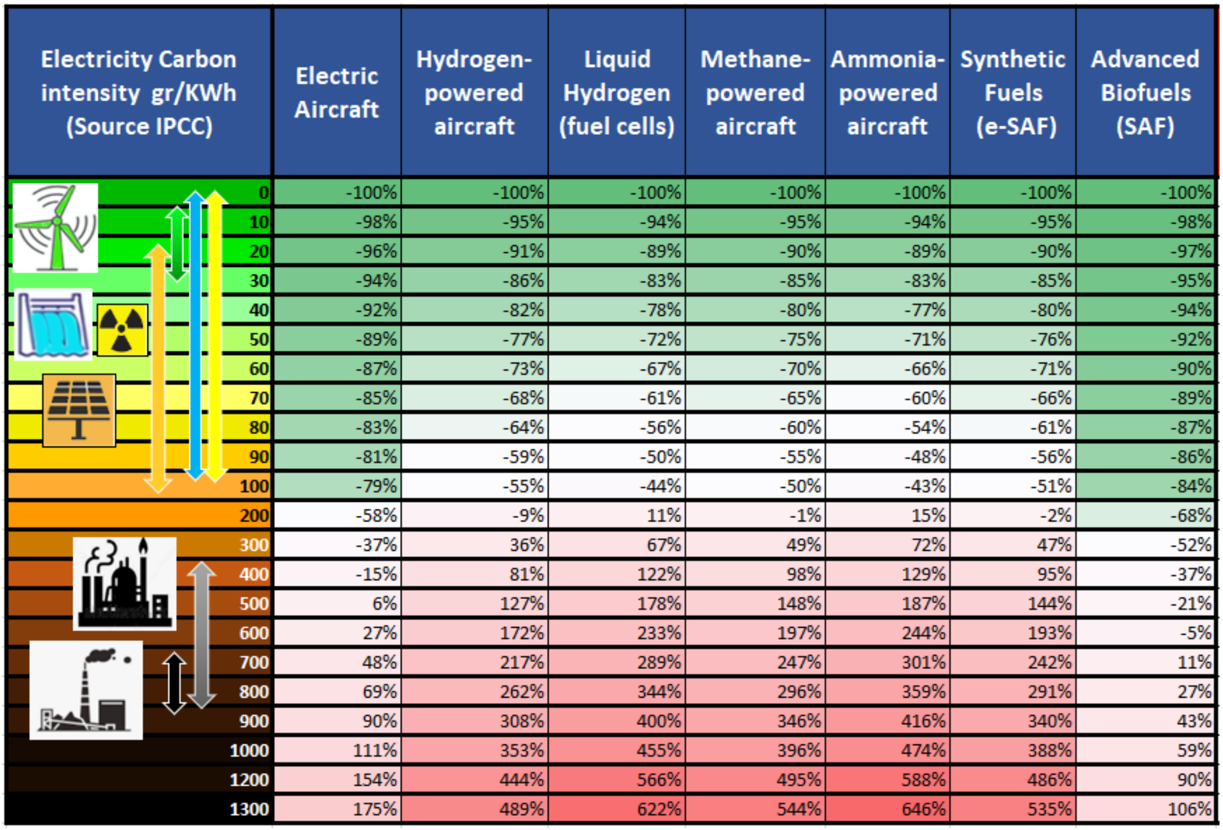


FIGURE 5: Worldwide Carbon Intensity of the produced electricity. Source: Electricity Maps, “Climate Impact by Area.” Accessed October 2023.

TABLE 2: Percentage of decarbonization compared to current aviation fossil fuel for the different sustainable aviation fuels (Well to Wake) based on electricity carbon intensity. Source: Table created by the authors for the paper.



Electricity Carbon intensity gr/KWh (Source IPCC)	Electric Aircraft	Hydrogen-powered aircraft	Liquid Hydrogen (fuel cells)	Methane-powered aircraft	Ammonia-powered aircraft	Synthetic Fuels (e-SAF)	Advanced Biofuels (SAF)
0	-100%	-100%	-100%	-100%	-100%	-100%	-100%
10	-98%	-95%	-94%	-95%	-94%	-95%	-98%
20	-96%	-91%	-89%	-90%	-89%	-90%	-97%
30	-94%	-86%	-83%	-85%	-83%	-85%	-95%
40	-92%	-82%	-78%	-80%	-77%	-80%	-94%
50	-89%	-77%	-72%	-75%	-71%	-76%	-92%
60	-87%	-73%	-67%	-70%	-66%	-71%	-90%
70	-85%	-68%	-61%	-65%	-60%	-66%	-89%
80	-83%	-64%	-56%	-60%	-54%	-61%	-87%
90	-81%	-59%	-50%	-55%	-48%	-56%	-86%
100	-79%	-55%	-44%	-50%	-43%	-51%	-84%
200	-58%	-9%	11%	-1%	15%	-2%	-68%
300	-37%	36%	67%	49%	72%	47%	-52%
400	-15%	81%	122%	98%	129%	95%	-37%
500	6%	127%	178%	148%	187%	144%	-21%
600	27%	172%	233%	197%	244%	193%	-5%
700	48%	217%	289%	247%	301%	242%	11%
800	69%	262%	344%	296%	359%	291%	27%
900	90%	308%	400%	346%	416%	340%	43%
1000	111%	353%	455%	396%	474%	388%	59%
1200	154%	444%	566%	495%	588%	486%	90%
1300	175%	489%	622%	544%	646%	535%	106%

Using coal to produce the electricity would increase CO_2 equivalent emissions by a factor of 1 to 6, depending on the type of aircraft technologies and fuel used compared to the current fossil jet fuel. As an example, the European Commission has defined a decarbonization level of 70% for aviation fuels to be recognized as sustainable.

2.1.5. Summary of the Energy Needs

In the previous sections, we estimated the amount of WTW electricity required in 2050 based on worldwide forecasted aviation traffic for the various technologies available to decarbonize the aviation sector. This is summarized in Table 3.

TABLE 3: Summary of the electricity needs. Source: Table created by the authors for the paper.

	WTW energy needs	**% related to 2050 worldwide electricity 50,000 TWh**
100% Electric Aircraft Scenario	7,500 TWh	15%
100% Hydrogen-powered Aircraft Scenario	16,000 TWh	32%
100% Liquid Hydrogen (fuel cells) Scenario	20,000 TWh	39%
100% Methane-powered aircraft	17,500 TWh	35%
100% Ammonia-powered aircraft	20,200 TWh	40%
100% Synthetic Fuels (e-SAF)	17,000 TWh	34%
100% Advanced Biofuels (SAF) Scenario	5,600 TWh	11%

The amount of energy required to decarbonize aviation is huge, and there is an urgent need to scale up the production of renewable and clean energies, whatever the option that is chosen.

Table 4 gives more details presenting a summary of the WTW electricity required in 2030, 2040, and 2050 by various aircraft technologies and fuels to power all departing flights worldwide, based on the ICAO LTAG Scenario 1, along with the corresponding number of equivalent nuclear reactors, offshore wind turbines, and square kilometers of photovoltaic panels needed (based on EU27+UK average solar irradiance).

It should be emphasized that an annual efficiency enhancement of 1.16% has been considered, encompassing improvements in engine efficiency and aerodynamics. In the case of electric battery-powered aircraft, simulations were conducted using a dedicated version of BADA[3] tailored for this purpose. Scenarios for 100% electric aircraft considered battery pack capacities ranging from 500 Wh/kg (2030) to 5000 Wh/kg by the year 2050. Any variation in battery pack energy density affects aircraft's energy efficiency and its maximum achievable range, which will in turn affect the overall electrical energy needs for aviation.

For hydrogen-powered and fuel cell aircraft, the analysis incorporates a liquid hydrogen fuel tank with a gravimetric index ranging from 50% in 2030 to 70% in 2050. Additionally, the assessment includes a fuel cell power density of 1.6 kW/kg and an assumed 50% efficiency by the year 2050. For the 100% synthetic fuels scenario, 4 MJ (2030) to 1.54 MJ (2050) has been used to produce 1 MJ of synthetic fuel. Finally, for the 100% advanced biofuels scenario, 1.16MJ (2030) to 0.5 MJ (2050) have been considered to produce 1 MJ of biofuel well to tank.

None of the 100% scenarios will be implemented in 2050. All decarbonization roadmaps that have been published so far consider a mix of different solutions including electric, hydrogen aircraft, and SAF for long hauls. However, the proportion of each solution may vary from one region to the other, and Table 4 may help to assess the regional energy needs for different scenarios. The next section is explaining how to use this table to assess a regional scenario.

TABLE 4: Well to Wake electricity required in 2030, 2040 and 2050 by various aircraft technologies. Source: Table created by the authors for the paper.

Electricity production/scenario	100% Electric Aircraft	100% liquid Hydrogen powered Aircraft	100% Liquid Hydrogen (fuel cells)	100% liquid Methane powered aircraft	100% Ammonia powered aircraft	100% Synthetic Fuels (e-SAF)	100% Biofuels (SAF)
WTW Electricity needed for the aviation in TWh considering 2030 WTW efficiencies and 2030 forecasted traffic	2,900	6,800	9,400	7,200	8,600	21,000	5,400
% related to 2030 worldwide electricity 38,400 TWh	8%	18%	24%	19%	22%	78%	20%
A net square shape of X km * X km of solar Photovoltaic panels (26% efficiency of 3.98 KWh/m2/day avg solar irradiation)	88	134	158	138	151	242	123
NB offshore 15-MW wind turbines (load factor 50%)	44,292	103,699	142,983	108,904	131,279	319,117	82,177
NB 911MW nuclear reactor (Load factor 78,45%)	465	1,088	1,500	1,143	1,378	3,349	862
WTW Electricity needed for the aviation in TWh considering 2040 WTW efficiencies and 2040 forecasted traffic	4,600	10,200	13,000	11,000	12,900	20,200	5,700
% related to 2040 worldwide electricity 44,200 TWh	10%	23%	30%	25%	29%	46%	13%
A net square shape of X km * X km of solar Photovoltaic panels (30% efficiency of 3.98 KWh/m2/day avg solar irradiation)	102	153	173	158	172	221	117
NB offshore 17-MW floating wind turbines (load factor 55%)	55,454	123,984	160,208	133,043	156,948	246,185	69,299
NB 911 MW actual nuclear reactor (Load factor 80%)	711	1,591	2,055	1,707	2,014	3,158	889
NB 1650 MW EPR nuclear reactor (Load factor 84%)	374	836	1081	898	1059	1661	467
WTW Electricity needed for the aviation in TWh considering 2050 WTW efficiencies and 2050 forecasted traffic	7,500	16,000	20,000	17,500	20,200	17,000	5,600
% related to 2050 worldwide electricity 50,000 TWh	15%	32%	39%	35%	40%	34%	11%
A net square shape of X km * X km of solar Photovoltaic panels (37% efficiency of 3.98 KWh/m2/day avg solar irradiation)	118	172	191	180	194	184	105
NB offshore 20-MW floating wind turbines (load factor 60%)	70,843	151,922	186,092	166,162	192,295	163,765	53,168
NB 911 MW actual nuclear reactor (Load factor 84%)	1,111	2,382	2,918	2,606	3,015	2,568	834
NB 1650 MW EPR nuclear reactor (Load factor 84%)	613	1,315	1,611	1,439	1,665	1,418	460

2.1.5.1. Example of Regional Scenario

Each country or each region has its own specificities. The decarbonization pathway will depend on local resources and available technologies, and the associated energy demand will vary accordingly. The presented table 5 could be used as a tool to estimate local energy needs.

Let us consider a fictive scenario for a region willing to decarbonize some departure flights by 2030. In 2019, the total consumption of the departing flights from this region was 10 million tons of jet fuel. Depending on the local specificities of the region, it has been decided that 1% from these 10 million tons of departure jet fuel will be replaced by hydrogen-powered aircraft, and 5% of the 10 million tons of total departure jet fuel will be replaced by biofuels. What do we need in terms of energy to achieve this scenario?

Knowing that the total worldwide 2019 fuel consumption was 328 million tons of jet fuel[2], 10 million tons represent about 3% of the worldwide jet fuel and **1%** of the 10 million tons represent **0.03%** (**3%** x **1%**) of the worldwide jet fuel.

To replace these 0.03% of fuel by hydrogen-powered aircraft, we need to consider the column for the 100% hydrogen-powered aircraft scenario to estimate the amount of energy needed for these 0.03%.

Table 5, showing the 2030 demand for liquid hydrogen, shows that **100%** of the current fossil jet fuel replaced by **100%** of liquid hydrogen aircraft would require **6,800 TWh**. Therefore, **1% of hydrogen-powered aircraft by 2030 would need 2 TWh of electricity per year** (6,800 TWh x 0.0003 (0.03%)). It is also equivalent to **31** (103,699 x 0.03%) offshore 15 MWh wind turbines at 50% load factor or equivalent to a net square shape of "2 km x 2 km" at 3.98 KWh/m^2 irradiance ("134 x 134 km" x 0.03% = 5.4 km^2 = a net square of 2.3 km x 2.3 km) or about 0.33 911 MW nuclear reactors at 78% load factor (1,088 x 0.03%).

For biofuels, we can use the same methodology while considering the column for the 100% advanced biofuels scenario (Table 6).

TABLE 5: Well to Wake electricity required in 2030 for liquid hydrogen. Source: Table created by the authors for the paper.

Electricity production/scenario	100% liquid Hydrogen powered Aircraft
WTW Electricity needed for the aviation in TWh considering 2030 WTW efficiencies and 2030 forecasted traffic	6,800
% related to 2030 worldwide electricity 38,400 TWh	18%
A net square shape of X km * X km of solar Photovoltaic panels (26% efficiency of 3.98 KWh/m2/day avg solar irradiation)	134
NB offshore 15-MW wind turbines (load factor 50%)	103,699
NB 911MW nuclear reactor (Load factor 78,45%)	1,088

TABLE 6: Well to Wake electricity required in 2030 for biofuels. Source: Table created by the authors for the paper.

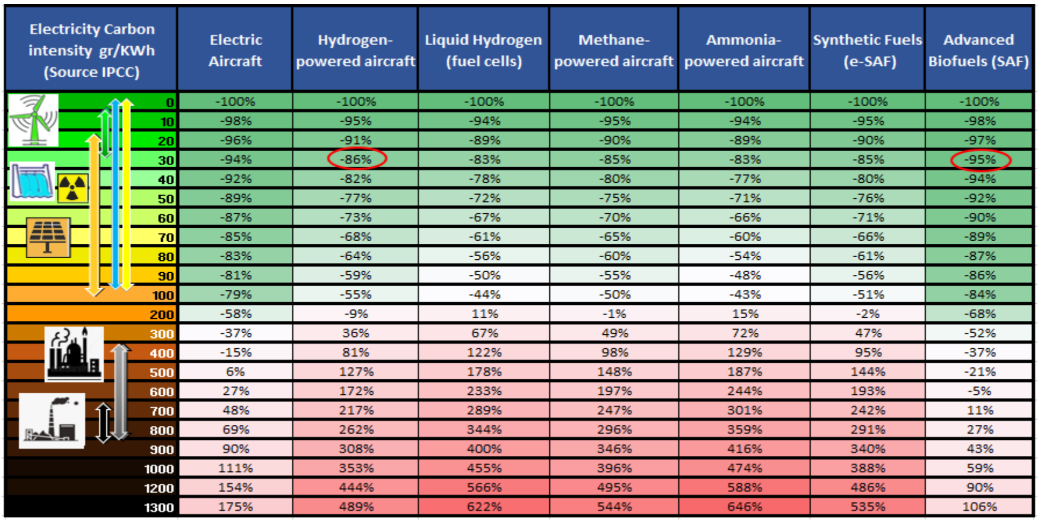
Electricity production/scenario	100% Biofuels (SAF)
WTW Electricity needed for the aviation in TWh considering 2030 WTW efficiencies and 2030 forecasted traffic	5,400
% related to 2030 worldwide electricity 38,400 TWh	20%
A net square shape of X km * X km of solar Photovoltaic panels (26% efficiency of 3.98 KWh/m2/day avg solar irradiation)	123
NB offshore 15-MW wind turbines (load factor 50%)	82,177
NB 911MW nuclear reactor (Load factor 78,45%)	862

Knowing that the total worldwide 2019 fuel consumption represents 328 million tons of jet fuel, 10 million tons represent 3% of the worldwide jet fuel and **5%** of the 10 million tons represent **0.15%** (**3%** x **5%**) of the worldwide jet fuel.

100% of the current fossil jet fuel replaced by **100%** of biofuels (SAF) would require **5,400 TWh**. Therefore, to have **5% of biofuels by 2030 out of the 10 million tons, we need 8.1 TWh of electricity per year** (5,400 TWh x 0.0015 (0.15%)). It is also equivalent to **123** (82,177 x 0.0015 (0.15%)) offshore 15 MWh wind turbines at 50% load factor or equivalent to a net square shape of "4.8 km x 4.8 km" at 3.98 KWh/m^2 irradiance ("123 km x 123 km" x 0.15% = 22.7km^2 = a net square of 4.8 km x 4.8 km) or about 1.3 911 MW nuclear reactors at 78% load factor (862 x 0.15%).

The final potential CO_2 reduction of this regional scenario will depend on the carbon intensity of the energy that will be used to produce both the hydrogen and the biofuels as described in the table 7.

For instance, in our scenario, considering a source of electricity at 30gr/kWh of carbon intensity, the production of biofuels would reduce its CO_{2eq} compared to Current fossil jet fuel by 95%. Replacing 5% of the current jet fuel by biofuels would reduce the emissions of this region by 4.8% (5% x 0.95 (95%)). With the same methodology, replacing 1% of the current jet fuel by hydrogen-powered aircraft would decarbonize by 0.86% (1% x 0.86 (86%)). In total, with a scenario of 1% of hydrogen-powered aircraft and 5% of biofuel, the Region would reduce the emissions from the aviation sector by 5.6% (4.8% + 0.86%) in 2030.



Electricity Carbon intensity gr/KWh (Source IPCC)	Electric Aircraft	Hydrogen-powered aircraft	Liquid Hydrogen (fuel cells)	Methane-powered aircraft	Ammonia-powered aircraft	Synthetic Fuels (e-SAF)	Advanced Biofuels (SAF)
0	-100%	-100%	-100%	-100%	-100%	-100%	-100%
10	-98%	-95%	-94%	-95%	-94%	-95%	-98%
20	-96%	-91%	-89%	-90%	-89%	-90%	-97%
30	-94%	-86%	-83%	-85%	-83%	-85%	-95%
40	-92%	-82%	-78%	-80%	-77%	-80%	-94%
50	-89%	-77%	-72%	-75%	-71%	-76%	-92%
60	-87%	-73%	-67%	-70%	-66%	-71%	-90%
70	-85%	-68%	-61%	-65%	-60%	-66%	-89%
80	-83%	-64%	-56%	-60%	-54%	-61%	-87%
90	-81%	-59%	-50%	-55%	-48%	-56%	-86%
100	-79%	-55%	-44%	-50%	-43%	-51%	-84%
200	-58%	-9%	11%	-1%	15%	-2%	-68%
300	-37%	36%	67%	49%	72%	47%	-52%
400	-15%	81%	122%	98%	129%	95%	-37%
500	6%	127%	178%	148%	187%	144%	-21%
600	27%	172%	233%	197%	244%	193%	-5%
700	48%	217%	289%	247%	301%	242%	11%
800	69%	262%	344%	296%	359%	291%	27%
900	90%	308%	400%	346%	416%	340%	43%
1000	111%	353%	455%	396%	474%	388%	59%
1200	154%	444%	566%	495%	588%	486%	90%
1300	175%	489%	622%	544%	646%	535%	106%

TABLE 7: Electricity carbon intensity and % of decarbonization from different aircraft technologies Source: Table created by the authors for the paper.

2.1.6. Conclusion and Suggestions

Like any transport mode, the aviation sector is facing an increasing pressure to have net-zero emissions by 2050. Electrification is a very promising solution, but aviation faces an additional complexity as flying requires a high energy density. Therefore, it is more likely that by 2050, a mix of aircraft technologies will co-exist. Zero emission aircraft (electric, hydrogen, methane, ammonia…) and conventional aircraft will share the skies with their specific needs in terms of infrastructure, fuels, and energy demand. Development and operating costs will require the support of the financial sector or public funding.

There is a need to quickly upscale the production of advanced biofuels and synthetic fuels as they can be used to rapidly decarbonize the current conventional fleet as a drop-in solution. Disruptive technologies will take more time, especially for long-haul flights. Electric and hydrogen aircraft seem to be very promising for short and medium hauls and regional/business aviation segments, but they also require the upscaled production of green hydrogen and renewable energy. Technologies to capture CO_2 will also be essential to either produce e-SAF or to capture and store the remaining emissions by 2050.

As described in the previous sections, the aviation sector will require a huge amount of low-carbon or renewable energy to produce the necessary fuels for the different aircraft technologies. It is essential to ensure that enough clean/green energy will be available at an affordable price to the aviation sector to achieve its decarbonization objectives.

Ultimately, unlike road transport, entry into the market of new aircraft will take more time due to the slow pace of fleet renewal where most aircraft have a lifespan of 20 years. This additional challenge can slow down the decarbonization potential of aviation, and a faster fleet renewal should be incentivized.

2.2. Road Sector

2.2.1. The Decarbonized Energy Demand in the Road Transport Sector Towards 2050

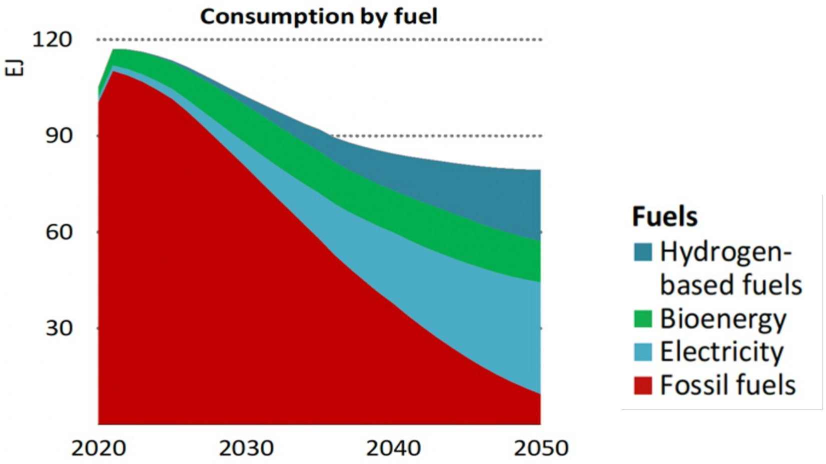
The entire transportation sector is a major contributor to carbon dioxide (CO_2) emissions, accounting for about 21.73% of global energy-related CO_2 emissions.[25] Where the Road traffic carbon emissions, meanwhile, account for 71.28% of the overall traffic sector.[26] In recent years, there has been a growing concern about the impact of these emissions on climate change and the need to reduce them to achieve carbon neutrality by 2050.

To significantly curtail carbon emissions from the road transportation sector, a pivotal strategy involves transitioning to renewable energy. The integration of renewable energy sources is not just beneficial, but essential for achieving targeted emissions reductions. This shift aligns with broader global efforts to mitigate e climate change and move toward a more sustainable, low-carbon energy landscape.

2.2.2. The Use of Clean or Low-carbon Energy in the Road Sector

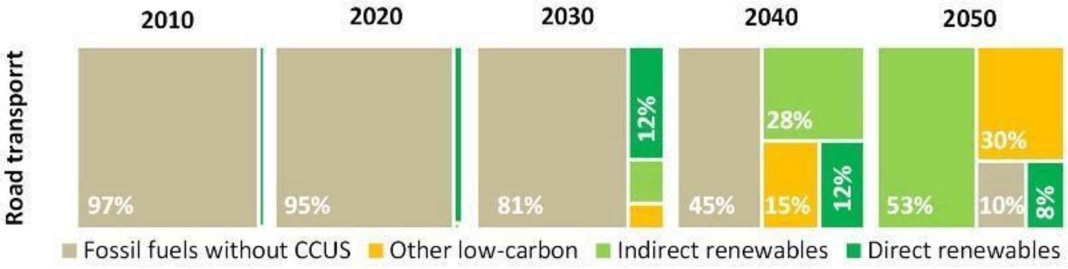
According to the International Energy Agency's Net Zero Emissions by 2050 Scenario, the fossil fuel dependency is projected to reduce gradually from around the year 2020 and reduce sharply from the year 2040 onwards (Figure 6). Specifically, the fossil fuel share in road transport is expected to reduce to less than 75% by 2030 from over 90% in 2020 and decline further to approximately 10% by 2050. Concurrently, a transformative shift towards cleaner energy is anticipated. By the early 2040s, electricity is forecasted to emerge as the primary energy source for road transport, constituting 45% of the sector's total final energy consumption by 2050. This will be followed by hydrogen-based fuels at 28% and bioenergy at 16%. These projections not only signify a substantial transition towards cleaner energy but also align with the overarching demand trends in the global transportation sector. Therefore, the evolving energy landscape underscores the imperative for strategic interventions in the road transport sector to meet global decarbonization objectives.

FIGURE 6: Global transport final consumption by fuel type in the NZE (IEA).[27]



In the context of the global carbon neutral goal, the use of clean energy in the field of road transportation plays an important role in reducing carbon emissions in the entire transportation industry with the forms of clean energy in the future including electricity from renewable sources, hydrogen energy, and biofuels, etc. According to the IEA report Net Zero by 2050: A Roadmap for the Global Energy Sector, the share of renewable energy in road transport is expected to increase from 4% in 2020 to around 20% by 2030, and over 60% in 2050 (Figure 7).

FIGURE 7: Fuel shares in total energy use in electricity generation in the NZE (IEA). Notes: Indirect renewables: Use of electricity and district heat produced by renewables; Other low-carbon: nuclear power, facilities equipped with CCUS, and low-carbon hydrogen and hydrogen-based fuels.[28]



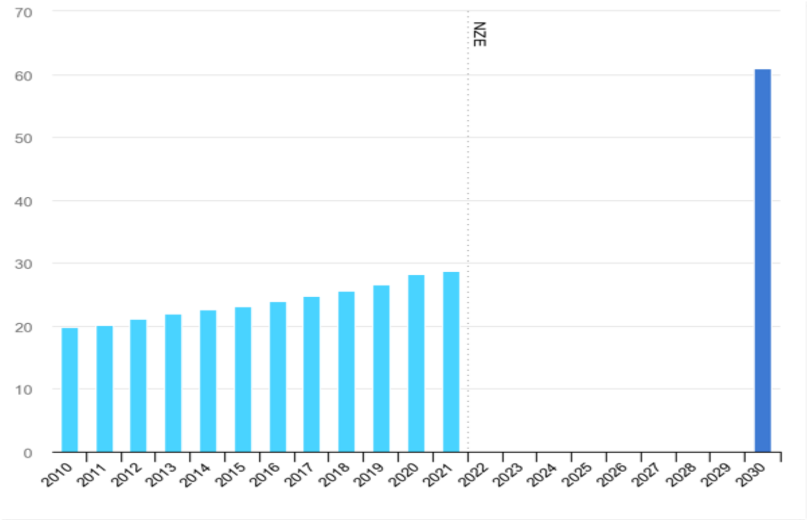
2.2.2.1. Electricity

In 2021, the global Electric Vehicle (EV) fleet consumed about 50 TWh of electricity, with a mere 0.5% from renewable sources.[29] This proportion is expected to increase substantially, reaching 20.5% by 2040, aided by the falling costs of solar and wind power. Concurrently, the IEA forecasts a significant expansion in renewable energy capacity, from 2,400 GW to approximately 4,800 GW between 2022 and 2027, aligning with the rapid uptick in global EV adoption.[30] This growth in renewables will contribute to meeting the increasing electricity demand from the transport sector while reducing greenhouse gas emissions.

The share of renewables in total electricity generation globally increases from 29% in 2020 to over 60% in 2030[34] and to nearly 90% in 2050[35] (Figure 8).[32]

According to the International Hydrogen Fuel Cell Association's projection, the electricity demand for EVs in road transport will reach 11,250 TWh by 2050.[33] Meanwhile, the IEA Renewable Energy Report estimates that renewable energy supply capacity will attain 25,620 TWh in the same year. This indicates that renewable energy supply will significantly exceed EV electricity demand, offering substantial scope for future road transport electrification.

FIGURE 8: Renewables share of power generation in the Net Zero Scenario, 2010-2030.[31]



2.2.2.2. Hydrogen and Hydrogen Derivatives

Hydrogen can be produced from a variety of sources, including renewable energy sources such as solar and wind power. Therefore, hydrogen energy has the potential to be a scalable and sustainable solution to the road transport energy needs.

The demand for hydrogen as a clean fuel is expected to increase significantly in the coming years. Based on the 2022 IEA Global Hydrogen Review, the demand for hydrogen in sectors such as transport, power, and buildings increased by 60% in 2021, such increased demand from these sectors amounting to approximately 40 kt H_2. This figure corresponds to a mere 0.04% of the global hydrogen demand. Most of this demand is concentrated in road transport, which observed a significant increase because of the accelerated deployment of Fuel Cell Vehicles (FCVs)—particularly hydrogen fuel cell heavy-duty trucks in China. The IEA projects that the demand for hydrogen in the overall energy demand will increase from 2.5% in 2021 to around 18% in 2050.

According to the International Hydrogen Council, hydrogen technology can provide 18% of the world's energy needs by 2050, and by then, more than 425 million vehicles worldwide will use hydrogen fuel cells. According to the International Energy Agency's "Net Zero Emissions in 2050: Global Energy Roadmap", the global demand for hydrogen energy will reach 528 million tons in 2050, of which hydrogen energy consumption in the transportation sector will account for about 40%, or 211 million tons.

Hydrogen Derivatives (Production and Use Cases)
Due to the chemical and physical properties of hydrogen, in many use cases, such as longer distance transport, it is reasonable to convert hydrogen into derivatives like methanol or ammonia. These chemicals are widely used and traditionally produced from natural gas, oil, or coal.[34] However, low-carbon methanol and ammonia can also be produced, e.g., through the use of low-carbon hydrogen. This way, hydrogen derivatives can play a major role in the transition to a low-carbon economy in general, but also in the transportation sector. For road transportation, low-carbon methanol is especially important. In a subsequent processing step, low-carbon methanol can be converted into low-carbon gasoline (MTG plant "Methanol-to-Gasoline").

Low-carbon E-methanol
Climate-friendly methanol technologies are based on the production of low-carbon hydrogen from water electrolysis powered by renewable energy. Conventional methanol plants use steam reforming of natural gas (or even coal). Methanol is called e-methanol when it is produced from hydrogen that was produced from renewable power, e.g., from wind, solar, geothermal or hydropower.

Methanol fuel for vehicles is a mixture of gasoline, methanol, and additives. According to the blending ratio of methanol, it can be divided into M15 (methanol content 15%), M30, and up to M100 for a methanol-only fuel. At present, China is focusing on promoting the use of M100.

The carbon dioxide required for methanol synthesis is recovered from biogas or other fermentation plants. It comes from all kinds of applications, such as flue and exhaust gases from chemical and petrochemical complexes, cement plants, or steel mills.

Plants for the production of e-methanol are usually small-scale plants with capacities of 50-500 tons of e-methanol per day. However, studies have already been conducted for plants with capacities of up to 10,000 tons of e-methanol per day. For these small-scale plants to be economically viable, they should at best be able to compete with conventional plants. Key cost drivers are capital expenditure, availability and cost of renewable energy, potential methanol transport restrictions and costs, CO_2 emission restrictions, and carbon taxes. Not surprisingly, the aforementioned economies of scale of conventional large-scale plants result in more favorable production costs. A case study on costs and production capacities for Northern Europe can be found in the appendix. In summary, total production costs amount to 519€/ton of methanol. For comparison, IRENA estimates the production costs of e-methanol at 400-700 USD/ton.

Beyond its application as a fuel for transportation, methanol can also be used as an energy carrier or storage for renewable electricity which opens the opportunity for sector coupling.

Low-carbon methanol from natural gas

The conventional large-scale methanol plant using natural gas to produce 5,000 ton methanol per day uses Autothermal Reforming (ATR) with synthesis gas production by partial oxidation. For the production of low-carbon methanol this “ATR only” methanol technology was further optimized.[35] In this process, the CO_2 produced at various points is almost completely converted into methanol. In addition to natural gas, low-carbon H_2 produced from renewable energy is required.

In the production of this low-carbon methanol, the following Key Performance Indicators (KPIs) are particularly noteworthy:

- CO_2 recovery rates of up to 99% are achievable.
- CO_2 emissions per ton of low-carbon methanol are correspondingly lower than for “green” methanol.
- Production capacity is increased by almost 25% through the use of the resulting CO_2. The production costs per ton of low-carbon methanol are therefore comparable to those for gray methanol — thus many times cheaper than “green” methanol will ever be.

A corresponding commercial large-scale plant for the production of 6,150 tons per day of low-carbon methanol is currently being planned (almost all project development activities including basic engineering and financing are completed) and is expected to be financially close in 2023.

2.2.2.3. Fuels from Biomass and Organic Waste

The term biofuel refers to all sorts of fuels that are produced using organic matter as initial feedstock. This can include crops, forestry residues, algae, and recycled restaurant grease. Depending on feedstock characteristics and the production technology, biofuels can be used for a range of different applications. According to the Net Zero Emissions by 2050 studies by the IEA, IRENA, BP, and Shell, the contribution of bio-energy to primary energy supply could be between 10% and 20%.

First-generation (1G) biofuels are produced from types of biomass commonly used for food, such as corn, wheat, soybeans, and sugarcane, through the fermentation of sugars and starches in the biomass into fuels such as ethanol. Markets and technologies for first-generation biofuels are well established and widely used around the world. If they were rapidly expanded, they would directly compete with sufficient food supply. Second-generation (2G) biofuels, however, are produced from cellulose, such as grasses and fast-growing trees. The processes used to produce them are more complex and less advanced than those for 1G biofuels.

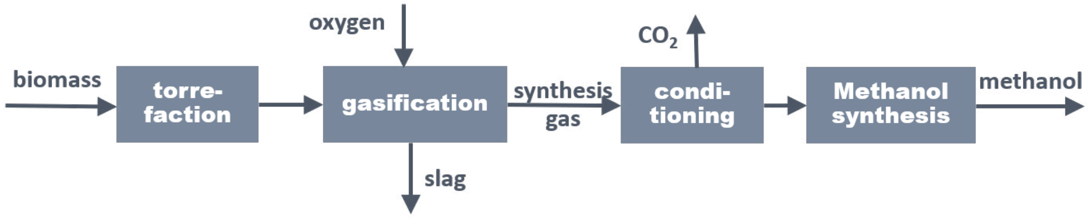
Different countries are at different stages in the application of biofuels in the road sector. In China, biofuels are still in the demonstration stage. In July 2021, the National Energy Administration of China issued the "Guiding Opinions on Energy Work in 2021", which clearly stated that it is necessary to accelerate the demonstration of non-food biofuel ethanol industries and pointed out that the development of cellulose ethanol will be the key direction of development, effectively switching from 1G to 2G biofuels. In the United States, ethanol is the most widely used biofuel. Most vehicles in the US can use gasoline-ethanol blends containing up to 10 percent ethanol, E10 (by volume). Flexible fuel vehicles can use E85, a gasoline-ethanol blend containing up to 85 percent ethanol. In Europe, biofuels so far make up a small fraction of fuels.

Low-carbon Methanol Based on Biomass

Not only ethanol, but also low-carbon methanol can be produced through gasification of biomass wastes. Especially interesting is using wood from short rotation plantations (SRPs), as they are used for paper production in regions south of the Brazilian rainforests. SRPs are tree plantations grown on a short rotation cycle, typically of less than 15 years, to produce woody biomass for various applications such as biofuels.[36]

Figure 9 illustrates the main technical approach to produce low-carbon methanol from biomass.

FIGURE 9: simplified concept of low-carbon methanol production based on biomass.
Source: Figures created by authors for paper.



For the production of low-carbon methanol via this route, the following KPI's are particularly noteworthy:

- CO_2 recovery rates of up to 90% are achievable.
- CO_2 released during the production of methanol was previously biologically extracted from the atmosphere, i.e. the process is climate-neutral.
- CO_2 emissions per ton of low-carbon methanol are accordingly comparable to e-methanol based on power from renewable energy sources (see above).
- No carbon capture technology is used.
- Approximately 2.9 kilograms of biomass are required per liter of low-carbon methanol.

A corresponding demonstration plant on a semi-commercial scale, in which the two complex process steps of torrefaction and gasification have been successfully implemented, has been in operation for several years.

Low-carbon Gasoline

As described above, the production of synthesis gasses is mostly based on natural gas, coal and crude oil (crude oil distillates), or biomass as feedstock. If the latter is available in sufficient quantities, it can be converted into such synthesis gas via gasification. Effectively, this gas is a mixture containing mainly carbon monoxide (CO) and hydrogen (H_2) along with varying amounts of other gasses. The synthesis gas thus obtained can be further converted into low-carbon gasoline, either via the Fischer-Tropsch process or via synthesis to methanol and subsequent conversion in an MTG plant, as mentioned above. If plant-based fuels are produced in this way, CO_2 emissions can be reduced by up to 90%. There is further potential for CO_2 savings if renewable energy is also available.

In general, there is a risk that the area used to grow biomass will reduce the space available for food crops. Production processes based on second-generation biomass are accordingly the focus of research and development. In the appendix, a schematic figure showing the Biofuel technology of Avril, Axens, CEA, Total, Thyssenkrupp Industrial Solutions, and IFPEN (IFP Energies Nouvelles) with a high TLR can be found. This process mainly uses waste and residues such as wood cuttings or straw, which do not compete with proximity fuels. Roughly estimated, this biorefinery costs 0.8-1.3 billion euros so that production costs are in the range of 0.8-1.5 € per liter of low-carbon fuel.[37] It should be emphasized that this technology also enables the production of biokerosene/SAF in large quantities—which explains the high level of interest from airlines, among others.

Hydrotreated Vegetable Oil-Diesel (HVO-diesel)

Hydrotreated vegetable oils (HVOs) are produced from natural vegetable oils by catalytic reaction with hydrogen. This process produces hydrocarbon mixtures with similar or even better properties compared to corresponding fractions from crude oil, essentially kerosene and diesel. Also, HVO could become more important as a kerosene substitute for aircraft, as an alternative to the costly Fischer-Tropsch synthesis. The raw material for HVO are vegetable oils that do not compete with food production as they are incinerated otherwise after use. In case low-carbon hydrogen or low-carbon methanol is used, the CO_2 reduction compared to fossil diesel is 90% and more.[38]

HVO Availability and Production Volumes

In 2020 the world HVO production amounted to 6.2 million metric tons with Europe (3.4 million tons) and the US (2.1 million tons) as the main focus.[39] This is expected to more than quadruple by 2025 as a result of plants already under construction, especially in the US with a projected 12.6 million tons/year and with 11.3 million tons/year in Europe.[40] The majority of HVO is sold in the form of blends with conventional diesel in the range of 10-50%. Though HVO is a reasonable option for low-carbon mobility, its estimated total potential is limited; only 213 million tons of vegetable oils were produced worldwide in 2021.

The global market for used vegetable oils and fats is not very transparent, so that a very rough estimate of the available potential for HVO is 50-80 million tons per year. This would be equivalent to 6-10% of current diesel or 15-25% of current kerosene consumption worldwide.

2.2.3. New Energy Vehicles (NEV)

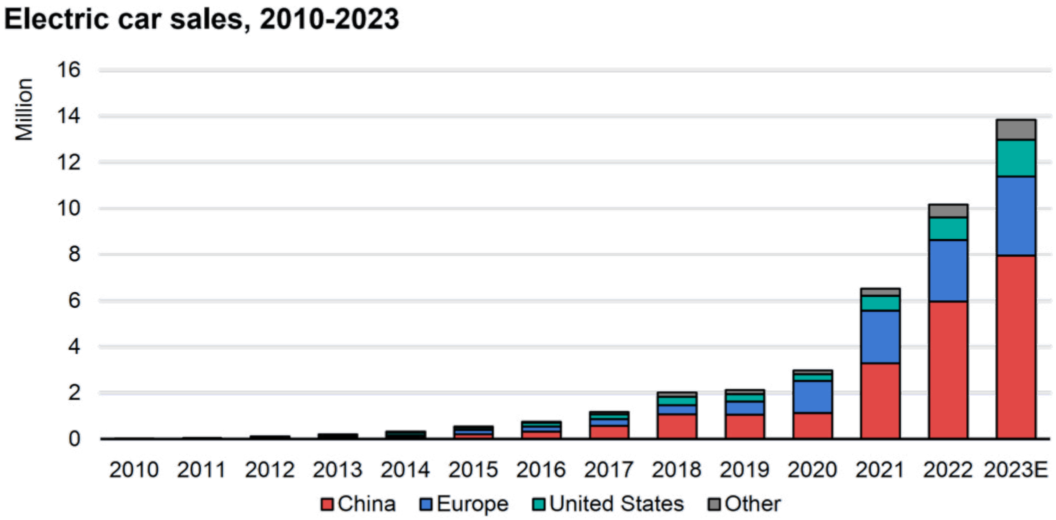
In the pursuit of a sustainable and de-carbonized future, NEVs have emerged as a promising solution for the transportation sector. The complementary development of electric vehicles (EVs) and fuel cell vehicles (FCVs), alongside worldwide deployment of renewable energies, present a unique opportunity to address climate changes and global energy security. The following sections will explore three parallel technology pathways for the integrated development of renewable energies and clean fuels with zero and low-carbon vehicles; the sections will highlight key considerations and outline strategies for policymakers.

As of now, the NEV market is predominantly led by EVs, while FCVs are in their nascent stage. Both aim to reduce fossil fuel dependency and environmental impact but differ in their applications due to distinct power sources and technologies. EVs, FCVs, and hybrid vehicles each offer distinct advantages tailored to specific use-cases due to differences in energy density. EVs, currently in a phase of rapid development, are suited for shorter-range scenarios due to their existing battery technology. FCVs, with their higher energy density by weight, are optimal for heavy-duty, long-distance applications. Hybrids, with their flexible energy utilization, fill the gap by excelling in intermediate-range scenarios. These different types of vehicles collectively provide a range of sustainable options for various transportation requirements, different customer needs and different using scenarios.

2.2.3.1. Electric Vehicle (EV)

Electric vehicles (EVs) are automotive transport options powered by electric motors, utilizing energy stored in rechargeable batteries. Compared to traditional internal combustion engine vehicles fueled by fossil energy, EVs offer key advantages such as zero tailpipe emissions, reduced greenhouse gas output when charged with renewable energy, and lower operational costs due to fewer moving parts.

FIGURE 10: Electric car sales global, 2010-2023E (IEA analysis based on EV Volumes). Note: Electric cars – including battery electric vehicles (BEVs) and plug-in hybrid electric vehicles, 2023 sales ("2023E") are estimated based on market trends through the first quarter of 2023, Source: IEA analysis based on EV Volumes.[41]



Despite a 3% contraction in the global internal combustion engine (ICE) car market in 2022, EV sales—including battery electric vehicles (BEVs) and plug-in hybrids (PHEVs)—surged by 55% to exceed 10 million units, with China contributing 6 million to this total (Figure 10). This acceleration underscores the exponential growth in EV adoption, as the market share rose from 9% in 2021 to 14% in 2022. Early data from 2023 indicates robust growth, projecting nearly 14 million EV sales for the year—a 35% increase over 2022 figures and an estimated 18% market share.[42]

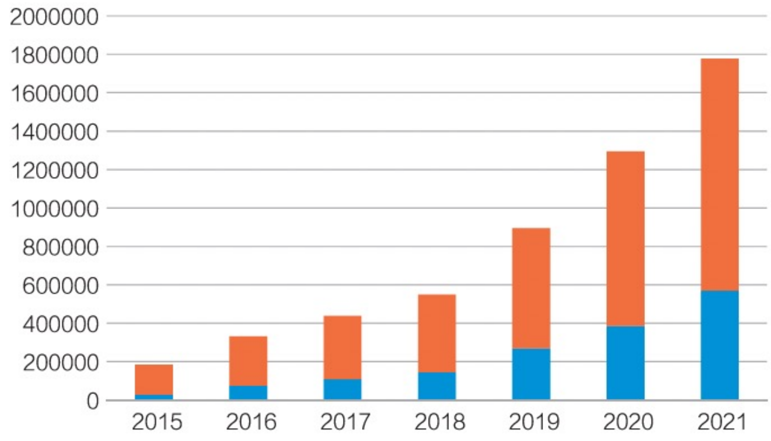
Tesla remains the global market leader, capturing 18.2% of global EV sales in 2022, amounting to approximately 1.31 million units.[43] Other key players include Chinese firms like BYD, which holds a dominant 45% market share in China,[44] and BAIC, as well as traditional automakers such as Volkswagen and General Motors. In Europe, Tesla, Stellantis, and Volkswagen lead the market, while in the US, Tesla continues to dominate, but brands such as Ford, Hyundai, and Kia are also gaining traction.

The top-selling Tesla Model Y offers two configurations distinguished by their power systems. The rear-wheel-drive version features a single motor and a lithium iron phosphate battery, achieving a range of 545 km. The long-range all-wheel-drive variant utilizes dual motors and a ternary lithium battery, extending the range to 660 km. Another high-performing model, the BYD Yuan PLUS, employs a lithium iron phosphate blade battery and offers two range options under CLTC conditions: 430 km and 510 km. These leading models effectively match the performance and range of traditional fossil fuel vehicles, making them viable options for both urban and inter-city travel.

EV Charging Infrastructure

A sound charging infrastructure system is an important guarantee for the popularization of electric vehicles. With the continuous growth of electric vehicle sales, the charging infrastructure in various countries is also constantly developing. According to the IEA, from 2015 to 2021, the number of publicly accessible charging infrastructure has increased from 184,000 to 1.8 million, an increase of about 37% in 2021 compared to 2020.

FIGURE 11: Changes in the number of public charging facilities in the world from 2015 to 2021 (IEA).[45]



Battery-swap Stations
As of 2022, battery-swap stations have emerged as a pivotal element in the EV infrastructure, offering rapid charging and user convenience. China dominates this sector, followed by the US and Europe. These stations are categorized based on their technical capabilities, such as automated or manual swapping mechanisms. While they require substantial investment in real estate, power supply, and standardization, their operational costs can be offset by leveraging the stored batteries for grid services. The global market for battery-swap stations is poised for growth, fueled by increasing EV adoption and the quest for efficient charging solutions.

What would be required to succeed?
Despite the rapid progress in EV technology, these are the main technical difficulties that the industry is grappling with:

Range: One of the main challenges with EVs is the shorter driving range compared to traditional ICE vehicles. EV producers not only must match ICE range, but also dissuade the popular consumer belief that ICE vehicles are higher performing.

Charging Infrastructure: While there has been significant investment in charging infrastructure, there are still challenges in establishing a comprehensive and reliable charging network, especially in remote or underdeveloped areas.

Recycling and Sustainability: Proper disposal and recycling methods need to be developed to avoid environmental hazards and ensure sustainability of the electric vehicles.

Safety Measures: Another critical concern is the safety of the energy storage systems, particularly the flammability of the electrolyte in current lithium batteries. Addressing this issue is paramount to ensure consumer trust and broader adoption of EVs.

Raw Material Shortage: The EV market faces challenges related to the availability and sourcing of critical raw materials like lithium, cobalt, and nickel, essential for battery production. Scarcity or geopolitical constraints on these materials could impact the scalability and cost-effectiveness of electric vehicles.

Here are some of the new technologies along with some possible solutions that could potentially solve these challenges:

Battery:

- **Improved Energy Density:** Currently, lithium-ion batteries used in EVs have an energy density around 260 Wh/kg at the cell level. To enhance the range and performance of EVs, this figure needs to rise significantly. Reaching an energy density of 500 Wh/kg could potentially double the range of current EV models.

- **Innovation in Battery Technology:** Lithium-ion batteries (LIB) have been a cornerstone of EV technology, yet they rely heavily on rare and costly materials like cobalt. Alternative materials, such as sodium, magnesium, and solid-state electrolytes, hold immense promise. Solid-state batteries (SSB) have a reported power density of 500 Wh/kg (almost twice that of LIB), and Asian and European automakers have announced plans to establish SSB production in the next few years. For instance, SAIC has announced a plan to achieve a production capacity of 100,000 units of SSB EVs around 2025.[46]
- General Battery System Improvements: Improve the safety of the battery system, reduce costs, improve the accuracy of the battery management system, and develop new battery systems. Improve battery cell energy density and voltage platform.

Electric Motor:

- Develop advanced, efficient, and high-performance electric motors and continuously optimize efficient powering methods. Continuously improve the power density of the motor and the power density of the controller, improve the efficiency, specific power, and specific torque of the motor.

Infrastructures:

- **Smart Charging Technologies:** Vehicle-to-Grid (V1G) or "smart charging" enables dynamic adjustment of EV charging rates and schedules, based on grid demands and peak-valley pricing. This unidirectional energy transfer enhances grid efficiency, reduces infrastructure costs, and promotes renewable energy use. It involves grid, service provider, and user engagement, optimizing charging costs and balancing system loads for broader economic and social benefits.
- **Advanced Charging Infrastructures:** Although more advanced charging infrastructures are developing rapidly across continents, represented by the presence of ultra-fast chargers in the US and battery-swap stations for heavy-duty (HD) vehicles in China, both technological and business innovations advancement are needed to proliferate further and improve charging infrastructures.
- **PV-ESS-EV Charging Micro-grid**: Integrating solar distributed PV power generation, Energy Storage Systems (ESS), and Electric Vehicle (EV) charging, serves as a multifaceted solution for road transport decarbonization. It enhances renewable energy utilization and ensures EV life cycle sustainability while bolstering micro-grid flexibility and stability. The system offers ancillary services such as peak-shaving and valley-filling, and can operate both as part of a larger grid or independently, thereby improving local load reliability and mitigating impacts on the broader power infrastructure.

Vehicle Design:

- **Vehicle-to-Grid (V2G) Technology:** V2G technology allows EVs to not only draw power from the grid but also send excess energy back to the grid. This bi-directional flow of energy enables EVs to serve as mobile energy storage devices, helping to balance the grid and provide power during peak demand periods. Currently in its exploratory phase, it enables bidirectional energy flow between EVs and the electrical grid, serving multiple stakeholders. It facilitates grid peak-shaving and load adjustment through real-time data exchange, thereby enhancing grid stability and promoting renewable energy utilization. This contributes to a balanced electricity supply and demand, aiding in greenhouse gas reduction[49].
- **Intelligent Chassis**: These intelligent chassis, incorporating adaptive suspension and regenerative braking, can significantly enhance vehicle performance and efficiency. These systems allow for real-time adjustments to driving conditions, optimizing energy usage, and extending battery life. Rapid advancements in sensor technology and machine learning algorithms are key to realizing the full potential of intelligent chassis in EVs.
- Integrated design of chassis, electric brake, and electric drive system to realize platform-based and integrated design of products and improve overall performance.
- Improve vehicle modularization and systematic design technology, and further enhance the safety and reliability of the vehicle power system platform.

Battery Recycling:

- A circular economy approach to EVs involves designing vehicles and their components with the aim of maximizing their lifespan, recyclability, and reusability. To create a circular or 'closed loop' supply chain by retrieving, recycling, and recirculating raw materials such as cobalt, copper, and nickel from end-of-life batteries.

Vehicle-to-home (V2H) Technology:

- Vehicle-to-Home (V2H) technology enables EVs to function as energy storage units, supplying power to homes during peak demand or outages. The technology offers dual benefits: it serves as an emergency power source and can reduce electricity costs by allowing off-peak charging and peak-hour energy supply. Despite its nascent stage, V2H is gaining traction globally, particularly in countries with high EV adoption such as Japan and Norway, as automakers and energy firms explore its potential.[47]

2.2.3.2. Fuel Cell Vehicle (FCV)

Fuel cell vehicles (FCVs) offer a path to decarbonization but face challenges such as limited infrastructure and high costs. FCVs use fuel cells to convert hydrogen energy into electrical energy to power the vehicle. It is an important technical direction that supports the realization of carbon neutrality. In order to promote the development of FCVs, more than 40 countries around the world have released hydrogen energy or fuel cell vehicle development strategies and roadmaps in recent years, as a result, the number of fuel cell vehicles in Europe is expected to reach 4.245 million by 2030, and in China it will reach about 1 million.[48]

By the end of 2022, there were 66,732 FCVs globally, with a 36.6% YoY increase. South Korea led in sales, accounting for 51% of the market, while China, focusing primarily on commercial FCVs, became the second-largest market with a 25% share (Figure 12, Figure 13). Japan and South Korea view hydrogen as pivotal for decarbonization and have introduced national hydrogen strategies. These plans encompass the entire hydrogen value chain and set quantitative targets, particularly emphasizing transportation. In China, the focus is on commercial FCVs, which make up nearly 98% of the market, contrasting with other countries that concentrate on passenger FCVs. According to the Hydrogen Council, the global fleet of hydrogen-powered fuel cell electric vehicles could exceed 4.5 million by 2030, driven by market expansion and cost reductions.[49]

FIGURE 12: Cumulative Global FCV Sales and Year-on-year Growth Rate. Figure created by authors for paper. [50]

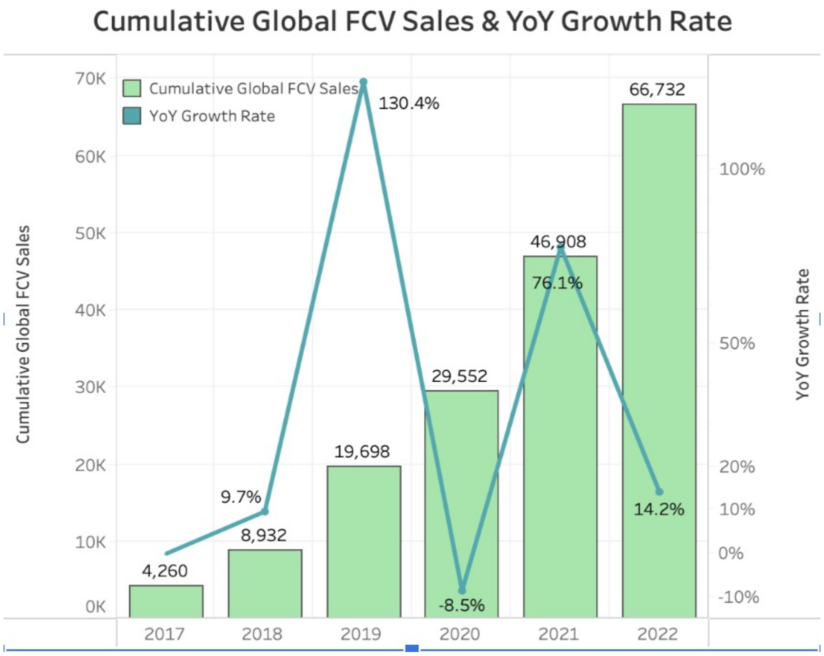
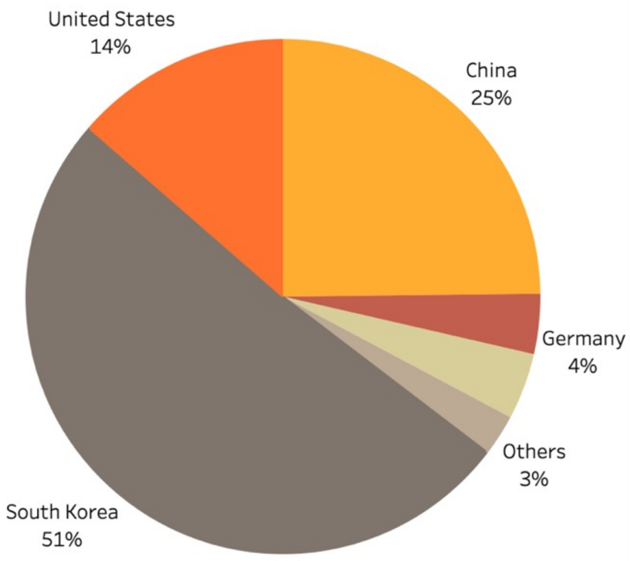


FIGURE 13: Global FCV 2022 Sales by Country. Figure created by authors for paper.[51]



To foster FCV adoption, infrastructure for hydrogen production, storage, and distribution needs expansion. Government initiatives like those in Japan and South Korea can serve as models for a coordinated approach to overcome these challenges.

Hydrogen Refuelling Stations (HRS)
As of June 2023, approximately 950 hydrogen refueling stations (HRS) are operational globally, and it is expected that there will be more than 10,000 hydrogen refueling stations worldwide by 2050. Led by China, Japan, and South Korea, with significant expansion in Europe and the US, the global HRS market is projected to grow at a CAGR of 28.4% from 2019 to 2025, driven by rising demand for zero-emission vehicles and supportive government initiatives.[52]

Categorized by hydrogen supply methods, hydrogen refueling stations can be classified into off-site hydrogen refueling stations and on-site hydrogen refueling stations. Off-site HRSs do not have the same equipment as on-site HRS: Hydrogen is transported from hydrogen production facilities using long tube trailers, liquid hydrogen tankers, or hydrogen pipelines. The hydrogen is then compressed and delivered to high-pressure hydrogen storage tanks at the refueling station. From there, it is dispensed using hydrogen dispensers into the fuel cell vehicles.

On the other hand, on-site HRS has an internal hydrogen generation system. The methods of on-site hydrogen generation include water electrolysis, natural gas reforming, and renewable energy-based hydrogen production. Hydrogen produced on-site needs to undergo purification and drying processes before being compressed, stored, and dispensed.

The current mainstream HRS globally are predominantly off-site. This preference is largely due to the logistical and economic advantages of centralized hydrogen production, which allows for economies of scale and more efficient distribution. Off-site HRS also circumvents the need for on-site purification and drying processes, thereby simplifying station infrastructure and reducing operational complexities.

What Would Be Required to Succeed?
FCV development is currently at a stage akin to early EV development, with major markets establishing hydrogen fueling networks and incentivizing adoption. However, the sector faces several ongoing technical challenges:

- **Hydrogen Production and Cost:** Green hydrogen is more sustainable but costlier than natural gas-derived hydrogen. Achieving cost parity is essential for FCV viability. Policy incentives could play a role in reducing production costs.

- **Storage and Transport:** Hydrogen's low energy density complicates storage and transport, requiring more efficient solutions such as high-pressure tanks.
- **Fuel Cells:** Fuel cells currently operate at 50-60% efficiency, with a target of exceeding 70% for broader FCV adoption.
- **Vehicle and Component Costs:** The high cost of FCVs is largely due to expensive fuel cell stacks and storage systems. The need for advances in core materials such as carbon paper and catalysts could reduce these costs, making FCVs more competitive, is critical.
- **Policy and Market Support:** Zero-emission mandates, carbon pricing, and hydrogen production incentives are crucial for FCV adoption and could also influence hydrogen production methods and costs.
- **Infrastructure Scarcity:** The current number of HRS in the world is not enough to support the large-scale development of FCV. The rapid growth in the number of HRS can solve the convenience of FCV hydrogen refueling. The large-scale construction of infrastructure can also reduce both the cost of HRS and the end-use cost of FCV.

Here are some suggestions that could possibly solve them:

Hydrogen Energy Production: Encourage the research and application of renewable energy hydrogen production technology, develop high-efficiency water electrolysis hydrogen production technology, reduce the cost and energy consumption of water electrolysis, and improve comprehensive benefits. Continue to develop cutting-edge technologies such as photocatalytic hydrogen production and biological hydrogen production.

Hydrogen Energy Storage and Transportation: Encourage 30-50 MPa high-pressure hydrogen transportation technology research and product development, realize the commercial application of liquid hydrogen technology in the energy field, promote the commercial demonstration of regional hydrogen transmission pipeline networks, and encourage efficient storage and transportation new technologies research and application.

Infrastructure: Increase investment in hydrogen refueling stations, increase filling pressure, such as 70 MPa hydrogen refueling stations, and increase investment and use of liquid hydrogen refueling stations.

70 MPa HRS offer higher charging pressure, which allows for a higher flow rate of hydrogen when refueling. They can also deliver a larger amount of hydrogen in a given time, allowing for longer driving ranges for hydrogen FCVs. This could help address the limited driving range when compared to traditional ICE vehicles.

Fuel Cells: Improve and innovate electrode materials and cell stack structures, optimize durability control strategies, increase cell stack volume power density, develop low-cost material components, and reduce costs.

Vehicle On-board Hydrogen Storage System: Improve the mass hydrogen storage density and volume hydrogen storage density of the vehicle-mounted hydrogen storage system, reduce the cost of the hydrogen storage system, increase the use of 70 MPa IV tank, and master the composite material technology in the liquid hydrogen temperature zone.

Type IV hydrogen tanks, also known as composite hydrogen tanks, as the latest generation of FCV vehicle-mounted hydrogen storage tanks, have the advantages of light weight, enhanced safety, corrosion resistance, and they can store hydrogen at high pressures, typically up to 700 bar, allowing for a high storage capacity. This makes them suitable for applications that require longer driving ranges, such as fuel cell vehicles.

Vehicle: Increase system power, improve vehicle performance, lifespan and fuel economy, and reduce vehicle cost.

2.2.3.3. Hybrid

Hybrid vehicles serve as a transitional technology in the automotive landscape, particularly in regions where full electrification or hydrogen fuel cell adoption is still in nascent stages. These vehicles combine internal combustion engines with electric motors to offer a more fuel-efficient and eco-friendly alternative. Market leaders in this segment include Toyota, with its iconic Prius and top-selling 2022 RAV4 Hybrid models. Other key players such as Honda, Hyundai, and

Ford are also making strides, along with emerging local brands such as BYD in Europe and China.

Incorporating hybrid technology offers several advantages, including lower carbon emissions compared to traditional fossil-fueled vehicles. However, it's important to note that while hybrids emit less carbon than their fully fossil-fueled counterparts, they are not entirely carbon-neutral. They offer better fuel efficiency and quicker refueling times compared to fully electric vehicles, but come with their own set of challenges. These include high initial costs, limited battery capacity, and a continued reliance on fossil fuels, making them less ideal for achieving complete decarbonization.

What Would Be Required to Succeed?

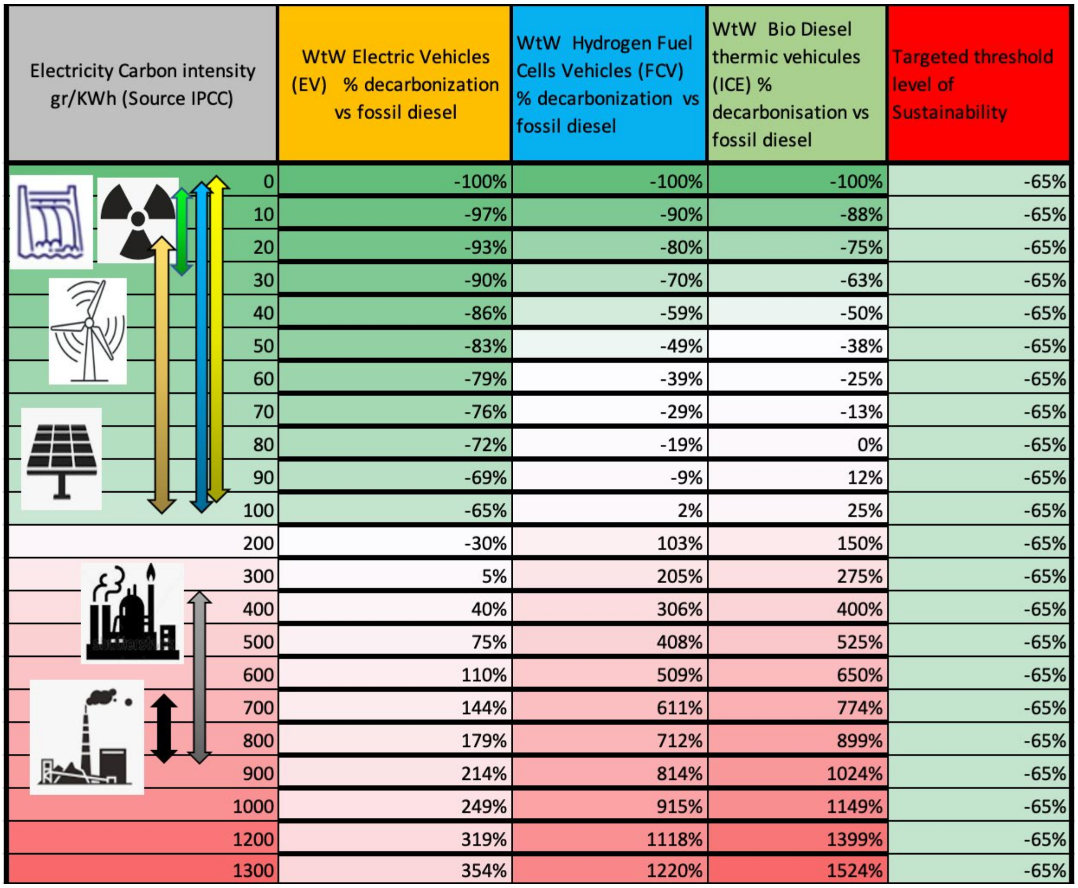
- Develop lean combustion technology and active fuel technology with multiple combustion modes to expand the best combustion area, improve engine thermal efficiency, and optimize engine operating area.
- Develop high-efficiency, high-specific-power motors, develop hybrid powertrains with better fuel-saving effects, applicable to all working conditions, and better platform versatility.
- Improve the efficiency and reliability of the electromechanical coupling system, reduce the cost of the electromechanical coupling system, and improve the efficiency of the hybrid powertrain.
- As hybrid vehicles increase in number, a sustainable system for recycling or repurposing spent batteries is necessary. Each hybrid vehicle battery pack can contain up to 40kg of lithium, a valuable resource that can be reused or repurposed.
- Incentives from policymakers, such as tax credits or subsidies, could play a significant role in encouraging the adoption of hybrid vehicles.
- Utilizing e-fuels in internal combustion engines can effectively lower the carbon footprint, as these fuels can be produced using renewable energy sources. Similar to the recycling potential of lithium in hybrid vehicle batteries, e-fuels present an opportunity for circular economy approaches, capturing CO_2 emissions for fuel synthesis and thereby closing the carbon loop.

2.2.4. Summary of the CO_2-eq Saving

The CO_2-equivalent emissions of an EV depend largely on the source of the electricity used to charge the battery. In terms of tailpipe emissions, EVs emit no CO_2 or other GHGs. The CO_2-eq emissions of hybrid vehicles depend on the balance of electric and petrol/diesel use. In general, hybrid vehicles have lower CO_2-eq emissions than conventional internal combustion engine vehicles but higher emissions than EVs. The only emission from the FCV is water vapor, therefore the CO_2-eq emissions are essentially zero at the tailpipe. However, the CO_2-eq emissions associated with producing and distributing the hydrogen can be substantial, particularly if fossil energies are used.

Table 8 shows the percentage of decarbonization according to the carbon intensity of the electricity, according to the IPCC (Intergovernmental Panel on Climate Change) data.

TABLE 8: Electricity carbon intensity and % of decarbonization from different road transport technologies. Table created by the authors for the paper.



Electricity Carbon intensity gr/KWh (Source IPCC)	WtW Electric Vehicles (EV) % decarbonization vs fossil diesel	WtW Hydrogen Fuel Cells Vehicles (FCV) % decarbonization vs fossil diesel	WtW Bio Diesel thermic vehicules (ICE) % decarbonisation vs fossil diesel	Targeted threshold level of Sustainability
0	-100%	-100%	-100%	-65%
10	-97%	-90%	-88%	-65%
20	-93%	-80%	-75%	-65%
30	-90%	-70%	-63%	-65%
40	-86%	-59%	-50%	-65%
50	-83%	-49%	-38%	-65%
60	-79%	-39%	-25%	-65%
70	-76%	-29%	-13%	-65%
80	-72%	-19%	0%	-65%
90	-69%	-9%	12%	-65%
100	-65%	2%	25%	-65%
200	-30%	103%	150%	-65%
300	5%	205%	275%	-65%
400	40%	306%	400%	-65%
500	75%	408%	525%	-65%
600	110%	509%	650%	-65%
700	144%	611%	774%	-65%
800	179%	712%	899%	-65%
900	214%	814%	1024%	-65%
1000	249%	915%	1149%	-65%
1200	319%	1118%	1399%	-65%
1300	354%	1220%	1524%	-65%

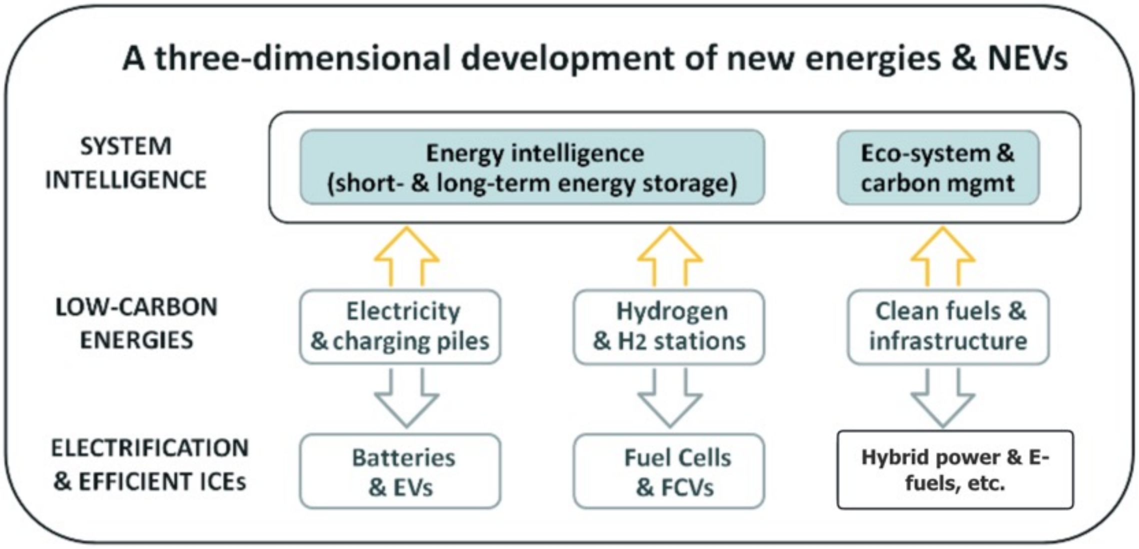
2.2.5. Conclusion

Based on their own resource endowments, industrial development foundations, upstream and downstream industrial chain supporting conditions, and future development plans, different countries around the world should choose different technical paths selectively to promote energy transformation in the road transportation sector. The technical paths can refer to the EV, FCV, and Hybrid, technical routes. Due to the existence of a certain degree of carbon emissions, hybrids are currently only a transitional technology for transition to zero-emission final technology. EVs and FCVs are currently the main technology route choices for road transportation energy transformation, but in the future, the use of zero-emission energy sources such as renewable energy power generation for EVs and FCVs will be the main development trend.

Automotive electrification holds immense potential to revolutionize the transportation sector and drive the global energy transition. Early investments and groundbreaking technologies made by various countries, as mentioned above, are setting the stage for a transformative shift towards a sustainable future.

The scale-up potential of hydrogen and low-carbon electricity is becoming increasingly apparent. By focusing on technology pathways, implementing targeted policies, and establishing favorable regulatory frameworks, the three-dimensional development of renewable energies, NEVs, and low-carbon vehicles is not only paving the way for sustainable mobility but also fostering global economic growth through enhanced international cooperation and knowledge sharing (Figure 15).

FIGURE 14: Three-dimensional development of new energies & NEVs. Figure created by the authors for the paper.



2.3. Train Sector

Rail has the potential to play a major role in the future of transportation and its decarbonization considering the advantages that it offers in terms of speed, time saving, comfort, and load volumes (for both, passengers and freight), all of which combined allow this transportation mode to be very efficient and sustainable. Today rail networks carry approximately 8% of global motorized passenger movements and 7% of freight transport.[53] Light rail and metro offer a fast and reliable alternative to road travel, high-speed rails are a substitute for short intracontinental flights, and freight rail can grant high-capacity goods movements across long distances facilitating relatively easy access to supply chains. Granting affordable access to these rail alternatives also contributes to the acceleration of economic development as it facilitates the transportation of people and goods in less time.

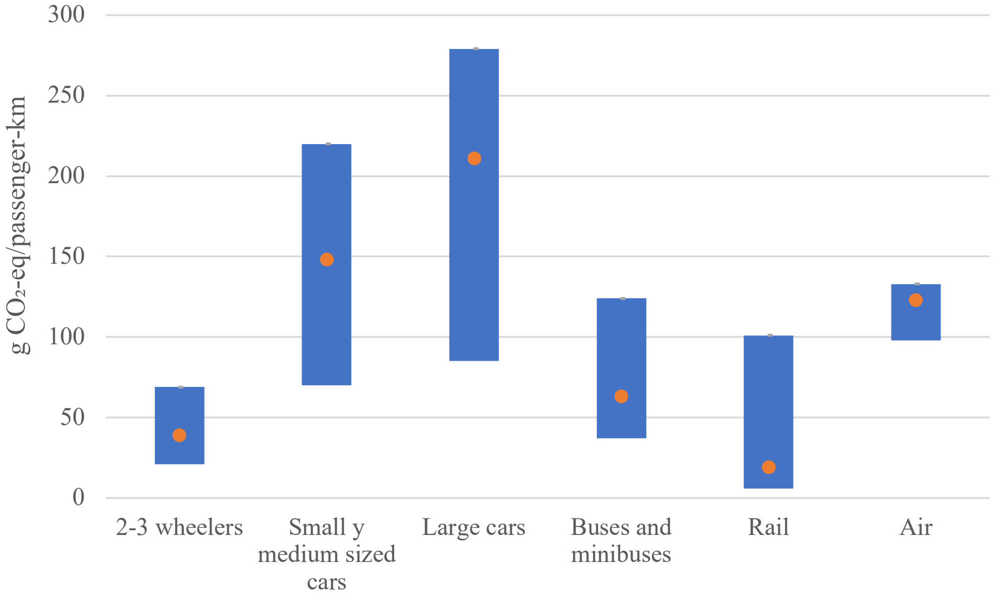
In a context where climate change is a daily concern, rail offers the ability to transport large volumes of people or freight at a faster speed than cars or trucks, even faster than other mass transportation modes, with less energy consumption, and consequently, lower carbon emissions per passenger or per ton. When substituting road travels, rail contributes to traffic congestion reduction as well as local pollutant and greenhouse gas (GHG) emissions decrease. In fact, rail is among the most energy-efficient and lowest-emitting transport modes. In contrast with the volumes that carry, it only consumes 2% of total transport energy demand. Rail is also the transport sector that is most electrified; three-quarters of passenger traffic and half of freight rely on electricity and the remaining relies mostly on diesel. However, beyond its general benefits around energy consumption, rail deployments need to attend to other considerations, and weight costs versus potential benefits when compared against more flexible ways of transport in terms of frequency, routes, and pricing, mostly in rural and suburban areas.

IEA analysis reveals that rail services consume less than 0.6 million barrels per day (mb/d) of oil (about 0.6% of global oil use) and around 290 terawatt-hours (TWh) of electricity (more than 1% of global electricity use).[54] They are responsible for about 0.3% of direct CO_2 emissions from fossil fuel combustion and the same share (0.3%) of energy-related emissions of fine particulate matter ($PM_{2.5}$). These high efficiency rail operation means that rail saves more oil than it consumes and more emissions than it generates, so, if all services currently performed by railways were carried by road vehicles, such as cars and trucks, then the world's transport-related oil consumption would be 8 mb/d (a 15% increase) and transport-related GHG emissions would increase by 1.2 gigatonnes (Gt) CO_2-equivalent (CO_2-eq) on a well-to-wheel basis.

Comparatively, rail emissions per passenger-kilometer are currently on average around one-sixth those of air travel, one-tenth those of cars, and one-third those of buses and minibusses on a “well-to-wheels” (wing/wake) basis as shown in Figure 15. The emissions from electrified rail are even lower, especially when electricity is generated from renewable or nuclear resources.[55]

Besides its intrinsic strengths, rail faces various challenges; cost, availability, congestion, and security. Rail infrastructure is a capital-intensive business depending on diverse factors including costs of land, labor and materials, tracks per line, track electrification, topography and intended operation speed. Therefore, high throughputs are required to minimize unit costs.[56] In this regard, infrastructure and economic feasibilities impact rail services availability globally, mostly in remote areas and developing economies. Rail networks also face congestion struggles according to time of the day with overcrowding arising when the demand approaches (or surpass) its capacity with direct impact on travel quality.[57] In terms of security, it is necessary to avoid interruptions in order to assure the constant flow of people and freight and avoid that the transportation system itself becomes a mean of attacks.

FIGURE 15: Well-to-wheel (wake/wing) GHG intensity of motorized passenger transport modes. Source: IEA, 2022.



From a consumer perspective, preferences are primarily linked to ticket and freight prices (and its ease of purchase), reliability, punctuality, rail density and convenience of service from an end-to-end travel experience, including accessibility, distances, departure and arrival times and simplicity of boarding process. There are passengers willing to switch from plane and car to rail as a more sustainable mode of transport, which increase decarbonization considerations among consumers but are not reflected yet as a critical preference that impacts the decision to buy rail tickets.[58]

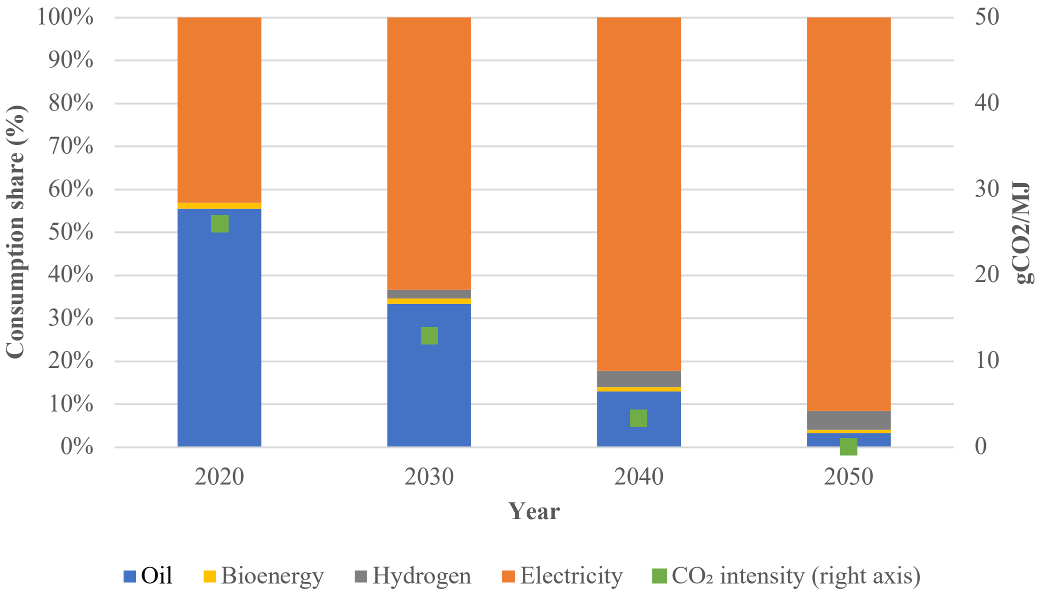
2.3.1. The Decarbonized Energy Demand in Train Transport Sector Towards 2050

In a net zero emissions (NZE) scenario by 2050, policies promote modal shifts and more efficient operations across transport modes and market reforms to ensure adequate economic signals to unlock new business models, mobilize private expending and boost behavioral changes to accelerate the use of certain fuels or technologies that contribute to the reduction of CO_2 and other GHG emissions into the sector. IEA estimates that around 55% of cumulative emissions reductions in the pathway to NZE to 2050 are linked to consumer choices related to the adoption of technological and more efficient developments, as well as changing lifestyle patterns.[59]

IEA’s report “Net Zero Emissions by 2050” points that the global transport sector emitted over 7 Gt CO_2 in 2020, and nearly 8.5 Gt in 2019 before the Covid-19 pandemic. In the NZE scenario, transport sector CO_2 emissions are slightly over 5.5 Gt in 2030, and by 2050 they are around 0.7 Gt, a 90% drop when compared to 2020 levels. By 2040, almost half of the total energy consumption accounts for electricity, followed by hydrogen-based fuels and bioenergy in approximately one-third and one-sixth respectively. Rail projections show that passenger modalities nearly double its share of the total transport activity with special growth in urban and high-speed rail, contributing to the fall of emissions from 95 Mt CO_2 in 2020 to virtually zero by 2050.[60]

It is important to consider that under the NZE scenario all new tracks on high-throughput corridors are electrified, while hydrogen and battery electric trains are adopted on rail lines where throughput is too low to an economically viable overhead lines construction. Together, electricity and hydrogen powered trains, represents nearly 96% of total energy consumption of the subsector. In consequence, oil use drops from 55% of total energy consumption of the rail in 2020 to 3% in 2050. Figure 16 resumes this information.

FIGURE 16: Global energy consumption by fuel and CO_2 intensity in the rail sector in the NZE by 2050. Source: IEA, 2021.



2.3.2. Future perspectives in rail transport

To achieve the NZE scenario by 2050, heavy investment in passenger and freight rail transport electrification, and new infrastructure deployment and automation became crucial to meet demand growth due population and urbanization increasing trends, as well as the continuous focus on sustainability concerns.

2.3.3. Electrification

As stated before, today almost 75% of passenger rail transport and approximately 50% of rail freight transport are powered by electricity. Europe, Japan, Korea, and Russia are the regions with the highest share of electric train activity.[61] Electrified rail routes have higher utilization rates than non-electric ones. The former routes fivefold the passenger-kilometers per kilometer track carry, and twice as many tonne-kilometers when compared to the latter, so payback periods for the electrification investment costs are shorter.[62] However, the pace of electrification varies considerably by region or country, and several are making electrification central to their net-zero objectives. Asia and Europe are two examples of regions that have significantly increased their share of electrified tracks in the past decade.[63]

Electric trains supply electricity from the grid to their motors to produce traction, so these trains do not have to spend energy to move their power plant and unused stored fuel like diesel ones. Electricity powered trains also exploit the benefits of regenerative braking; this means that the train has the capability to generate electricity while braking and feeds electric power back to the grid. Around 20% of train electricity consumption can be recovered with this method;[64] such innovation increases energy efficiency and economic feasibility.

Moreover, the electric engine's power is only limited by the electricity it can receive from the overhead line or third rail, while diesel heavy engines are limited by its size and ability to cool down. Data shows that electric trains are twice as powerful as diesel locomotives (Table 9).

TABLE 9: Electric and diesel trains comparisons. Source: RailDecarb21 (2021).

	ELECTRIC		**DIESEL**		
	Traction Type	**Power at Rail**	**Traction Type**	**Power at Rail**	**Electric to Diesel Ratio**
Freight loco	Class 92	5,040 kW	Class 66	2,214kW	**228%**
Passenger loco	Class 87	3,700 kW	Class 50	1,560 kW	**237%**
Multiple unit	Class 385	500 kW	Class 170	260 kW	**193%**
High Speed Train – per coach	Class 390	567 kW	IC 125 Class 220	311 kW 480kW	**182%** **118%**
Bi-mode – per coach	Class 801	502 kW	Class 220 GE 720kW engine	335 kW	**150%**

Besides environmental convenience, financial and economic benefits from electrification include lifetime operational and maintenance savings around 3 MUSD (million United States of America dollars) per vehicle, and increased revenue and better utilization. In addition, innovations have reduced electrification costs. Technical advantages involve greater freight speeds and tonnage, as well as increased capacity and timetable resilience.[65] Below are summarized other economic and technical advantages gathered in RailDecarb21 report:

- Greater passenger capacity on routes with frequent stops and increased ability to recover from delays.
- Lower rolling stock capital cost.
- Lower rolling stock operational costs, due to fuel costs.
- Lower rolling stock maintenance costs due to the much smaller number of moving parts and the requirement to overhaul diesel engines regularly to 'as new' condition.
- Greater train reliability.
- Smaller fleet requirements due to increased reliability, since fewer trains are out of service for maintenance.
- Reduced health and environmental impact from diesel engine idling, particularly at stations, and noise.
- Lower track maintenance costs, driven by lower track forces from lighter power units.

At this point, it is important to stress that it is very unlikely that, by 2050, battery electric trains or hydrogen powered trains can substitute direct electric rail powered environments. First, because hydrogen powered rails are inherently less efficient than electric ones, and second, besides the potential and fast improvements in the battery industry, volume and weight requirements for this technology would increase train dimensions.[66]

2.3.3.1. What would be required to succeed?

Inevitably, when considering electrification to improve transport efficiency and comply with environmental objectives, the generation mix composition arises. Industrialization and population growth estimated for the next decades will increase energy demand, so governments and policy makers have to reassure energy and climate commitments within investors, reduce barriers to renewable project developments and prioritize renewables stimulus packages that generate economic and social value chains.[67] These actions are linked to the fulfillment of NZE targets. Accordingly, fossil fuel subsidies must be eliminated and encouraged – through adequate economic signals – the adoption of low carbon technologies.[68]

There are technical challenges to face that rely on the region's development and its characteristics. To be reliable, electric trains need a consistent and stable power supply and not all regions can offer these attributes. Full electrification of the transport sector could carry side effects too. For example, it may bring increasing pressure on electricity grids, so additional investments will be required to minimize the risk of power disruptions.[69]

Rail infrastructure is expensive. The deployment of overhead lines or third rails is associated with high upfront costs. For a rail development project to pay off, high passenger or freight throughput is strictly necessary. IEA's high rail scenario by 2050 shows that annual average savings on road infrastructure total 270 billion USD and savings on vehicles (including cars, trucks, and aircraft) are around 670 billion USD. To achieve these savings, the high rail scenario requires additional annual average investment of 290 billion USD (around 750 billion USD in total), most of which is for urban and high-speed rail infrastructure.[70] Another costly process that stakeholders could find is the upgrading of the existing rolling stock, especially with assets that may not be easily retrofitted. In this context, strong policies regarding subsidies and easy access to credit with competitive conditions are required.

Modal shift, especially from short-haul air travel to high-speed rail, is determined by the routes that lower construction costs. Average annual investment in rail infrastructure is 640 billion USD between 2018 and 2050. In addition, travel time between cities is also an important factor to consider. To be a competitive alternative rail journey must be time saving compared to available flight options. Finally, the demand has to be large enough to achieve the economic viability of the investments required for rail connection. According to IEA, in 2015, 14% of global flights could be competitively shifted to high-speed rail under current typical flight and high-speed rail conditions, without the need for costly bridge or tunneling infrastructure.[71]

Grant high passenger throughput also depends on consumer behaviors and preferences, so the understanding of these trends by rail operators become necessary to achieve the modal switch. For travelers, price, safety, and core product offering (including convenience, reliability, and speed) are the key drivers for choosing a mode of transport. Operators must consider these factors to attract new passengers and enhance the travel experience upon their existing rail networks.[72]

New offerings and differentiated pricing could increase modal share. Positive models in the airline industry, like low-cost approach, can be adapted to the rail sector. Dynamic pricing, new fare types, temporary discounts, or multi-pass offers tailored to consumer behavior are among other operational approaches. On the other hand, passenger experience can be enhanced by the expansion of onboard services such as increased digital connectivity, luggage concierge, pet transportation, and food-ordering services.[73]

The adoption of digital technologies could optimize rail operations and integrate rail more comprehensively with other mobility services. Mobility-as-a-service (MaaS) allows to integrate passenger information to facilitate a smooth end-to-end experience. When MaaS is combined with advanced analytics, it could provide insights on where, when, and how each means of transportation are used to help operators offer better service and connections.[74]

In the long-term, increasing capacity investment in high-density, high-speed, and high-frequency networks is required. A McKinsey's report points out that density, speed, and frequency are three factors that position train travel as an efficient and convenient passenger service. On a global level, developing this level of service may be the way to grow rail modal share, and indicates significant investment in new infrastructure, digitally enabled train operations, and rolling stock.[75]

2.3.3.2. Battery electric trains

Battery electric trains are an alternative to electrify the rail fleet in areas where deployment of conventional overhead lines is not feasible due to capital costs. Energy for this technology is derived from rechargeable batteries driving the traction motors. These trains offer most of the benefits of overhead line equipment (OLE) trains, including the capability to capture braking energy (which could be stored using the batteries) and the reduction in GHG emissions.

Battery traction rail has 81% of the energy efficiency of electric trains and can provide comparable acceleration with them.[76] However, they face challenges regarding its autonomy, the need of charging stations, battery weight/volume relationship, and its costs.

German Lower Saxony's state-owned transport company LNVG announced in late July 2023 that it will replace its diesel-powered units with battery cell ones, after they tested 14 hydrogen-cell trains in its passenger operations for over a year. It hopes that from 2029 the network can introduce 102 new battery electric and 27 OLE trains on one particular route that will be completely electrified, allowing the diesel-fueled trains to leave the tracks by 2037. LNVG stated that the electric trains are cheaper than the hydrogen and fossil alternatives.

Another German state, Baden-Württemberg, published in December 2022 a comparison study between hydrogen and battery electric trains as an alternative to change the diesel traction units in its rail networks, and concluded that it will no longer consider hydrogen traction alternatives as they are more expensive over a 30-year period. Transport Technology Consult Karlsruhe (TTK) and Komobile, study responsible, examined 16 non-electrified routes from Baden-Württemberg considering infrastructure requirements, costs, maintenance, energy requirements and CO_2 emissions. In most cases, battery hybrid trains seemed to be the best alternative. Data showed that hydrogen alternatives could be between 60% and 80% more expensive than battery hybrid or electric multiple unit trains.

In 2021, the North American railroad company BNSF conducted a pilot with a Wabtec battery-electric locomotive, which was in commercial service between Barstow and Stockton in California, US. This was the first battery-electric freight locomotive in North America. The pilot demonstrated an 11% reduction in fuel consumption and greenhouse gas emissions when compared with the standard diesel units that operated along the same route.[77]

2.3.3.2.1. What would be required to succeed?

To store the same amount of energy, batteries require about 21 times the storage volume of a diesel tank, and about 61 times the weight of the latter, therefore battery sizing is a major challenge in industry.[78] Besides battery size, battery powered trains could be less efficient than electric trains due to energy losses related to energy conversion; hence they should be designed to be easily retrofitted to overhead operation once transitional term is completed.

Battery trains have a range of 60 to 80 km before they need recharging, limiting its autonomy. Fast charging technologies are being developed, but usually waiting times are not operationally acceptable between train stops. In this context, battery traction rail is suitable for short end-to-end journey distances.[79]

2.3.3.3. Super and ultracapacitors alternatives

Electric rail transportation systems use supercapacitors to enhance voltage and the regenerative braking energy recovery. Supercapacitors energy density is lower than a battery, but has higher power density. In consequence, they can bridge some gaps associated with battery use, mostly when high peak power is required for improving general fuel efficiency.

There are several benefits to using supercapacitor and rapid charging technology on light rail systems:

1. **Reduced energy consumption:** supercapacitors store energy during regenerative braking and can deliver power to the train during acceleration, reducing the in-rush and the amount of energy needed from the electrical grid. This reduces overall energy consumption and can result in significant cost savings.

2. **Reduced carbon footprint:** by reducing energy consumption, the use of supercapacitor and rapid charging technology can also reduce the carbon footprint of the light rail system. This makes public transportation a more sustainable option and can help cities meet their climate goals.

3. **Faster charging times:** supercapacitors can be charged in just a few minutes, allowing rapid charging at stations. The trains can reduce downtime and increase service frequencies.

4. **Lower operating costs:** the use of supercapacitors and rapid charging technology can reduce operating costs by reducing energy consumption, increasing service frequency, and extending the life of the train's batteries. Besides, it has the potential to eliminate the power cables along the track.

5. **Improved reliability:** supercapacitors have long cycle lifetimes, can deliver high power output, and are less prone to failure than traditional batteries. This can result in improved reliability and fewer service interruptions, making public transportation a more attractive option for commuters.

An example of the use of supercapacitors and rapid charging on the station to run a light rail system is found in Charlotte, North Carolina, where the S70 light rail system is. This system uses Siemens Sicharge UC charging stations and Sitras Energy Storage systems. Supercapacitor technology allows for fast charging in just a few minutes, which is crucial for maintaining the frequent service required by the light rail system.

The supercapacitors are charged at the stations during brief stops, and this stored energy is then used to power the trains during acceleration, which reduces energy consumption and lowers operating costs. The S70 light rail system in Charlotte has reduced its energy consumption by up to 30% compared to traditional light rail systems.

Siemens has also implemented supercapacitor technology and rapid charging in other light rail systems, such as the S70 light rail system in Sacramento, California, and the S700 light rail system in San Diego, California. These implementations have been successful in improving energy efficiency, reducing operating costs, and providing more sustainable public transportation options.

2.3.4. H_2 fuel cells

Increasing focus on sustainability, and the recent development of new technologies that could make hydrogen fuel more affordable and efficient, have renewed the interest in its use for the rail sector in the past years. However, as stated before, nowadays hydrogen alternatives could not beat electric ones due its costs when compared.

Hydrogen powered trains could help to deploy and develop slow to medium speed regional services, where electrification may be costly and difficult. Moreover, this technology provides quieter operation than diesel trains, improving life quality and minimizing the impact of rail operation on the value of real estate located close to the tracks. Hydrogen fuel cells combine hydrogen stored in its tanks and oxygen from the air to produce electrical power for rail traction. Only water vapor and condensation are produced, so hydrogen powered trains are CO_2 direct emission-free. When hydrogen is produced from renewable sources, its carbon intensity is heavily lowered depending on the source of the electricity. For more details in this aspect refer to Table 10.

Regional passenger trains (also known as regional multiple units), light rails, trolleys, shunters, mining locomotives and other proof-of-concept locomotives have been subject of trials for the application of FCH technology. Back in 2019, Fuel Cells and Hydrogen Joint Undertaking (FCH JU) in cooperation with Shift to Rail Joint Undertaking (S2R JU) conducted a series of studies to assess the state of the art, the business case, the market potential, and technical and non-technical barriers to the use of FCH technology in different rail applications in Europe. The reports show that by 2030, almost 20% of newly purchased train vehicles in Europe could be powered by hydrogen. In the short term, multiple units would be the most mature FCH application to become cost-competitive when compared with diesel-powered trains. This technology could replace 30% of diesel trains within this decade.[80]

In terms of capital expenses and operational costs, reports and market studies point that the relatively high investments for the rail and hydrogen infrastructure can be compensated for by the lower fuel and maintenance charges, especially when hydrogen associated technologies costs continue to fall. Based in different cases, fuel cell and hydrogen (FCH) train technology are suitable over other alternatives when used on longer non-electrified routes (considering the economic feasibility and clean transition to current diesel trains) of over 100 km and can be especially used for last mile delivery routes. Another advantage is that FCH trains enable operation with very short downtimes of less than twenty minutes and are also able to withstand long operating hours of more than eighteen hours without refueling.[81] Additionally, FCH trains offer high technical performance with similar flexibility and versatility as diesel fleets with similar characteristics, as well as reasonable economic performance when low-cost hydrogen production is possible. Meanwhile GHG emissions, noise and local contaminants are dramatically reduced.[82]

Absolute emission savings will depend on the carbon intensity of the electricity mix, but FCH trains provide important reductions in NOx and particulates emissions, as stated before. CO_2 emissions impact FCH trains depends also on the source of the hydrogen used for operation. When produced via electrolysis from water, it can be the cleanest option when the electricity is generated from renewable sources (green hydrogen). If the hydrogen is produced from natural gas via steam methane reforming (gray hydrogen), it can reduce the emissions by up to 40 % compared to diesel.[83]

The aforementioned report highlights that the total cost of ownership (TCO) of FCH trains remains higher than the diesel technology in the base case scenario, despite lower maintenance costs compared to diesel powered train., However, in regional passenger trains it can already be cost competitive with diesel today if energy to produce hydrogen is affordable, allowing on-site electrolysis. In an optimistic case, data shows that if the electricity price and hydrogen consumed per kilometer are lower and the diesel price reaches EUR 1.35 per liter, FCH becomes the least costly alternative.[84]

2.3.4.1. What would be required to succeed?

Deployment of FCH technology requires a systemic approach to the rail environment and the articulation of actions from different fronts, due its high dependency on economic efficiency and the positive signals from the average reduction in energy prices. These fronts include H_2 value chain, multimodal approaches, interoperability, refueling infrastructure, industrial H_2 supply, regulations and permitting processes, service and maintenance requirements, safety concerns and technology specifications, each one briefly explained below and in Figure 17:

- **Renewable H_2 value chain:** it is necessary to deploy hydrogen generation assets at the multi-MW commercial scale necessary to power large FCH train fleets. Hydrogen cost is interlinked with the cost of electricity used to generate it, so the sourcing and pricing of electricity as well as the asset utilization levels of power-to-gas plants should be carefully considered. Inherent long-term planning of the railway environment can match with the necessity of heavy investments in H_2 production assets, which could facilitate mid or long-term offtake agreements between hydrogen producers and rail operators lowering the gas prices.
- **Multimodal approach:** As discussed before in this document, hydrogen is not only an energy vector for rail uses but for other modes of transport. This means that other modes of transport could be powered by the same hydrogen production and refueling stations. The share of infrastructure could decrease operating costs as utilization rates of the assets increase. However careful planning and execution are necessary to comply with suitable complexity and interdependency indexes.
- **Interoperability with other infrastructure:** Rail infrastructure and its individual components must function cohesively, as well as its different stakeholders. With hydrogen introduction as a power source, safety protocols, product standards and regulations will need to be re-evaluated to ensure all unique possible scenarios that come with the introduction of this energy vector are being previously evaluated including changes in train dimensions, possible interactions with electrified catenary, examination of existing standards and requirements for hazardous materials transportation. Another excellent example where interoperability plays a major role is in cross-border transportation, which requires the compatibility of countries' electrical systems to allow the proper deployment of a rail environment.
- **H_2 refueling infrastructure:** Hydrogen Refueling Stations (HRS) must be built to strictly foreseeable capacity requirements for cost optimization. If unnecessary overcapacity is introduced with no short-term expansion plans, underutilization arises and thus increases TCO per train. Modular solutions, thus, offer gradual expansion capabilities of the HRS environment while the fleet grows, increase the performance of the value chain and optimize its costs.
- **Industrial H_2 supply:** Hydrogen is a product or byproduct of chemical processes in certain industries like oil and gas refining, fertilizer, metallurgy, and glass manufacturing, and usually is discarded through flaring. In this regard, optimization opportunities are offered to take full advantage of such excess of hydrogen if used as fuel for transportation, and especially in FCH trains. To maximize the benefits, production and consumption should be at near locations, and additional investments to purify hydrogen for use in fuel cells should be justified by the fuel consumption volumes of FCH trains.

- **Regulation and permitting processes:** Regulation should be relevant and specific to rail applications, including thus regarding safety. Regulations should be ahead, or in tune at least, with technological advances in order to offer a flexible and standardized framework where new and cleaner transport modes can deploy and develop within minimal costs and unnecessary or impractical time-consuming requirements.
- **Service and maintenance requirements:** Experts have pointed out that given the design features of FCH powered trains, they will have lower service and maintenance requirements, consequently lower costs compared to diesel technology in the long run. However, initial investment including the retraining of maintenance staff, could be a constraint. Service and maintenance requirements of FCH related infrastructure like electrolyzers, HRS and modifications to existing train maintenance workshops, should also be considered.
- **Safety concerns of local community:** Local communication and engagement are a must in the design and execution of management strategy of any FCH train development project. Questions and concerns among different communities into the limits of the influence area of any FCH rail project must be evacuated to reduce risks and remove eventual barriers during the project.
- **Technology specifications (fuel cells, hydrogen tanks):** FCH technology has certain technology specifications that need to be carefully considered in the design process. Depending on the type of fuel cell used in a fuel cell system, several extra components might need to be part of the powertrain. Driven by the performance requirements of a specific use case, these components may ultimately demand too large a space, thereby complicating the implementation. Fuel cells can be complemented by batteries for use cases where power requirements are variable. With the correct design of a battery based on a defined use case, the cost of fuel cells can be reduced through such hybridization. It is important to note that hydrogen tanks have certain limitations in terms of connectors and currently must be placed in the same train segment as the fuel cells, which negatively influences the refueling process.

Other barriers to the widespread adoption of FCH technology in rail are shown in Figure 18. These barriers include technological and non-technological concerns, whereby about 80% of them relate to all FCH rail applications (means multiple units, mainline locomotives, shunters and so on).

Addressing short-term R&I projects, three critical priority and other high priority barriers can be attended simultaneously: scalable designs, storage design and financing mechanisms; other important barriers are deployed in Figure 18 and Figure 19.[85] Technological barriers are mostly related to optimization potential of the FCH train itself or the components of its environment to enable this technology to match or outperform diesel and electric trains. On the other hand, most non-technological barriers are linked with lack of experience, knowledge, and specific framework conditions for FCH technology in the rail environment.

A study performed by Roland Berger on behalf of the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU) and the Shift2Rail Joint Undertaking (S2R JU) points three major topics or R&I projects that should be addressed before FCH trains can be introduced to the European rail market: “large-scale demonstration of Multiple Unit train fleets”, “development, engineering and prototype operation of shunters or mainline locomotives”, and “technology development for optimized hydrogen storage system for FCH rail applications”.[86] The first one can provide and articulate the economic resources for an initial deployment of up to 15 trains that will ideally be supplied by a single large-scale HRS to achieve economies of scale (in the context of Europe). This pilot project also could show the potential of the FCH technology at scale, increase operational and commercial experience around FCH trains and be the platform through which FCH train specific financing mechanisms are developed and established.[87]

The second listed topic can solve the lack of FCH technology knowledge, including the lack of Shunter and Mainline Locomotive specific experiences by developing new FCH Shunters/Mainline Locomotives, or retrofitting them, and finally closing the current supply gap and unlock additional market potential in new rail segments. The last one allows us to close the hydrogen storage technology gaps through an integrated technology development project for optimized hydrogen storage systems in FCH rail applications. In addition, projects could generate new engineering concepts for storing more energy in the available space or evaluate the optimized supply pressure of hydrogen in relation to the hydrogen supply chain.[88]

FIGURE 17: Schematic representation of FCH train eco-system including selected focus topics. Source: FCH JU and S2R JU, 2019.

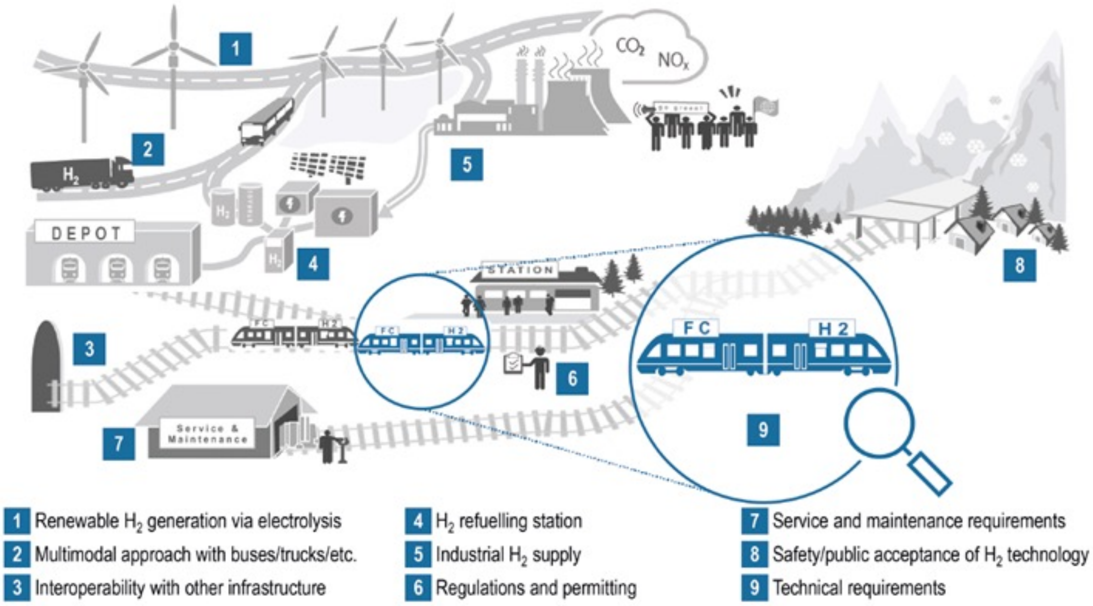
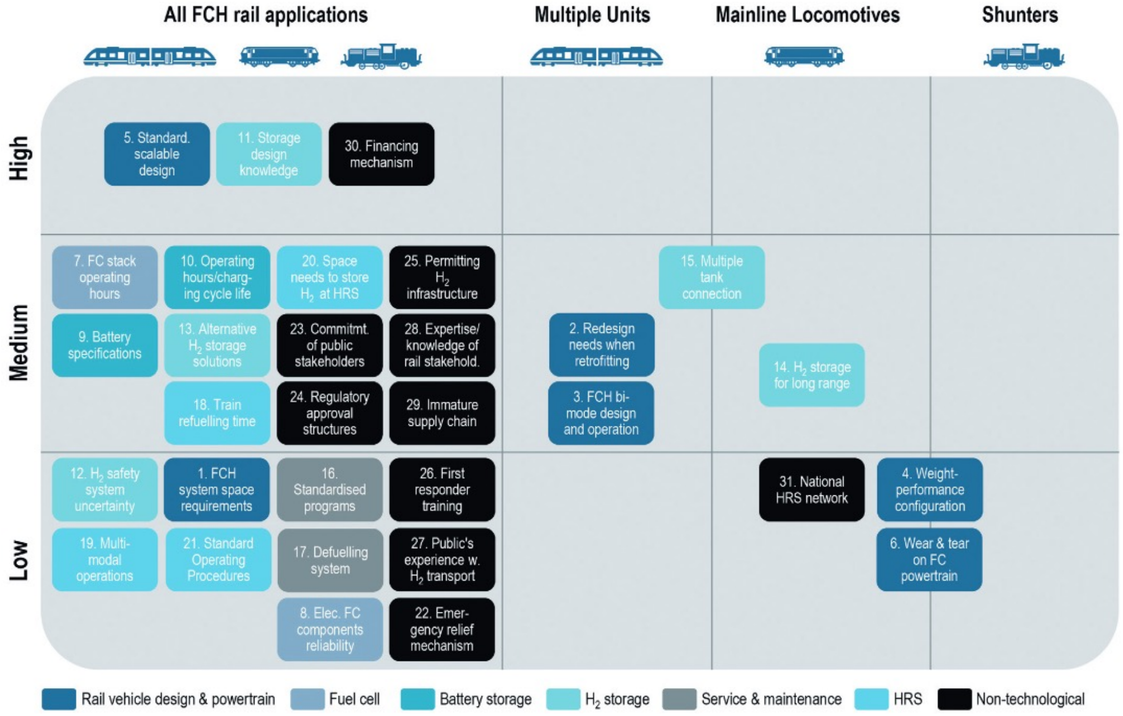


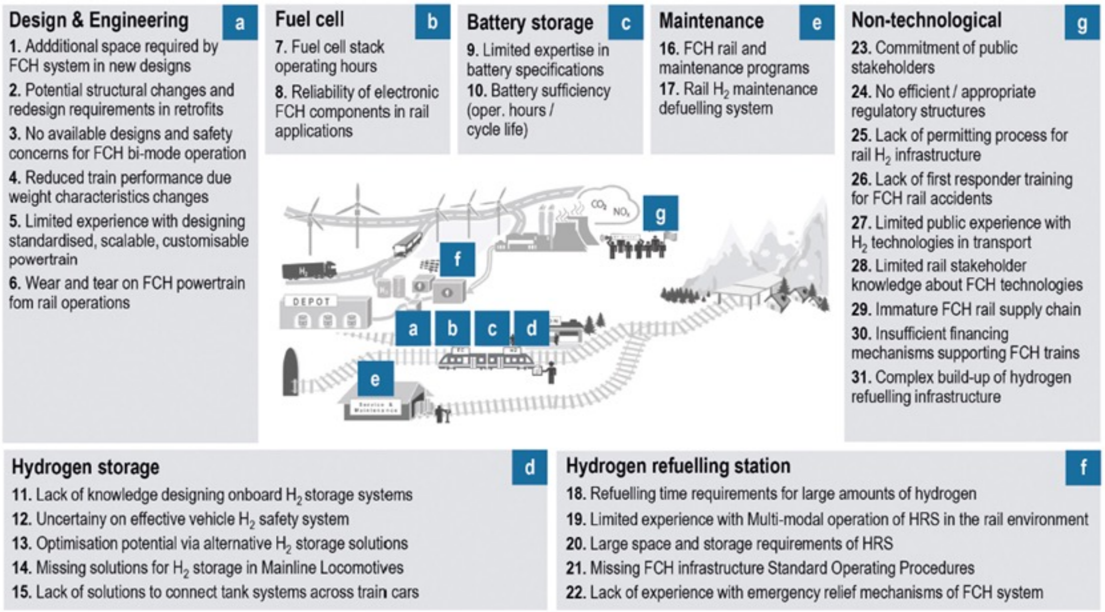
FIGURE 18: Barriers clustered per FCH train application by priority level of attention for short-term R&I. Source: Roland Berger in FCH JU and S2R JU, 2019.



	All FCH rail applications	Multiple Units	Mainline Locomotives	Shunters
High	5. Standard. scalable design 11. Storage design knowledge 30. Financing mechanism			
Medium	7. FC stack operating hours 10. Operating hours/charging cycle life 20. Space needs to store H_2 at HRS 25. Permitting H_2 infrastructure 9. Battery specifications 13. Alternative H_2 storage solutions 23. Commitmt. of public stakeholders 28. Expertise/knowledge of rail stakehold. 18. Train refuelling time 24. Regulatory approval structures 29. Immature supply chain	2. Redesign needs when retrofitting 3. FCH bi-mode design and operation	15. Multiple tank connection 14. H_2 storage for long range	
Low	12. H_2 safety system uncertainty 1. FCH system space requirements 16. Standardised programs 26. First responder training 19. Multi-modal operations 21. Standard Operating Procedures 17. Defuelling system 27. Public's experience w. H_2 transport 8. Elec. FC components reliability 22. Emergency relief mechanism		31. National HRS network	4. Weight-performance configuration 6. Wear & tear on FC powertrain

Rail vehicle design & powertrain · Fuel cell · Battery storage · H_2 storage · Service & maintenance · HRS · Non-technological

FIGURE 19: Overview of short-term R&I project to investigate relevant topics. Source: FCH JU and S2R JU, 2019.



Design & Engineering a

1. Addditional space required by FCH system in new designs

2. Potential structural changes and redesign requirements in retrofits

3. No available designs and safety concerns for FCH bi-mode operation

4. Reduced train performance due weight characteristics changes

5. Limited experience with designing standardised, scalable, customisable powertrain

6. Wear and tear on FCH powertrain fom rail operations

Fuel cell b

7. Fuel cell stack operating hours

8. Reliability of electronic FCH components in rail applications

Battery storage c

9. Limited expertise in battery specifications

10. Battery sufficiency (oper. hours / cycle life)

Maintenance e

16. FCH rail and maintenance programs

17. Rail H_2 maintenance defuelling system

Non-technological g

23. Commitment of public stakeholders

24. No efficient / appropriate regulatory structures

25. Lack of permitting process for rail H_2 infrastructure

26. Lack of first responder training for FCH rail accidents

27. Limited public experience with H_2 technologies in transport

28. Limited rail stakeholder knowledge about FCH technologies

29. Immature FCH rail supply chain

30. Insufficient financing mechanisms supporting FCH trains

31. Complex build-up of hydrogen refuelling infrastructure

Hydrogen storage d

11. Lack of knowledge designing onboard H_2 storage systems

12. Uncertainy on effective vehicle H_2 safety system

13. Optimisation potential via alternative H_2 storage solutions

14. Missing solutions for H_2 storage in Mainline Locomotives

15. Lack of solutions to connect tank systems across train cars

Hydrogen refuelling station f

18. Refuelling time requirements for large amounts of hydrogen

19. Limited experience with Multi-modal operation of HRS in the rail environment

20. Large space and storage requirements of HRS

21. Missing FCH infrastructure Standard Operating Procedures

22. Lack of experience with emergency relief mechanisms of FCH system

2.3.5. Biofuels

Alternative fuels, such as biogas, biomethane, bioethanol, biomass, and liquid biofuels, could be used instead of diesel for rail traction, offering a short to medium-term alternative as a transition technology from fossil fuels where railway operations still rely on them. Biofuel is a renewable alternative to petroleum diesel which has higher carbon intensity levels (due to the source of the fuel, having captured CO_2 in the life cycle of the biofuel) and particulate emissions, so the use of biofuels reduces the detriment to air quality after its burning process. The use of renewable fuel provides energy security as well as safety benefits.

The most promising option for biofuels in the rail transportation sector is biodiesel. The global consumption of liquid fuel by the railways, which is mostly diesel, is likely to be up to 30 million tons (1.380 PJ). The EU only accounts for 15 % of the industrialized countries' use of diesel on the railways, whereas the consumption is dominated by the US (70 %). In the US the consumption of liquid fuels by railways was growing (from 1990 to 2002), whereas in the EU and Canada liquid fuel consumption was decreasing (UIC 2007).

Some of the pros of biofuels use in railways operation include environmental benefits regarding air quality and particulate emissions, lower toxicity when compared to fossil sources and higher physical properties. On the other hand, increased fuel consumption derived from lower energy content and adverse physical properties of biofuels are also displayed.

Several trials and use experiences with biodiesel in rail transport have been carried globally, mostly promoted in conjunction with European operators. Other projects were executed in France, Germany, Czech, Hungary, India, and the United States of America.

According to the IEA, biodiesel, and renewable diesel significantly increased in 2021 compared to 2019. This increase is the result of renewable diesel demand in the US and Asia. Asia's biofuel production levels are more than the total European biofuel production levels. However, besides the better economic viability of biodiesel compared to diesel, there are issues in terms of supply. For example, while biodiesel is considered readily available throughout the US, access to renewable diesel is more widespread in the west coast.[89]

2.3.5.1. What would be required to succeed?

Biofuel use faces challenges such as long-term data about the impact of emissions, reliability, and fuel consumption. Alongside the availability of fuels blends, there is a significant lack of technical standards within the industry.

To promote a wider and accelerated use of biofuels in the rail industry, tax incentives and mandates could be necessary. Also, it will be important to consider the economic signal of these policies and the cost of producing biofuels, especially the extra costs that will be transferred to consumers or taxpayers.[90]

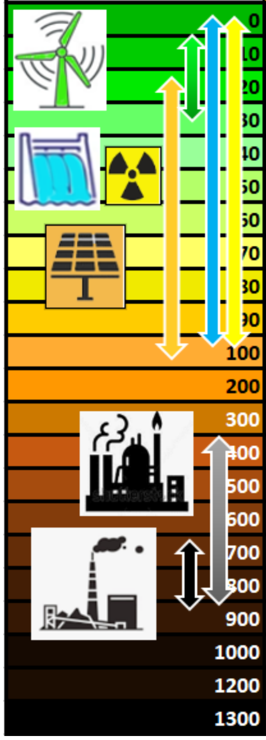
The use of biodiesel as small blends may not require any modification to existing locomotives. However, warranties of locomotives for biodiesel blends require consultation, besides the articulation with manufacturers to introduce new optimal characteristics for future trains using these blends. Longer life of rail locomotives may be a barrier to a rapid biodiesel blend adoption.[91]

2.3.6. Summary of the CO_2-eq saving

The extent of decarbonization in the rail industry is dependent on energy consumption, and the percentage of decarbonization achieved in the resultant fuel is influenced by the carbon intensity of the electricity sources used. Carbon intensity measures the amount of carbon dioxide (CO_2) emissions released to produce one kilowatt hour (kWh) of electricity. Electricity generated from fossil fuels like coal and gas has a higher carbon intensity since the production process creates CO_2 emissions.

To be considered sustainable, the European Commission has defined a decarbonization level of 65% for the sustainable fuels. Table 10 shows the percentage of decarbonization compared to current rail fossil fuel according to the carbon intensity of the electricity needed to produce the different sources of train fuels required to decarbonize the sub-sector.

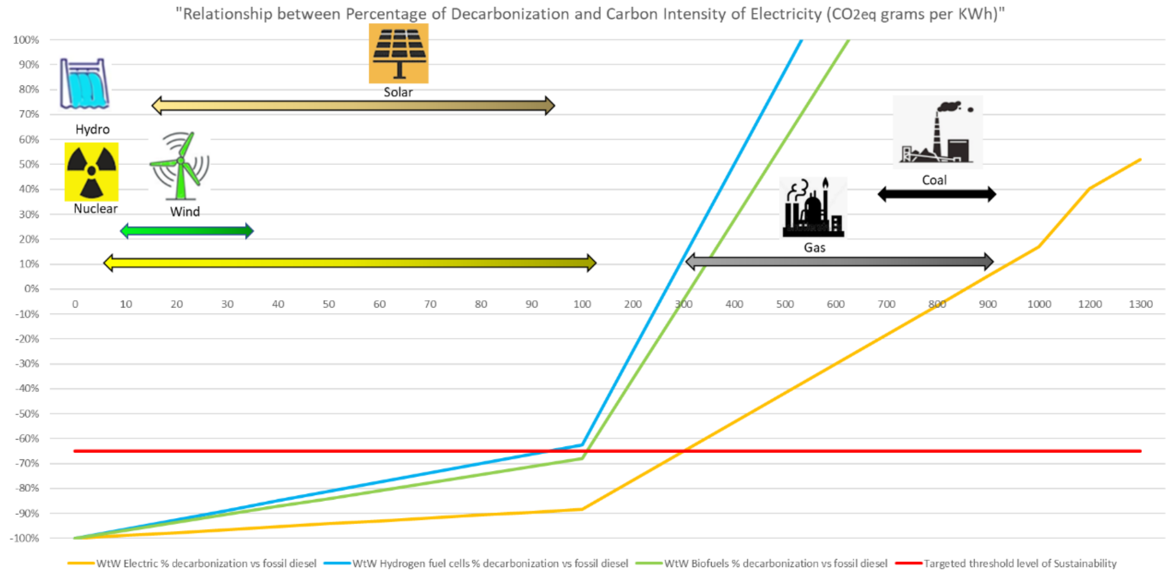
TABLE 10. Percentage of decarbonization compared to current rail fuel demand for the different sustainable train fuels based on electricity carbon intensity. Source: Figure created by authors for report.



Electricity Carbon intensity gr/KWh (Source IPCC)	WtW Electric % decarbonization vs fossil diesel	WtW Hydrogen fuel cells % decarbonization vs fossil diesel	WtW Biofuels % decarbonization vs fossil diesel	Targeted threshold level of Sustainability
0	-100%	-100%	-100%	-65%
10	-99%	-96%	-97%	-65%
20	-98%	-92%	-94%	-65%
30	-96%	-89%	-90%	-65%
40	-95%	-85%	-87%	-65%
50	-94%	-81%	-84%	-65%
60	-93%	-77%	-81%	-65%
70	-92%	-74%	-78%	-65%
80	-91%	-70%	-74%	-65%
90	-89%	-66%	-71%	-65%
100	-88%	-62%	-68%	-65%
200	-77%	-25%	-36%	-65%
300	-65%	13%	-4%	-65%
400	-53%	50%	28%	-65%
500	-42%	88%	60%	-65%
600	-30%	125%	92%	-65%
700	-18%	163%	124%	-65%
800	-7%	201%	156%	-65%
900	5%	238%	188%	-65%
1000	17%	276%	220%	-65%
1200	40%	351%	284%	-65%
1300	52%	388%	316%	-65%

As expected, and explained in the aviation chapter, nuclear power has the best performance among non-renewable energy sources, but not sufficient to allow a median decarbonization of different rail alternatives rather than electric powered units. Considering its carbon intensities (for more detail refer to 3.1.4 section in aviation chapter), renewable energy sources, such as offshore wind have a high median decarbonization ranging from -82% to -91%, and within this energy source only electric trains would pass the -65% threshold level of sustainability. To be considered as sustainable, electricity for the production of hydrogen or synthetic fuel must be lower than 30 gr CO_2eq/kWh, as shown in Figure 20.

FIGURE 20: Relationship between percentage of decarbonization and carbon intensity of electricity in a NZE scenario by 2050. Source: Figure created by authors for report.



2.3.7. Summary of the energy needs

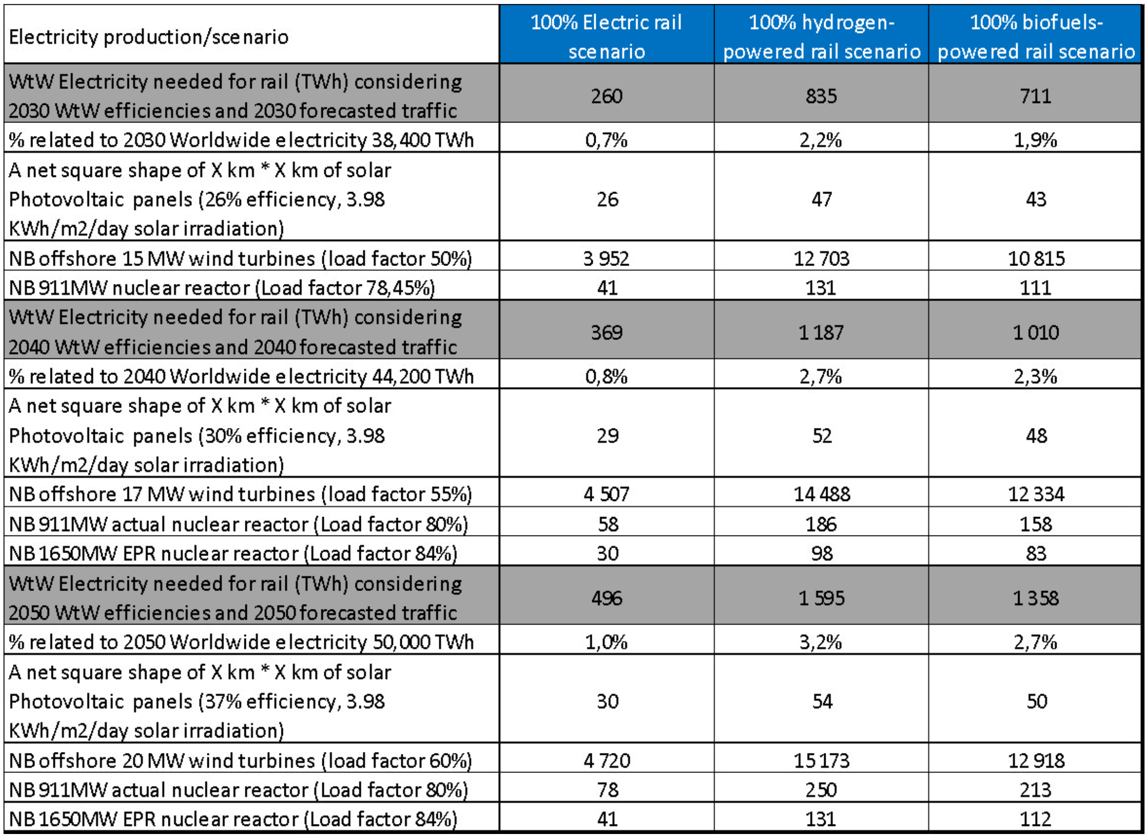
Table 11 summarizes the amount of WtW electricity required in 2050 based on worldwide forecasted train traffic for the various technologies available to decarbonize the rail sector.

TABLE 11: WtW electricity required in 2050 based on worldwide forecasted train traffic from different technologies. Source: Table created by authors for report.

	WtW energy needs	**% related to 2050 worldwide electricity 50,000 TWh**
100% Electric Rail Scenario	496 TWh	1 %
100% Hydrogen-powered Rail Scenario	1,595 TWh	3,2 %
100% Biofuels Scenario	1,358 TWh	2,7 %

Table 12 presents a summary of the electricity required by various technologies to power all rail operations worldwide, along with the corresponding number of equivalent nuclear reactors, offshore wind turbines, and square kilometers of photovoltaic panels needed (based on EU27+UK average solar irradiance). Considering worldwide energy demand projections for 2030, 2040 and 2050, generating the required electricity for this demand would require the deployment of a certain number of low-carbon, renewable sources of electricity.

TABLE 12: Quantities of electricity (TWh) and number of square shape surfaces of photovoltaic solar panels, wind turbines or nuclear reactors to produce the yearly energy for all the long-haul rail operation from 2030 to 2050 (IEA). Source: Table created by authors for report.



Electricity production/scenario	100% Electric rail scenario	100% hydrogen-powered rail scenario	100% biofuels-powered rail scenario
WtW Electricity needed for rail (TWh) considering 2030 WtW efficiencies and 2030 forecasted traffic	260	835	711
% related to 2030 Worldwide electricity 38,400 TWh	0,7%	2,2%	1,9%
A net square shape of X km * X km of solar Photovoltaic panels (26% efficiency, 3.98 KWh/m2/day solar irradiation)	26	47	43
NB offshore 15 MW wind turbines (load factor 50%)	3 952	12 703	10 815
NB 911MW nuclear reactor (Load factor 78,45%)	41	131	111
WtW Electricity needed for rail (TWh) considering 2040 WtW efficiencies and 2040 forecasted traffic	369	1 187	1 010
% related to 2040 Worldwide electricity 44,200 TWh	0,8%	2,7%	2,3%
A net square shape of X km * X km of solar Photovoltaic panels (30% efficiency, 3.98 KWh/m2/day solar irradiation)	29	52	48
NB offshore 17 MW wind turbines (load factor 55%)	4 507	14 488	12 334
NB 911MW actual nuclear reactor (Load factor 80%)	58	186	158
NB 1650MW EPR nuclear reactor (Load factor 84%)	30	98	83
WtW Electricity needed for rail (TWh) considering 2050 WtW efficiencies and 2050 forecasted traffic	496	1 595	1 358
% related to 2050 Worldwide electricity 50,000 TWh	1,0%	3,2%	2,7%
A net square shape of X km * X km of solar Photovoltaic panels (37% efficiency, 3.98 KWh/m2/day solar irradiation)	30	54	50
NB offshore 20 MW wind turbines (load factor 60%)	4 720	15 173	12 918
NB 911MW actual nuclear reactor (Load factor 80%)	78	250	213
NB 1650MW EPR nuclear reactor (Load factor 84%)	41	131	112

Example of regional scenario

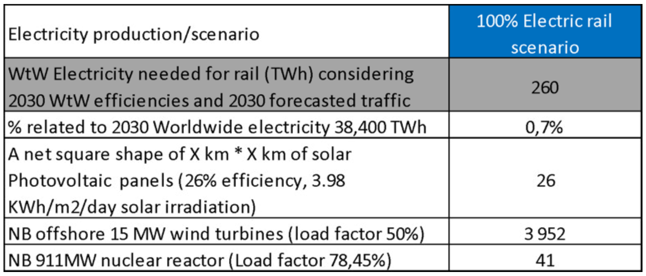
Consider a possible scenario where a regional government is willing to decarbonize some of their rail routes by 2030. In 2020 the total consumption of the routes from this region was 3 million tons of diesel. It has been decided that 40% of those 3 million tons of diesel are being replaced by electric-powered rail units and 20% by hydrogen-powered trains. What do we need in terms of energy to achieve this scenario?

With a total worldwide consumption of 28 million tons of diesel by 2020, 3 million tons represent about 10.7 % of the worldwide diesel and 40% of the 3 million tons represent 4.29% (10.7% x 40%) of the worldwide diesel. To replace these 4.29% of diesel by electric-powered trains, we just need to consider the column for the 100% Electric-powered Rail Scenario to estimate the amount of energy needed (Table 13).

The extract of Table 12 shows that **100%** of the current diesel replaced entirely by electric powered trains would require **260 TWh**. Therefore, **40% of electric-powered trains for the studied region by 2030 would require 11.15 TWh of electricity per year** (260 TWh x 0.0429 (4.29%)). It is also equivalent to **170** (3 952 x 4.29%) offshore 15MWh wind turbines at 50% load factor or equivalent to a net square shape of “5.4 km x 5.4 km” of solar photovoltaic panels at 3.98KWh/m^2 irradiance (“26 km x 26 km” x 4.29% = 31.27 km^2 = a net square of 5.4 km x 5.4 km) or about 1.76 MW nuclear reactors at 78% load factor (41 x 4.29%).

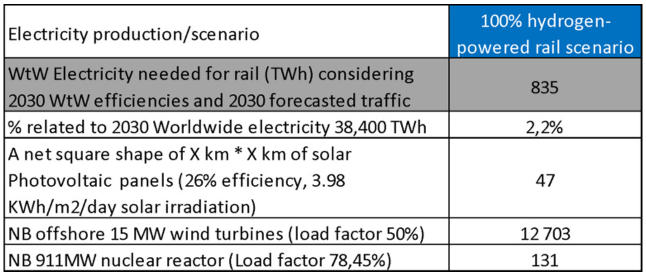
For hydrogen cell trains, we use the same procedure while considering the column for the 100% Hydrogen-powered rail Scenario:

TABLE 13: Table 12 extract for 100% electric rail scenario by 2030. Source: Table created by authors for report.



Electricity production/scenario	100% Electric rail scenario
WtW Electricity needed for rail (TWh) considering 2030 WtW efficiencies and 2030 forecasted traffic	260
% related to 2030 Worldwide electricity 38,400 TWh	0,7%
A net square shape of X km * X km of solar Photovoltaic panels (26% efficiency, 3.98 KWh/m2/day solar irradiation)	26
NB offshore 15 MW wind turbines (load factor 50%)	3 952
NB 911MW nuclear reactor (Load factor 78,45%)	41

TABLE 14: Table 12 extract for 100% hydrogen-powered rail scenario by 2030. Source: Table created by authors for report.



Electricity production/scenario	100% hydrogen-powered rail scenario
WtW Electricity needed for rail (TWh) considering 2030 WtW efficiencies and 2030 forecasted traffic	835
% related to 2030 Worldwide electricity 38,400 TWh	2,2%
A net square shape of X km * X km of solar Photovoltaic panels (26% efficiency, 3.98 KWh/m2/day solar irradiation)	47
NB offshore 15 MW wind turbines (load factor 50%)	12 703
NB 911MW nuclear reactor (Load factor 78,45%)	131

Compared with the 2020 fuel consumption, 3 million tons represent 10.7% of the worldwide diesel demand, so 20% of those 3 million tons represent 2.14% (**10.7%** x **20%**) of the worldwide diesel consumption.

Therefore, to replace 20% **of diesel trains by 2030 in the region, it's necessary to have 17,87 TWh of electricity per year** (835 TWh x 2,14% (20%)). It is also equivalent to **272** (12 703 x 0.0214 (20%)) offshore 15 MWh wind turbines at 50% load factor or equivalent to a net square shape of "6.9 km x 6.9 km'' at 3.98KWh/m^2 irradiance ("47 km x 47 km" x 2,14% = 47.27 km^2 = a net square of 6.9 km x 6.9 km) or about 2.8 MW nuclear reactors at 78% load factor (31 x 2.14%).

The final potential CO_2 reduction of this regional scenario will depend on the carbon intensity of the energy that will be used to shift between fuel powered trains, and electric or hydrogen ones. In our scenario, considering a source of electricity at 20 gr/kWh of carbon intensity, the shift to electric-powered locomotives would reduce its CO_2eq compared to current fossil jet fuel by 92%. Replacing 40% of the current diesel by electric-based units would reduce the emissions of this region by 36.8% (40% x 0.92 (90%)). In the same way, replacing 20% of the current diesel by hydrogen-powered rails would decarbonize by 15% (20% x 0.75 (75%)). In total, with a shift scenario of 40% by electric trains and 20% by hydrogen-powered, the Region would reduce the emissions from the aviation sector by 41.8 (15% + 36.8%) in 2030.

2.4. Maritime/Shipping Sector

Maritime shipping enables global trade, transporting 11.5 billion tons of goods each year, or 80% of the total goods produced around the globe. In the process, it consumes some 300 million tons of marine fuels (12.6 EJ in 2022) and emits around 1 billion tons of CO_2 — roughly 2-3% of the total anthropogenic emissions. Compared to the gigantic volume of activities, this modest impact testifies to the extremely high efficiency of maritime shipping. Data compiled by the Global Logistics Emissions Council (GLEC) in 2019 highlights that, with today's emissions intensity expressed as grams of CO_2 equivalent per ton-kilometer freight, shipping is aligned with rail.[92] **Compared to road and air transport, shipping's emissions intensities are** in the range of **one tenth and one hundredth** respectively.

The industry has developed over millennia into a highly complex system of commercial interests and technological solutions, the intricacies of which are a real challenge to regulate in view of decarbonization. To name a few: A commercial ship's **owner, charterer, cargo owner, operator, and crew** may be different entities The ship is built by a **yard**, sails on **international waters** and call ports regulated by their own **port authorities**, while flying a **flag** that is often unrelated to the nationality of any of the parties above. Each of these parties may be subject to a different jurisdiction. The business interests of each party may be in conflict with one another. The yard may maximize profits by minimizing specialty-built ships. The ship's owner may not invest in high-efficiency measures if the ship does not afford premium chartering rates. The charterer pays for the bunker and wants it cheap. Ports make available bunkering terminals and, critically, must ensure safety. The bill eventually goes to the cargo owner, who wants to minimize scope 3 emissions. Regulating the industry across various jurisdictions so that responsibilities are assigned in the correct way and control can be carried out is a true challenge. The International Maritime Organization (**IMO**), is the UN body presiding over the industry's environmental regulations. The IMO has already an utmost complex task in defining how the industry must move: the organization comprises an Assembly of 174 UN members (almost all UN countries with access to the sea) in which decisions are taken mostly on a consensus basis.

Commercial shipping can be broadly classified in **liner** (sailing over regular routes with fixed schedule) and **tramp** (opportunistic itinerary depending on the availability of cargo and clients) services. Replacing traditional marine fuels with alternatives is simpler for liner service because the route and the bunkering ports are known. Tramp service is more challenging because the ship does not follow a fixed itinerary, the ports of call continuously change, and it is more difficult to schedule where and when to bunker.

Willingness to pay varies widely. Some products can more easily absorb the cost of decarbonization than others: shipping 30 m^3 of cargo (for example in a 20-foot container) from China to the US costs ~500 USD or ~16 USD/m^3. If the cargo is salt, shipping adds 16 USD/t to the price of salt (say ~100 USD/ton). If the cargo is trainer shoes, shipping adds ~0.16 USD per individual trainer pair (price is also ~100 USD/trainer pair). Low-carbon fuels can double or triple the cost of transport: a client buying sport shoes would not notice, while for a salt supplier the freight costs may cause losses of business opportunities.

2.4.1. Composition of Energy Demand for Shipping

Scenarios on the evolution of the shipping industry vary widely. There is a large uncertainty in projection of sea freight activities: Sardain et. al (2019) concludes that traffic in 2050 will be 240%-1,209% greater than in 2014.[93] In its fourth GHG study, the International Maritime Organization (IMO) concludes that transport work in 2050 will be 40%-100% higher than in 2020.[94] The efficiency of the voyages is however also set to increase. Overall, the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping predicts a modest decrease (~10%) from the 2020 energy demand, ~310 million t/y or ~13.2 EJ, or 3,670 TWh.[95]

Shipping requires energy for various activities; some of them are technological in nature, while others are purely operational. Distinguishing among them may be helpful because decarbonization strategies are activity-specific. The main technological components of energy consumption in shipping are:

Propulsion energy is the energy needed to move a ship against the resistance of water and wind. Propulsion energy is traditionally delivered by combustion of fossil marine fuels. Not all propulsion energy converts into motion: part of the energy is lost in inefficiencies at the engine. Decarbonization of propulsion energy can be achieved by implementing energy-efficient designs (air bubble lubrication systems, propeller boss cap fins, optimization of hull design, and others); implementing low-carbon propulsion means (low-carbon fuels, sails, batteries) and abating emissions with global warming potential N_2O, CH_4, and black carbon emissions).

Electricity consumption **during voyage**. Availability of electricity during a voyage is essential to control the engines and power deck machinery, lighting, air-conditioning, and ventilation. Depending upon the ship's service, electricity may be needed to provide amenities for passengers and for cargo management (for example, refrigeration). Electrical power is typically supplied by multiple auxiliary generators (gensets), often integrated with batteries, which guarantee electricity in case of gensets failure. Gensets seem to disproportionately affect the carbon intensity of a voyage because they often operate at a low load, where combustion is less efficient and methane slips (for LNG propelled ships), and black carbon emissions are higher. Technologies to decarbonize the electrical system comprise digital optimization of diesel engine speed control, using the main engine's shaft generators to harvest electrical power and direct electrification via batteries.

Electricity consumption **at berth**. A ship's operation requires electricity even when the ship is at berth. In most of the cases, auxiliary engines keep operating while at berth to generate electrical power. As a decarbonization strategy, electricity for a ship at berth in a port may be supplied by the port (shore power), or by batteries, if the port does not have the needed capacity.

Heat consumption **at berth**. Heat is required for various operations, including fuel oil and lubricating oil management. During the voyage, heat is provided by the main engine's flue gas. At berth, however, heat is supplied by combustion of fuel oil. Aijjou et al. have studied a medium sized container vessel sailing in the Mediterranean area and concluded that the **fuel consumption** was distributed as follows: **82% for propulsion, 13% for electrical power during voyage, 4% for electrical power at berth and 1% for heat consumption at berth**.[96] The operational components of the energy consumption are determined by how the ship executes a voyage.

Commercial decisions, for example, can cause a voyage to be operated over a longer route than strictly necessary. A **change of course** can happen multiple times during a voyage, particularly in the trading business, or in the case of extensive circumnavigations to avoid costly crossing of canals. Also, commercial decisions determine **bunkering strategies,** with ships bunkering sufficient fuel for a round trip to minimize bunkering costs (tankering). For these components, maximization of energy efficiency comes in conflict with maximization of earning. Higher fuel prices, expected for all advanced fuels, may limit the profitability of these practices.

Other operational components are not in the hands of the shipping operator: **weather**, **delivery time, delays, ballasting,** and more.[97] Digitalization services may improve these operational performances. Examples may include route optimization (depending upon the weather), speed and engine optimization (depending upon berth occupancy at the next port of call), minimization of emissions (by optimization of auxiliary engines load), and more.

2.4.2. Alternative Fuels in the Fuel Mix for Shipping

Once the energy efficiency improvements are harvested, there will still be a demand for propulsion energy in the form of a low-carbon fuel — or a fuel mix, which seems more likely. Alternative fuels for transportation are described in earlier chapters (for example aviation, road, and in the appendix). Here we give only a concise summary of pros and cons specifically for shipping. The fuel mix may include:

2.4.2.1. LNG

Pros: Combustion of liquified natural gas (LNG) releases roughly 20-25% less CO_2 than heavy fuel oil (HFO). LNG as a means of propulsion is already used extensively and there is supporting infrastructure in many ports.

Cons: Methane slip from engines and fugitive emissions throughout the value chain can be massive and the impact on climate devastating. There are technological and operational best practices that can limit the emissions to a minimum, but they are not applied where policies are not specific.

2.4.2.2. Bio-diesel (Fatty Acid Methyl Esters)

Pros: Already tested and approved for use in marine applications; available today at a few ports worldwide.

Cons: Low availability if the vegetable oil shall be a residue.

2.4.2.3. Liquified Biomethane and Liquified E-methane

Pros: Drop-in fuels for LNG-propelled ships. They are already in the fuel mix today, approved in the relevant ISO standard, and affordable technologies to produce liquid biomethane are already available today.

Cons: As for LNG, climate challenges because of methane slip and fugitive emissions from careless operations and insufficient technologies throughout the supply chain (including on-board).

2.4.2.4. Biomethanol

Pros: Low tank-to-wake emissions.

Cons: Insufficient and costly biomethanol production, low energy density.

2.4.2.5. Bio-oils (Pyrolysis and Hydrothermal Liquefaction)

Pros: Use in marine engines is not demanding and bio-oils as bunker may need less upgrading.

Cons: Not commercially available yet.

2.4.2.6. Blue Ammonia (From Fossil Fuels with Carbon Capture and Sequestration)

Pros: Ammonia does not release CO_2 upon combustion. "Blue" production method can deliver large capacity already today since it is based on known technologies; first trials of ammonia engines are successful.

Cons: Safety (in ports, on-board and in marine environment). Potential emissions of N_2O. Adoption of blue ammonia increases fossil fuel consumption.

2.4.2.7. Blue Hydrogen (From Fossil Fuels with Carbon Capture and Sequestration)

Pros: Fuel cell engines are more efficient than internal combustion engines; "blue" production methods can deliver large capacities.

Cons: As for blue ammonia, adoption of blue hydrogen increases fossil fuel consumption. Hydrogen storage is costly and/or takes up space. Hydrogen emissions may have indirect global warming potential.

2.4.2.8. Green Hydrogen, Green Methane, Green Methanol, and Green Ammonia (From Electrical Power via Electrolysis, and Carbon from Direct Air Capture: PtX)

Pros: (Specifically as to the production method) Can be based on entirely renewable sources of electricity and carbon (except materials of construction).

Cons: Low energy efficiency, requires massive amounts of renewable power. There is skepticism on the effective pace of roll out of zero carbon electricity to support the use of PtX as fuels.

2.4.2.9. Direct Electrification (Batteries)

Pros: Eliminates emissions and reduces noise to the benefits of marine environment and passengers; has very high energy conversion efficiencies. Can be used for partial fuel replacement; for example, instead of gensets. Batteries are already used in short-haul voyages (ferries).

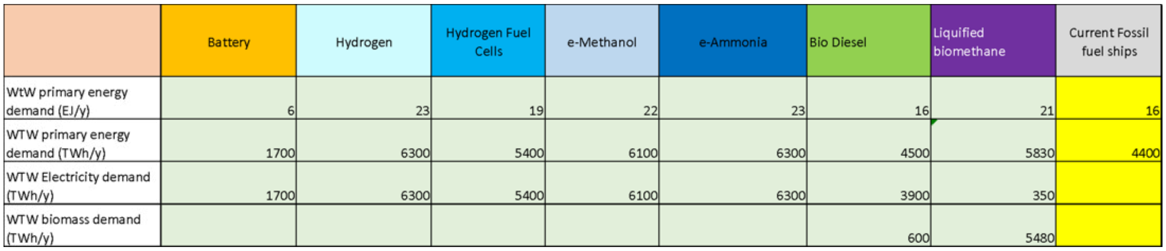
Cons: With present energy densities, and without changes in the bunkering strategies, batteries cannot replace main engines in long-haul voyages. Current batteries formulation raises concern about risk of fire.

2.4.3. The Decarbonized Energy Demand in the Shipping Sector Towards 2050

The main components of alternative fuels are electricity, mostly for PtX, and biomass, for biofuels. We have calculated the total energy demand, in exa-Joule (EJ) and tera-watt hour (TWh) per year for some selected alternative fuels in comparison with the fossil fuel currently used. The calculations are well-to-wake. The primary energy consumption of fossil fuel is 16 EJ/y (4,444 TWh) instead of the current 12.6 EJ/y (3,500 TWh) because we account for the losses of production, transport, etc. For the calculation we have used well-to-tank energy conversion efficiencies from published information. We have furthermore assumed that the tank-to-wake efficiency is the same for all internal combustion engines (37%). Tank to wake energy conversion efficiency for fuel cells is 42.5% and for battery propulsion 85.5%.

Figure 21 below shows the total WtW energy demand accounting for losses in the alternative fuel production and usage. Thanks to overall low energy conversion losses, battery propulsion requires less than half of the energy required today. Today, batteries are used sporadically, only on very short routes or to replace auxiliary engines) due to the low energy density. The comparison of Figure 21 underlines that advancements in energy density are critical to reduce the total energy demand for this industry. If energy were to be supplied by biodiesel, the demand would be in the same range as the original fossil fuel. Other alternative fuels require more energy due to production losses. For biofuels, Figure 21 shows the electricity and biomass demand to supply the required energy. Biofuels rely most on biomass and have low electricity demand.

FIGURE 21: Electricity and biomass demand to decarbonize shipping. Source: Made by authors for report.

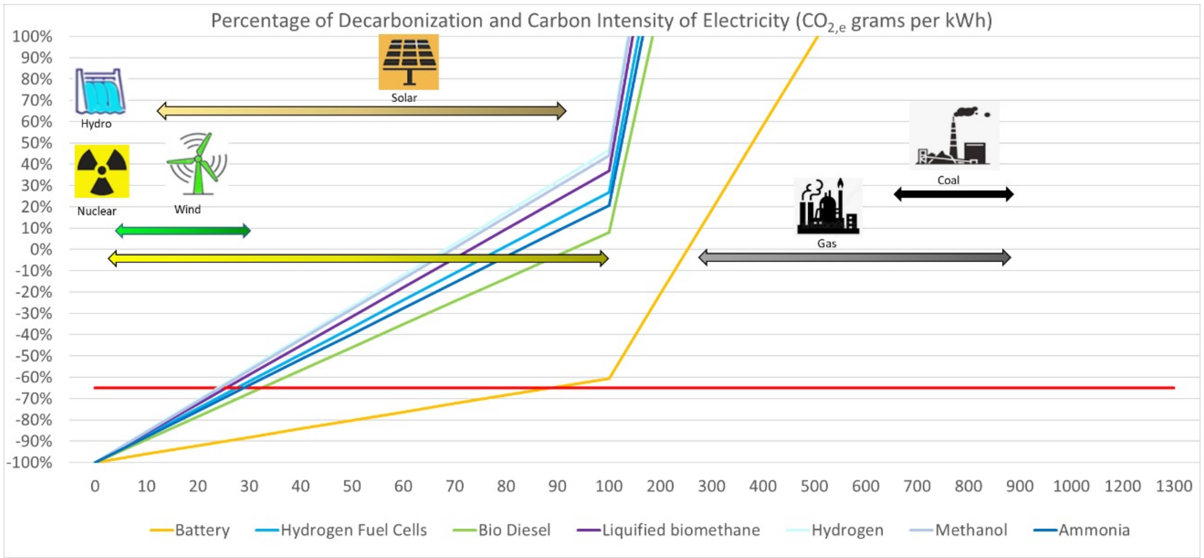


	Battery	Hydrogen	Hydrogen Fuel Cells	e-Methanol	e-Ammonia	Bio Diesel	Liquified biomethane	Current Fossil fuel ships
WtW primary energy demand (EJ/y)	6	23	19	22	23	16	21	16
WTW primary energy demand (TWh/y)	1700	6300	5400	6100	6300	4500	5830	4400
WTW Electricity demand (TWh/y)	1700	6300	5400	6100	6300	3900	350	
WTW biomass demand (TWh/y)						600	5480	

We calculated the change in the percentage of decarbonization depending upon the carbon intensity of electricity. Figure 22 shows the results and highlights that highly efficient technologies, such as battery electrics, can produce important decarbonization results even when they originate from electricity with high carbon intensity. For example, battery electrical propulsion can reduce emissions by more than 65% (sustainability threshold as per the European Renewable Energy Directive) if the carbon intensity of electricity is below 90 grams of CO_2 equivalent per kWh. Other fuels require electricity with far lower carbon intensity. Hydrogen, at the opposite end of the spectrum, requires electricity with a maximum 20 grams of CO_2 equivalent per kWh to pass the sustainability threshold and qualify.

The calculation accounts solely for the carbon intensity of electricity. However, other variables also contribute to determining the final ability of a fuel to decarbonize. For biofuels, for example, the biomass origin and quality is another important component. For all biofuels, release into the atmosphere of gasses and combustion products with global warming potential (methane, hydrogen, N_2O, black carbon, etc.) must be mitigated to a minimum.

FIGURE 22: Decarbonization efficiency and carbon intensity of electricity. Source: Figure made by authors for report.



2.4.4. Shipping Decarbonization Technology Path

According to the IPCC AR6 Working Group III, the world must reduce emissions by 40% by 2030 with respect to the 2010 emissions (Figure SPM.4) to limit global warming to 1.5°C.[98] For shipping, this translates into reducing the overall demand of energy from the 2023 level of 12.6 EJ to 6 EJ.

Current policies seem insufficient to achieve the interim target.

Various technologies aimed at improving energy efficiency are available today at a cost of less than 100 USD/$tCO_{2,e}$. According to the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, the widespread adoption of such affordable measures could reduce fuel consumption by 1 EJ by 2030.[99]

The remaining emissions reduction must be achieved through low-carbon fuels. Section 2.4.2 gives a list of pros and cons of the numerous candidates for decarbonization.

Various global institutions have created decarbonization scenarios that predict that many of those candidates may actually have a role to play to decarbonize shipping at some stage of the transition.[100] Currently, the industry is turning to LNG to satisfy interim decarbonization targets. According to the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, by 2025 and 2030, fossil fuels will still be clearly dominant, but a few percentages of total demand are satisfied by LNG. By 2030 blue ammonia enters the fuel mix and LNG is gradually replaced by liquified biomethane. By 2035, electric fuels will enter the mix, particularly with green ammonia. Decarbonization is full by 2050 and it is dominated by ammonia. Biomethanol, bio-oils, and biomethane are also important parts of the mix. The scenario results from estimates of availability of resources (renewable power, biomass), capacity buildup (constrained by construction time), and production costs under a flat global carbon levy of 230 USD/$tCO_{2,e}$. Different assumptions change the outcome and certain events may cause a completely different picture. Some of the most critical examples: no acceptance for blue fuels, no approval of ammonia operations, breakthrough in battery technology, or insufficient carbon levies.

At the moment there is still great uncertainty about future development and there are great expectations on ammonia. In absence of concrete safety approvals and fuel availability, first movers are directing their attention towards LNG/liquified biomethane and biomethanol. Bio-oils trigger high interest as potential drop-in; however, there are no current commercial manufacturing technologies.

2.4.5. Perspectives for the Council of Engineers for the Energy Transition in Shipping

Ports and ports infrastructure are at the core of cities and countries' development.[101] The recent IMO mandate on the use of alternative fuels as a bunker may trigger demand for alternative fuels production in developing economies. This, in turn, may create a local energy industry producing globally traded commodities.

This may represent an important opportunity for local development of communities in port areas. Neighboring regions may also enjoy opportunities for development if physical infrastructure for alternative fuels, manufacture and delivery, and/or certification systems of guarantees of origins and chain of custody recording systems are available or can be put in place.

A summary of important areas of attention for the Council of Engineers for the Energy Transition (CEET) embodying the four areas of focus requested by the UN Secretary General is in the following points:

Dissemination of Engineering-based Assessments: A lifecycle **climate impact label** applied on every sold product informs authorities, consumers, and technology developers of the burden created from a product "from cradle to grave", meaning the emissions from the value chain that manufactures and delivers a product to a consumer, from the use of the product and from product end of life disposal. This presents strong business opportunities for shipping, due to the low energy consumption of this transport type. At the same time, it forces shipping to eliminate emissions with high global warming potential, such as methane from LNG and bioLNG ships, N_2O and black carbon, besides CO_2. In the context of assessing the climate impact of a cradle-to-supply chain, we advise against the use of "standard" emissions intensity values. Instead, we advocate for asset- and value chain-specific assessments because experience shows that the difference between standard and specific values may be large, and the practice does not incentivize emissions reduction.

Identify Cutting-edge Bankable Technologies: The replacement of fossil fuels with alternative fuels increases the primary energy demand for almost all cases. Not so for **wind sails** propulsion and **batteries**, which actually decrease the primary energy demand. At the current status of development, both technologies may support shipping, but neither is able to completely displace fossil fuels. In particular, improvements in energy density for batteries is critical if long-haul shipping shall rely on EV propulsion.

Cross-border Regional Scale Systems: Abundance of natural resources has a regional character: the sun shines in geographies where wind may not blow and vice-versa; biomass may not be abundant in areas with high density populations that generate waste, and so on. Transporting primary energy may involve losses and transforming energy locally is often the most efficient option. There may be important opportunities in considering a cross-border approach, in which abundance of natural resources in one country can be made available to neighboring countries. For regional-scale systems to be effective, either **physical infrastructure** or **chain of custody certification and trading schemes** must be in place. Typical examples are Power Purchase Agreements (PPA) for renewable electricity or Guarantee of Origin certificates for biomethane.

Opportunities in the energy transition: The recent IMO mandate to gradually replace fossil fuels with low-carbon fuels triggers international demand for low-carbon fuels for shipping. A few ports on international shipping routes are located in emerging economies and the IMO mandate provides an opportunity for these to establish manufacturing facilities for energy and alternative fuels that may be sold at the price of globally traded commodities.

3. Recommendations

A List of Policy Measures and/or Incentives to Support the Transition to Net-zero Emissions and to Ensure that the Technological Solutions Could Be Implemented at an Affordable Price

3.1. General Recommendations

In the past years, trade and transport policies have been changing to grant more resilient supply chains. Policies had to be accelerated to minimize the consequences of the disruptions in global logistics due to the pandemic, increasing the importance of regionalization and shortest trading routes. In addition, the conflict between Russia and Ukraine had an impact on European and global energy markets, as well as on European climate and energy transition ambitions.

Despite the effects of the COVID-19 pandemic and the Ukraine war, the projected changes in world population, urbanization, and economic growth will significantly impact the demand for transport — an intensive emitting sector due to its dependence on fossil fuels. The transition towards decarbonized road transport is an imperative yet complex process, requiring a collaborative effort across the industrial chain, application side, and infrastructure development. Policymakers globally must leverage their power to incentivize and mandate this evolution, while maintaining balance between environmental needs and the increasing demand for economic development movement options.

In 2015, with the ratification of the Paris Agreement, countries around the world pledged to limit the global temperature increase to 1.5 °C by 2050. The transport sector must implement high ambition actions to reach the objectives pointed in this legally binding international treaty. The Intergovernmental Panel on Climate Change (IPCC) estimates point out the necessity of reducing total transport emissions between 2 and 3 GT to restrict the global average temperature increase to 1.5 °C by 2050. As nations worldwide commit to reducing emissions to net zero in the decades ahead, it is crucial to match these commitments with effective policies and strategies, and to boost the adoption of large-scale Negative Emissions Technologies (NETs), including direct air capture, carbon capture and storage (CCS), and even solar geoengineering. Developed economies, especially in Europe and North America, have been particularly active in shifting their energy systems to low-carbon alternatives.

According to the IEA's estimates, transport CO_2 emissions need to fall by 3% per year through to 2030 to achieve a net-zero scenario by 2050. In this regard, international coordination and cooperation is a must to achieve national emissions reduction targets, along with better regional connectivity with heavy investments in road and rail corridors. This will assure an efficient interoperability between the national transport systems as well as intermodal and multimodal hubs. These actions help to improve flows, reducing transport and trade costs and accelerating the shift to cleaner modes.

To drive the transition to net-zero carbon emissions by 2050, governments can introduce economic policies and incentives that encourage decarbonization of the transportation sector. These instruments include carbon tax or pricing, road pricing, and parking pricing. Also, subsidies for low-carbon technologies and regulations that mandate reductions in emissions need to be implemented. Other measures, such as the improvement of pedestrian and cycling networks or the expansion of public transportation and the improvement of its quality and customer experience will help in the emissions reduction objectives.

Europe has demonstrated significant emissions reductions through its pioneering carbon market, robust renewable electricity deployment policies, and promotion of low- or zero-emissions transportation options. The high taxation of fossil fuels, such as diesel and gasoline, has further incentivized a shift towards cleaner energy sources. The results are evident, with projections indicating deep reductions in the use of coal and other fossil fuels in the coming years.

In the US, the Inflation Reduction Act of 2021 allocated about $370 billion towards clean energy spending, predominantly in the form of tax credits for renewable sources such as wind and solar. These credits effectively hasten the retirement of the most expensive fossil fuel plants, reducing emissions while encouraging the adoption of cleaner energy sources.

A variety of policy measures have shown promise in promoting low-carbon energy consumption, such as electricity and hydrogen price subsidies and carbon pricing. In the electricity sector, clean energy tax credits have been especially effective in reducing retail prices, thus making clean energy more attractive to consumers. Hydrogen subsidies could potentially lower the cost of this promising but currently expensive energy source, especially in sectors like transportation. Meanwhile, carbon pricing can highlight the financial impact of carbon-intensive energy sources, encouraging consumers and businesses to select less carbon-intensive alternatives.

In 2022, global investment in clean energy technologies increased by 31%, with a particular focus on renewable power and electric transportation. However, a simultaneous growth in global CO_2 emissions underscores the considerable challenge of transitioning our vast global energy system away from polluting sources.

One of the main challenges of an incentive-based regulatory approach is the costs of the incentives. It needs to be funded, and most of the time it is done via a tax mechanism — meaning that all citizens will be involved, and not only the passenger. The whole society will have to contribute to the decarbonization effort of the transport sector and each of its sub-sectors, which could be seen as unfair from a societal point of view.

Economic instruments need to be teamed up with regulatory ones. Regulatory instruments include vehicle circulation restrictions in urban and congested areas, speed and parking restrictions, long term urban and land-use planning, and, in some cases, behavior shift oriented policies.

A mandate-based regulatory approach is another option and has been successfully used. For example, to expand the production of conventional biofuels (biodiesels), as it creates structural demand for these fuels and compulsory blending. Mandates also give long-term security to investors by de-risking investments. One of the main challenges of a mandate-based approach is the potential additional costs, especially at the beginning of a mandate when the fuel production is still limited. Mandates can also be combined with incentives to address this cost differential. Both mandates and incentives have their benefits and challenges. Selecting the best instrument depends on a mix of factors including economic efficiency, cost-effectiveness, distribution of benefits or costs, ability to address uncertainties, and political incentives. However, several decarbonizing measures are cross-cutting among transportation modes. Examples of these include:

- Accelerate the development of CO2 efficient and disruptive technologies while improving current fleet technologies. This could be enabled by funding programmes for the deployment of net-zero and innovative technologies. For instance, the ETS Innovation Fund is the EU fund for climate policy, with a focus on energy and industry. It aims to bring to the market solutions to decarbonize European industry and support its transition to climate neutrality while fostering its competitiveness.
- Encourage accelerated fleet renewal to significantly reduce CO2 emissions with modern and efficient transport units.
- Accelerate the development and deployment of low-carbon electricity.
- Accelerate the development and deployment of sustainable fuels.
- Accelerate the development and deployment of green hydrogen.

Motivate public and private investors to fund sustainable solutions for the sector via green funds, grants, state-backed loans, etc. (for instance, the EU Taxonomy in Europe). Green bonds were created to fund projects that have positive environmental or climate benefits. Data from the Climate Bonds Initiative shows that energy, buildings, and transport initiatives collectively sum up to 77% of the total green debt volume, 18% of which relies on the transport sector — so there is enough space to grow.[102]

In terms of energy, decarbonizing the transportation sector requires heavy investments in terms of production, infrastructure, and new technologies. National, regional, and international authorities could support or accelerate the transition to net zero by implementing policy measures that would:

- **Support early investments.**
- **De-risk investments.**
- **Support the ramp-up and deployment of low carbon electricity to produce low carbon energy (green hydrogen, sustainable fuels).**
- **Facilitate access to raw products, feedstock, renewable electricity, green hydrogen, or sustainable aviation fuels at an affordable cost.**
- **Avoid competitions between all transportation sectors for the same feedstock or for the same energy.**

3.2. Specific Recommendations for Accelerating Aviation Decarbonization

The Inflation Reduction Act (IRA) as defined in the US is a good example of an incentive-based regulatory approach. It includes significant incentives, tax credits, and subsidies for SAF production, clean hydrogen, and renewable energy, at a time when the global airline sector is desperate to see more affordable SAF on the market. The incentive-based approach could encourage the aviation sector and/or SAF producers to take innovative methods, develop safe technologies, and adopt better practices to accelerate their decarbonization effort.

On other hand, the ReFuelEU Aviation Initiative is a good example of a mandate-based regulatory approach. In June 2021, the European Climate Law was adopted, setting into law the EU target for 2030 of reducing greenhouse gas (GHG) emissions by at least 55% compared with 1990 levels, in line with priorities set out in the European Green Deal. On 14 July 2021, the European Commission presented a package of proposals to make the EU's climate, energy, land use, transport, and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared with 1990 levels — the Fit for 55 package. The package includes a proposal to ensure a level playing field for sustainable air transport, also known as the ReFuelEU Aviation initiative. The EU Commission proposes obligations on fuel suppliers to distribute sustainable aviation fuels, with an increasing share of SAF (including synthetic aviation fuels, commonly known as e-fuels) over time, in order to increase the uptake of SAF by airlines and thereby reduce emissions from aviation. The proposal also includes obligations on airlines to limit the uptake of jet fuel before departing from EU airports to what is needed for safe operation of flights, with the aim of ensuring a level playing field for airlines and airports and avoiding fuel tankering (additional emissions related to extra weight of aircraft carrying excessive amounts of fuel to avoid refueling at higher price).

The decarbonization of the aviation sector can be boosted by prioritizing other actions fostering the transition. They are listed below in three different categories of recommendations.

Prioritize Actions which result in the highest reduction in CO_2:

- Encourage air traffic management optimization and airspace modernization, which would benefit rapidly to all the flights.
- Encourage the industry to uptake higher levels of SAF on a voluntary basis where the market allows.
- Push for a larger share of e-SAF to motivate higher investment in green hydrogen production facilities.

- Facilitate access to feedstock of the SAF pathways and availability of affordable renewable energy for producing e-SAF, which will require a massive volume of renewable electricity and green hydrogen.
- Promote the research and development on the use of low-carbon technologies such as novel fuels (such as SAF and e-SAF) and aircraft (such as hybrid-electric or hydrogen aircraft).
- Promote direct air carbon capture and storage for aviation.

Support the transition through financial support and alliances:

- Encourage a coordinated approach between the aviation industry, electricity producers and the (e)-SAF industry to synchronize development and deployment of the different sustainable solutions (by joining alliances, such as the European Clean Hydrogen Alliance, Alliance for Zero Emission Aviation or the Alliance for Renewable and Low Carbon Fuels Value Chain (RLCF)).
- Engage the aviation sector as a strategic partner to define the national or international energy decarbonization strategy.

Balance carbon taxation with the need to maintain competitiveness:

- Monitor closely the impact of taxation on aviation to ensure fair tax treatment with other transport modes, avoid double taxation and carbon leakage, and preserve connectivity.
- Monitor the variations of the carbon market to assess inter alia the effects of potential energy crises and to mitigate the risks of carbon market volatility on the competitiveness and economic sustainability of the aviation sector.
- Earmark revenues collected from aviation-related taxes to foster aviation innovation and increase its funding capabilities.

3.3. Specific Recommendations for Accelerating Road Transport Decarbonization

Actions to accelerate road transport decarbonization are grouped in four sections and listed below:

Actions with impact in the CO_2 reduction:

- Enforcing regulations to create demand for low-emission vehicles is equally essential. The EU's CO_2 standards for cars and vans serve as an effective precedent, providing long-term investment security by stipulating compulsory emissions reduction targets for manufacturers. The inherent cost implication can be mitigated by coupling it with incentives.
- Transitioning to cleaner, more fuel-efficient technologies can drastically reduce the carbon footprint. Japan's Top Runner Program, which mandates the best available technology as the efficiency standard, is an effective policy model. Also, encouraging swift fleet renewal with more efficient vehicles, akin to Norway's EV incentive scheme, can minimize road transport's environmental impact.
- Shared mobility can be pivotal in reducing the number of vehicles on the road, leading to lower emissions per capita. It maximizes vehicle utilization and promotes a shift away from private vehicle ownership. Singapore's National Shared Mobility Program, encouraging ride-sharing services, is a noteworthy initiative in this domain.
- Advancements in zero-emission vehicles and innovative technologies can offer significant carbon reduction in road transport. Policies like the US's Advanced Research Projects Agency-Energy (ARPA-E) initiatives can stimulate breakthroughs and accelerate the sector's decarbonization.
- Carbon credits and trading systems are innovative market-based mechanisms to combat climate change. A carbon credit represents a reduction or removal of one ton of carbon dioxide emissions. Credits can be traded in carbon markets, essentially putting a price on emissions. The key difference between the two lies in their implementation:

while carbon credits offset emissions, carbon trading allows companies to buy the ‘right to pollute’ from those who pollute less. These systems are crucial to road transport carbon reduction as they incentivize companies to adopt cleaner technologies and reduce emissions. The EU Emissions Trading System (EU ETS), which allows trading of emission allowances among companies, is a model to replicate and adapt for the road transport sector. It could be expanded to incorporate all vehicle types, creating an all-inclusive solution for road transport decarbonization.

Support the transition through financial support and alliances:

- The provision of financial incentives to producers and consumers has shown success in influencing behavior towards decarbonization. An example to draw inspiration from is the US Federal Tax Credits for EVs, encouraging the production and consumption of electric vehicles. Nevertheless, the challenge lies in the sourcing of funds for such incentives, often leading to a broader tax burden.
- To finance the transition to green transport, public and private investments should be incentivized via green funds, grants, and state-backed loans, as seen in the EU Taxonomy model. Coordinated, cross-sectoral efforts, as observed in the European Green Vehicles Initiative, can further harmonize the transition.
- Financial incentives are critical in encouraging the adoption of cleaner technologies and vehicles. A comprehensive funding scheme could be envisioned, like Germany’s Federal Ministry for Economic Affairs and Energy, but with a dedicated focus on carbon reduction in road transport. This could involve grants for start-ups developing electric or hydrogen fuel cell vehicles, subsidies for installing EV charging infrastructure, and loan guarantees for companies investing in clean fleet vehicles.
- To promote the development of low-carbon power, various policies could be implemented, such as subsidies for renewable energy development, unrestricted travel for electric vehicles, and additional incentives. These measures, along with NETs and CCS, can contribute significantly to the shift towards a low-carbon energy system.

Balance carbon taxation with the need to maintain competitiveness:

- To maintain a fair competitive landscape, the impact of carbon taxation on the transport industry must be closely monitored. Singapore’s Carbon Pricing Bill, which taxes greenhouse gas emissions, serves as an example that balances carbon reduction and economic viability. Revenues from such taxation should be earmarked to fund transport sector innovation.

Policies for Stimulating Infrastructure Deployment:

- The development of necessary infrastructure, such as charging stations, is crucial to the transition to a low-carbon transportation sector. For example, the Biden administration has committed $174 billion towards winning the electric vehicle market, specifically allocating a portion of this fund for the development of charging infrastructure and the research and development of advanced technologies and manufacturing.
- Development of infrastructure is not limited to physical assets alone; it also involves improving the electric grid’s capacity to accommodate increased electricity demand from sectors such as transportation. In 2022, global investment in clean energy technologies, including renewable power and electric transportation, reached an estimated $1.1 trillion, highlighting the vast scale of the global energy system and the challenges of transitioning it towards clean sources. The demand for wind and solar energy is projected to increase dramatically, indicating a significant decline in the share of fossil fuels in the electricity mix by 2050.

There are others specific measures in major markets like China, Europe, and the United States of America than can be considered:

China

China has been a global leader in the promotion and development of electric vehicles (EVs), fuel cell vehicles (FCVs), and hybrid vehicles. Its strategic approach is founded on a range of policy measures and incentives designed to facilitate the transition to net-zero emissions.

China's commitment to green transportation began to take shape. With policies like the "Ten Cities, Thousand Vehicles" program, which was put in place in 2009, it encouraged the production and purchase of electric vehicles (EVs), fuel cell vehicles (FCVs), and hybrid vehicles. Direct purchase subsidies were significant, averaging RMB 60,000 ($9,400) per vehicle. This substantial financial incentive, coupled with preferential policies such as exemptions from license plate lotteries and reduced acquisition tax, motivated both manufacturers and consumers. The State Council's "Energy-Saving and New Energy Vehicle Industry Development Plan (2012-2020)" was another turning point. It set an ambitious goal of having 500,000 new energy vehicles on the road by 2015. This policy initiative propelled the number of EV sales from a modest 8,159 units in 2011 to a staggering 247,482 units in 2015, marking a 30-fold increase in just four years.

The period between 2015 and 2019 saw China rolling out the New Energy Vehicle (NEV) Development Plan (2016-2020). This policy reframed subsidies based on the range and energy efficiency of EVs, FCVs, and hybrids, encouraging the development of high-performance vehicles. Subsidies were extended to charging infrastructure, addressing a critical bottleneck in EV adoption. Additionally, China introduced the "dual-credit" policy in 2017, obliging automakers to meet quotas for NEVs or purchase credits from other companies, further incentivizing manufacturers to innovate and produce more NEVs. The combined effect of these policies led to explosive growth. By 2019, China boasted over 100 EV manufacturers, and its EV sales reached a record 1.2 million units, securing its position as the world's largest EV market.

The present phase (2020-2023) has seen the gradual phase-out of direct purchase subsidies, with the government shifting its focus toward policies promoting EV usage. Incentives such as free parking and toll waivers have been introduced, while the "dual-credit" policy has been further tightened, pushing automakers to produce more efficient EVs. Despite the reduction in direct subsidies, the average price of EVs has continued to decrease, from RMB 232,000 ($36,000) in 2011 to RMB 180,000 ($28,000) in 2023. This represents a price reduction of nearly 22%, made possible by continuous technology improvements and economies of scale. As of 2023, China has over 1.8 million charging piles, indicating a thriving infrastructure network.

China's EV, FCV, and hybrid vehicle subsidy policies have played a pivotal role in popularizing these vehicles. These measures enabled technological solutions to be implemented at affordable prices, resulting in significant industry growth and innovation. They also facilitated China's strategic transition towards sustainable transportation, supporting its commitment to reach peak CO_2 emissions before 2030 and achieve carbon neutrality before 2060.

Lessons from China's experience are valuable to other markets worldwide. These include the importance of phased policies — starting with purchase subsidies, transitioning to performance-based subsidies, and ending with use incentives — to drive market growth and technological development. Additionally, the dual-credit system could serve as a model for other countries to encourage auto manufacturers to produce more efficient and cost-effective EVs, FCVs, and hybrids. All these positioned China as a significant player in the global push for net-zero emissions.

Europe

The journey towards sustainable transportation in Europe has been marked by a distinct trajectory, differing significantly from other major markets like China or the USA. Europe's approach has been largely decentralized, with individual countries setting their own incentives and policy agendas in the early stages, contrasting with the centralized, top-down strategies seen in other regions.

During the early 2000s, Europe's focus on green transportation was largely country specific. Notably, Norway initiated comprehensive benefits for EVs as early as 2001, leading to the highest per capita number of all-electric cars globally by 2010. Yet, an EU-wide purchase subsidy or overarching policy directive for green vehicles was missing during this phase, starkly contrasting with China's central government directed "Ten Cities, Thousand Vehicles" program.

The period between the year 2011 and 2016 witnessed Europe adopting a more structured approach. Individual countries, like Germany, introduced national plans to promote EVs. Concurrently, the European Union focused on broader carbon reduction goals, culminating in the 2011 Transport White Paper, aiming for a 60% reduction in transport emissions by 2050. However, compared to China's exhaustive NEV Development Plan and financial incentives, Europe's efforts lacked uniformity and significant direct financial incentives.

The phase from 2017 to 2023 marked an aggressive push for green vehicles in Europe. Unlike China, which shifted away from direct purchase subsidies towards usage incentives, Europe maintained and even increased direct purchase subsidies. As of 2023, Europe has over 3 million EVs on the road, a significant increase from 500,000 in 2015. However, compared to China's vast infrastructure network of 1.8 million charging piles, Europe, with only 225,000 charging points as of 2020, faces an infrastructural challenge.

Europe's green transportation journey offers valuable lessons to other markets. Its success in promoting EV adoption through national-level initiatives demonstrates the effectiveness of policy incentives. However, its struggle with a fragmented approach early on underscores the importance of a coordinated, comprehensive strategy. The recent aggressive push for EVs through stringent emission standards and purchase subsidies demonstrates a commitment to sustainability that has driven significant market growth. Europe's case suggests that a combination of regulatory measures, financial incentives, and an emphasis on infrastructure development can be instrumental in promoting energy transition in the road transport sector. However, the need for improved charging infrastructure also highlights that financial incentives alone are insufficient, and holistic infrastructural development is crucial to support NEV adoption.

The United States

The United States has had a unique path in promoting NEVs and hybrid vehicles, marked by significant federal incentives supplemented by state-level initiatives. The US's blend of direct financial incentives and tax credits offers an interesting comparison to the more centralized strategies seen in regions like Europe or China.

In the initial phase (1992-2007), the United States' movement towards green transportation began with the Energy Policy Act of 1992. While it was designed to decrease the country's dependence on foreign oil and enhance air quality, this policy did not include substantial incentives specifically aimed at promoting electric vehicles, fuel cell vehicles, and hybrid vehicles. This lack of substantial direct financial incentives during this period marked a stark contrast to the European countries that introduced individual EV incentives, and China's comprehensive "Ten Cities, Thousand Vehicles" program. However, the landscape began to shift with the 2005 Energy Policy Act. This Act brought a new dimension to the market by offering tax credits for hybrid vehicles. The financial impact of this policy played a significant role in fostering the adoption of these vehicles. By the end of 2007, nearly 1.2 million hybrid vehicles were on the US roads, a substantial leap from the previous years. This demonstrated the effectiveness of tax credits as a market stimulus, though the fragmented nature of these early initiatives still contrasted with more centralized strategies seen elsewhere.

Between 2008 and 2016, the US federal government made a more assertive push towards promoting EVs and plug-in hybrids. The Emergency Economic Stabilization Act of 2008 was instrumental in this respect, establishing tax credits of up to $7,500 for plug-in electric vehicles. These federal incentives, combined with the dropping prices of EVs, led to a significant increase in EV sales. During this period, individual states also implemented their own additional incentives. For instance, California, one of the leading states in EV adoption, introduced additional purchase rebates and allowed EVs access to carpool lanes, a significant time-saving incentive for consumers. These state-level incentives, however, varied widely across the country, creating a patchwork of policies that lacked the central coordination of policies seen in Europe or China.

In the recent years (2017-2023), Despite an initial slowdown in the emphasis on green vehicles starting in 2017, a significant revival occurred from 2020 onwards. This was mainly due to the Biden administration's push towards greener transportation with the promotion of the NEV. The administration proposed extending the federal tax credit and investing $15 billion in infrastructure development, with a goal of building 500,000 charging stations across the nation by 2030. As of 2023, these policies have resulted in over 1.8 million EVs on US roads, a considerable increase compared to the previous decade. This underscores the effectiveness of federal tax credits in promoting EV adoption. However, in terms of infrastructure, the US lags behind Europe and China.

As of 2023, the US only boasts 100,000 public charging points, a figure that pales in comparison to Europe's 225,000 (as of 2020) and China's massive 1.8 million. These numbers reflect the necessity of a comprehensive infrastructure plan for supporting the widespread adoption of green vehicles.

The United States' path towards green transportation, marked by robust federal tax credits supplemented with diverse state-level incentives, provides valuable insights for other markets. The success of the federal tax credit in promoting EV adoption demonstrates the potential of such financial incentives in driving market transformation. However, the disparity in state-level incentives underscores the need for a more uniform policy approach. Additionally, while the recent focus on infrastructure development is a positive move, it highlights the critical role that comprehensive infrastructure planning plays in supporting the broad adoption of EVs, FCVs, and hybrid vehicles.

3.4. Specific Recommendations for Accelerating Train Decarbonization

In an NZE scenario by 2050, rail should play an important role in the transport sector, replacing cars, two/three wheelers, road (both passengers and freight), and air transport demand when integral benefits surpass costs and environmental concerns. Because the rail sector is inherently capital-intensive, appropriate economic, environmental, and social signals must be addressed to stakeholders through the establishment of policies and incentives, increasing rail projects attractiveness and feasibility.

To reach that scenario in such a way, it is required to:

- Minimize costs per passenger-kilometer or ton-kilometer moved, granting the conditions for the maximum network usage. Cost optimization requires actions from different fronts, that include, but are not limited to, public planning measures, rail integration and interoperability with other transport environments, adoption of international standards, and digitalization.
- Maximize revenues from rail systems, capturing or capitalizing land value and allowing the projects to be profitable.
- Charge the costs of adverse impacts from all forms of transport, not only for the infrastructure they use or need. These are generally executed through fuel taxation, but alternative means are necessary.

3.4.1. Actions which Impact in the CO_2 Reduction

- In its Rail Analysis, the IEA addresses that policies that promote high-density living and incorporate transport into urban development planning can help achieve high passenger throughput on urban rail networks. By the adoption of an integrated approach to transport, commuting times can be drastically minimized. Moreover, land use planning should accommodate city logistics by incorporating ideally located multi-modal hubs. Rail should be linked to cargo, cycling infrastructure, and zero-emission fleets. Transit-oriented development can connect urban rail with bus networks as well as pedestrian and cycle.
- Rail companies need to upgrade their rolling stock and further electrify services, starting with the most heavily utilized routes. The introduction of energy efficiency measures would both reduce environmental impacts and improve economic viability. New digital technologies offer the possibility to optimize train operation and articulate it with other transport and mobility services, increasing the rail attractiveness, reliability, and convenience. Technology and data analysis will facilitate a greater and more intense use of tracks, optimizing time and distances between services, and consequently boosting the operation capacity. At the same time, consumers will experience several improvements in the quality of the service — more comfort, safety, and possibly price signals — so they will continue engagement with rail over other transport modes. The rapid growth of artificial intelligence initiatives also offers vast opportunities to improve services for end-users through seamless integration across different modes and other measures and energy efficiency.
- Rail operators need to understand consumer preferences and offer a catalog of services that best suits those requirements depending on the customer profile and background. Dynamic pricing, new fare types, temporary

discounts, or multi-pass offers tailored to consumer behavior are among other operational approaches. On the other hand, passenger experience can be enhanced by the expansion of onboard services such as increased digital connectivity, luggage concierge, pet transportation, and food-ordering services.

3.4.2. Support the Transition through Financial Support and Alliances

- To pay off a rail project, high passenger or freight throughput is a must. High throughput is also key to ensure that rail transport comes with lower energy and carbon intensity per passenger- and ton-kilometer than other transport modes. Green bonds could be an excellent financial instrument that facilitates the capital and reduces the cost of financing the project by lowering interest rates.
- Governments have made public funding available to support rail through new or modernized infrastructure projects. For example, the European Union (EU) has defined various programs, and made funding available to support rail infrastructure projects, and countries have committed to projects that will improve and increase passenger rail services to relieve road traffic congestion, reduce emissions, and improve the sector's digital connectivity accordingly with the European Green Deal. However, effectiveness relies on the strategic decisions around where and how to invest and focus spending on projects that support their desired outcomes.[66] A McKinsey's article points out that the Next Generation EU facility and the Multiannual Financial Framework (MFF), which includes National Recovery and Resilience Plans (NRRPs) in the EU, can both facilitate around 86 billion EUR which could be used for rail projects between 2022 and 2028. Other countries have committed to rail funding at the national level, such as the Netherlands, which has committed approximately 2.5 billion EUR of its national growth fund to two important projects that will reinforce and expand key transit corridors to relieve congestion and increase rail capacity.[103]
- Other documents address market liberalization in order to improve economic competitiveness by increasing network utilization. Market liberalization gives new market entrants access to networks that in many cases have been previously controlled by a single operator. Possible benefits of this measure include the boost in general capacity, the ability to personalize customer services, the possibility of price discrimination, and cost optimization that could include digital and advanced analytics for planning.[104] This also helps to increase throughput and improve operational and energy efficiency, cutting costs and maximizing revenues. The EU has been in a long process for market liberalization in the rail sector to achieve a single European rail area, founded on ideals of minimizing competitive asymmetries and harmonizing national policies and regulations.
- Capitalizing land value benefits can also offset high capital investment costs. Land value capture has been a significant method of funding for various urban projects. The opportunity arises where the rail transport network developers purchase land at pre-railway prices and develop residential and commercial facilities, enabling them to capture the increase in property value induced by the railway operations. Governments could share in the risks and rewards by direct investment or through the taxation of higher value properties. The anticipated change in property value can mobilize debt financing. Positive experiences of land value capitalizations can be found in China and Japan.

3.4.3. Balance Carbon Taxation with the Need to Maintain Competitiveness

- Modal shift can be induced with different fiscal instruments. Policy makers must consider that making rail more viable is not only a matter of focusing on the specific sector, but also requires measures in possible alternative sectors. Fiscal policies such as congestion charges and emission taxes applied primarily to roadways and aviation sectors, and based on the use of the transport network and externalities, can directly increase the competitiveness of rail. For instance, internalizing the environmental and social externalities of aviation through a tax levied on aviation fuels would help level the playing field and make high-speed rail more cost-competitive for long-distance.
- A share of the revenues of some pricing policies such as road pricing, congestion charging, tolls, parking fees, fuel taxes, and others can also be earmarked for investment in high-capacity public transport infrastructure, while modal shift is encouraged by reducing the appeal of private vehicle use. Similarly, proceeds from transport taxation (e.g., registration and purchasing taxes) could be allocated to rail improvements and extensions. These models increase rail attractiveness increasing operational costs of private modes.

- Pricing policies could be coupled with access restrictions for individual vehicles in urban and crowded areas to boost public transport throughput. The shift could also be forced by immediate actions that change consumer behavior, like the establishment of prohibitions, as for example the recent French ban on short-haul domestic flights. The government decree states that any journey that is possible in less than two-and-a-half hours by train cannot be taken as a flight. The change is part of the country's 2021 Climate Law, and also reaches the use of private jets for short journeys. The new policy specifies the improvements that train services must take to meet the needs of passengers who would otherwise travel by air.[105]

3.5. Specific Recommendations for Accelerating Shipping Decarbonization

The largest contribution to shipping's emissions comes from freight operations, typically in a business-to-business environment. At a global level, the industry's environmental impact is regulated by the International Maritime Organization (IMO), a UN body that presides over the industry's environmental regulations through its Marine Environment Protection Committee (MEPC). The IMO is taking very important steps to hasten the transition. In 2011, the IMO adopted a set of rules (known as MEPC.202(62)) aiming to improve ships' sailing efficiency.[106] The rules created the concept of an Energy Efficiency Design Index (EEDI) and mandated progressive reductions of the index over the years. In 2016, the IMO introduced a mandatory data collection system for fuel oil consumption from ships (known as MEPC.278(70)). The IMO's efforts towards decarbonization were further strengthened in 2018, when the organization adopted the IMO's Initial GHG Strategy (MEPC.304(72)).[107] This established targets to reduce the carbon intensity per transport work by 40% in 2030, pursuing efforts to reduce carbon intensity by 70% by 2050 compared to 2008, and to reduce GHG emissions by at least 50% by 2050 compared to 2008. In July 2023, a revised strategy was adopted at MEPC 80. This further increases the industry's commitment by adopting zero net GHG emissions by 2050, with intermediate checkpoints mandating 5-10% uptake of zero or near-zero GHG emissions technology, fuels, and/or energy sources by 2030 (as opposed to, for example slow steaming); the targets are intermediate GHG emissions reduction of 20%-30% by 2030 and 70%-80% by 2040. The GHG emissions reduction targets shall consider well-to-wake emissions.

At a local level, other important initiatives are taken by the European Union (EU), with the inclusion of shipping in the EU Emission Trading Scheme (ETS) and in the "Fit for 55" package of regulations through the FuelEU Maritime, which imposes mandatory reduction on greenhouse gas emissions intensity already starting by 2025.[108]

Some elements of the new FuelEU maritime are very interesting and could be considered for application also in other regulatory systems. For example, FuelEU maritime allows "pooling" of ships compliance balance, meaning that a pool of several ships from the same fleet or different fleets can reduce the emissions intensity of their voyage by averaging the emissions intensity of the pool. In practical terms, a pool can reach compliance even if only one ship has actually sailed on low-carbon fuels. Since low-carbon fuels often require different engines and sometimes different ships or specific port infrastructures, the pooling mechanism is an excellent means to concentrate the decarbonization efforts on multiple ships and reduce the total costs of compliance.

Another interesting component of FuelEU maritime is the requirement that ports provide electricity to all ships at berth, thus avoiding the use of gensets at port. DNV and Ricardo executed a study for the IMO on readiness and availability of low- and zero-carbon ship technology and marine fuels. The report outlines various policy actions that may be beneficial to hasten the transition.[109] These range from support to development of new technologies (wind propulsion, on-board CCS), financial support to shipping operators (investments in newbuilds, risk of stranded assets, uptake of new technologies, higher cost for fuels), and investment in infrastructures (distribution and bunkering, safety, captured CCS).

The Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) studied early stages of the proposals for the FuelEU maritime and the EU ETS in details and flagged the risks: (a) Policies alone seem insufficient to achieve full decarbonization by 2050; (b) policies may be ineffective if penalties are not high enough; (c) failure to account for well-to-wake emissions of low carbon fuels may induce unintended consequences and support fossil fuels instead; and (d) focusing on the "carbon intensity" may be too reductive if other gasses with global warming potential may be emitted — shipping must include at least N_2O and CH_4 emissions.[110]

In particular, we want to flag the importance of methane emissions from vessels that transport or are operated with LNG or bioLNG, particularly considering that the use and transport of LNG to achieve short-term decarbonization targets is increasing. Evidence of significant emissions from these operations is massive. Technologies that reduce emissions to a minimum exist, but policies that enforce their use are insufficient.

In overall terms, we see also further challenges:

- Sea freight is an extremely energy efficient means of transportation and shipping's GHG emission intensity per ton and km transported is among the lowest (second only to rail). As long as there is no sufficient supply of low emissions fuels, it is important to avoid policies and subsidies that favor less energy efficient transportation means over shipping.
- Eligible alternative fuels must comply with minimum sustainability criteria. Those must limit the well-to-wake greenhouse gas emissions intensity applied on the specific value chain. This principle is not generally applied: the EU ETS accounts only for Tank-to-Wake emissions. The EU RED II, which, among others, specifies sustainability criteria, low-carbon fuels, and rules to calculate emissions, offers the possibility to use default values instead of true value chain values.
- The emissions of greenhouse gas and other chemicals associated with construction and decommissioning of assets seem to be consequently neglected. Policies supporting technology changes encourage construction activities and early retirement of assets. The impact of these activities on the overall emissions depends on the vessel utilization rate and on how construction and decommissioning are conducted. Chatzinikolau and Ventikos provide a summary of well performing activities.[111] Decommissioning is recognized as a potential source of pollution and health hazard and the resolution of the Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships, adopted by the IMO in 2009, is an attempt to regulate that.[112] However, the resolution is not yet in force.

Endnotes

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Appendix

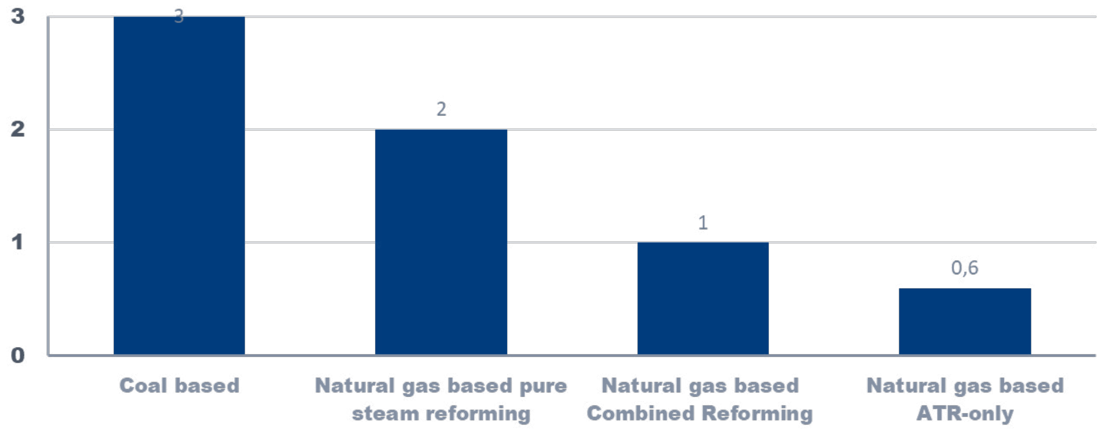
A.1 Hydrogen Derivatives Ammonia and Methanol Today

Ammonia, with a global production volume of over 185 million metric tons of ammonia per year, and methanol, with a global annual production of over 100 million metric tons of methanol, are basic products of industrial chemistry. Both are essentially produced on the basis of natural gas or coal. Main applications for ammonia and methanol are shown in Figure A. 1. Fuels produced via Fischer-Tropsch synthesis on the basis of natural gas or coal are niche products compared to production in petroleum refineries. Hydrogen is used primarily in the chemical industry, for example in the production of ammonia, nitrogen fertilizer, methanol, or in the cracking of hydrocarbons in petroleum refineries. Hydrogen is now very important as an intermediate product. CO2 is produced in synthesis gas production, among other ways, and also has its applications as a niche product. At the same time it is an important greenhouse gas in the earth’s atmosphere.

A.2 Low-carbon Methanol

Traditionally, methanol production has been based on natural gas or coal. Thanks to optimized technologies, economies of scale make plants with a capacity of 5,000 tons methanol/day and more relatively cost-effective. However, according to Figure A. 2, these plants have high greenhouse gas emissions.

FIGURE 24. 2: Plant with a capacity of 5.000 t methanol/day, CO_2 emissions of different technologies/feedstocks. Source: GasConTec (2023). Author’s Private Communication.



For example, a coal-based plant with a capacity of 5,000 tons of methanol/day emits about 3,000,000 tons of CO_2/year. Accordingly, methanol technologies for the production of methanol with a “low-carbon footprint” have been developed (e-methanol or “green” methanol), which are significantly more climate-friendly by not using fossil fuels. Other reasons for developing these technologies for the production of e-methanol were to move towards decentralized production and thus avoid transportation costs and import or CO_2 taxes.

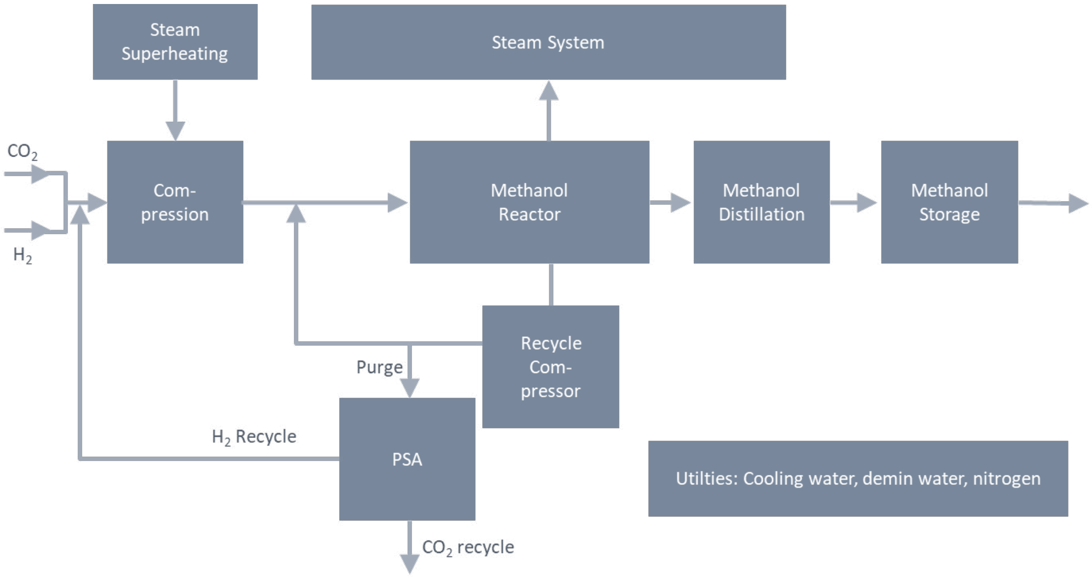
Today, one of the world’s most widely produced chemicals can be produced in an environmentally friendly way, and thus it serves as a low-carbon footprint feedstock for a wide range of industries and products. Methanol could be transformed from a CO_2-heavy pollutant to a carbon-neutral solution with the potential for an environmentally friendly future.

Case Study in Northern Europe

The investment cost for a plant with a capacity of 250 t e-methanol/day (or 85,000 t e-methanol/year) in Northern Europe is €250 million based on a “class 5” investment cost estimate (+/- 50%) according to AACE (American Association of Cost Engineers) rules. With an estimated owner’s cost of approximately 30%, the TIC (Total Installed Cost) amounts to €325 million.

Various auxiliary equipment is required to operate an e-methanol plant (see figure below). In addition to the auxiliary materials, cooling water and demineralized water, nitrogen, air, etc., a complex steam system is used for heat integration and the generation of electrical energy (e.g., for the compression of the hydrogen and CO_2 required for the methanol synthesis). In the following calculations, it is assumed in a rough approximation that the associated energy costs roughly balance each other out.

FIGURE 25. 3: Block flow diagram of the synthesis of an e-methanol plant. Source: Figure created by the authors for this report.



For the production of e-methanol from renewable hydrogen and CO_2, 2,100 Nm^3 of hydrogen and 700 Nm^3 of CO_2 are required per ton of e-methanol at 100% conversion. If, in the best case, 4.5 MWh are required per 1,000 Nm^3 of hydrogen, 9.4 MWh are required to produce 1 ton of e-methanol. Based on this, a 100 MW water electrolysis can produce 10.6 t e-methanol/h or 85,000 t e-methanol per year. 10.6 t e-methanol/h requires 14.6 t CO_2.

For the following determination of the production costs of e-methanol, it is assumed in the Northern Europe case study that cheap renewable electricity from hydropower plants is available for the operation of the water electrolysis, i.e., the plant can be operated continuously overall (and not fluctuating as in the case of the use of wind or solar energy).

TABLE 11: Overview of methanol production costs. Figure created by the authors for the paper.

Energy cost per ton of e-methanol (30 €/MWh x 9)	282 €/t of methanol
Cost per ton of CO_2 :.4 MWh): 40 €/t	55 €/t methanol
Financing costs (TIC = 320 million €, 30% equity, 70% loan with 5% interest, 10 years repayment):	132 €/t methanol
Total operating costs:	50 €/t methanol
Total production costs:	519 €/t methanol

In summary, the case study for Northern Europe proves that e-methanol is already a suitable energy storage and carrier medium for renewable energy producers under the aforementioned boundary conditions. For comparison, IRENA estimates the production costs of e-methanol at 400-700 USD/t.

Note: The calculations are based on the status in 2021. Investors, operators, and plant manufacturers are currently confronted with extreme uncertainty regarding the availability of materials and equipment, and also regarding business and contractual conditions, which generally make investments uncertain or even uneconomical. In the medium to long term, it is assumed that a scenario comparable to the situation in 2021 will arise.

A.3 Low-carbon Fuels from Biomass

For the production of low-carbon fuels based on the gasification of biomass and Fischer-Tropsch synthesis, approximately 9 kilograms of biomass (dry) are required per kilogram of low-carbon fuel. A corresponding biorefinery for the production of 245 tons of low-carbon fuels per day thus requires about 2,200 tons of biomass per day (about 70 truckloads per day). Roughly estimated, this biorefinery costs 0.8 - 1.3 billion euros. Thus, the production costs are in the range of 0.8-1.5 € per liter of low-carbon fuel. It should be emphasized that this technology also enables the production of biokerosene/SAF in large quantities — which explains the high level of interest from airlines, among others.

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