DNV

WHEN TRUST MATTERS

Energy Transition Outlook 2023

TRANSPORT IN TRANSITION

A deep dive into fuels, electricity, and infrastructure

FOREWORD

Our global transport system is already responsible for a quarter of global greenhouse gas (GHG) emissions. In the next three decades, the global vehicle fleet will grow from 1.2 billion to 2 billion vehicles, passenger flights will increase by 130%, and cargo tonne-miles at sea will expand by 35%. Can we accommodate that growth while reducing emissions? The short answer is that much of transportation will decarbonize, and emissions *will* reduce by some 40% by mid-century. But by then the relative contribution of transport to global emissions will have risen to one third, implying that the sector needs to tackle decarbonization with a much greater sense of urgency.

This fuel-centric forecast sets out our best estimates on the availability, costs, policy drivers, and likely uptake of decarbonization options. At the same time, we measure and forecast the decline of fossil fuel sources. We find, for example, that oil demand in transport will halve between now and 2050.

Decarbonizing transport is ultimately a fuel challenge. Transport emissions are distributed through the exhaust systems of over a billion vehicles, aircraft, and ships. These emissions cannot be captured to any meaningful degree and, in addition to CO_2, they invariably include other powerful GHGs and health-damaging particulate matter.

Electricity will, without doubt, be the main decarbonization route for transport – powering nearly 80% of the world's vehicle fleet by 2050. Recent advances in battery densities and electric motor technology suggest that electricity will make inroads into subsectors previously thought to be hard-to-electrify – like long-haul heavy trucking, and to some extent short-haul aviation.

There remain, however, very large transport subsectors that cannot feasibly electrify. Aviation is under enormous public and regulatory pressure to decarbonize. Biogenic sustainable aviation fuel will need to be produced in vast quantities but must be sourced sustainably. Hence, it will remain very costly, at least for the next 10 years, as will e-fuels that are energy-intensive to produce and rely on the widespread availability of green hydrogen that will only scale from the mid-2030s. These higher costs will need to be absorbed into the industry's value chains and socialized through higher tariffs and taxes.

First mover advantages are already apparent for airlines and transport companies working with those customers willing to pay a premium to reduce their scope 3 emissions. Ultimately, however, the decarbonization at scale will require an unprecedented public-private partnership across national borders and multilateral agreement on new standards. Movement in this direction is already taking root, for example, through the World Economic Forum's Clean Skies for Tomorrow initiative.

Similar, joined-up thinking and transnational public-private commitment is needed for the decarbonization of the maritime industry, where large-scale implementation of energy efficiency measures are needed and huge amounts of carbon-neutral fuels, like biofuels and hydrogen-based fuels.

In this decarbonization journey, collaboration will be the new fuel.

The many plans and pacts that are forming around green shipping corridors need to be actuated and scaled. Governments will need to formulate and implement plans to make their ports as attractive as possible to decarbonized shipping, while removing incentives for fossil-fuelled shipping by placing a sufficiently high price on emissions.

Key to this transition is a sense of perspective. By this I mean a science-based view on techno-economics of each fuel source. That includes a clear-eyed view on the well-to-wake efficiency of fuels and their accompanying emissions, as well as close attention to demand and supply dynamics. For example, in an ideal world, e-fuels might be the most convenient drop-in source. However, as we detail in this report, surplus renewable power and electrolyser capacity will not be available at scale for well over a decade; even then, large energy losses in the manufacture of e-fuels will have to be considered.

I hope that this report, grounded as it is in DNV's *Energy Transition Outlook* model, helps our customers and their stakeholders establish that sense of perspective and collaborate even more meaningfully to tackle the transition to a decarbonized transport future. Too much is at stake to allow for either hesitation or wishful thinking.

As ever, I look forward to your feedback.

Remi Eriksen

Group President and CEO

DNV

HIGHLIGHTS

- Transport has a severe **emissions** challenge. Its share of overall emissions grows from 25% of today to 30% by 2050.
- The central difficulty for transport is that much of it will remain **fossil fuel-dependent,** even though electricity will revolutionize the road transport (78% of which will be electric by 2050).
- **Transport services** will grow significantly in the next 30 years (roughly double the number of road vehicles, 130% growth in airline passenger trips, and a 35% growth in cargo tonne-miles in shipping), but overall energy demand from transport grows only slightly from 105 EJ/yr in 2020 to 114 EJ/yr in 2050 mainly because of the **efficiencies associated with the electrification** of road transport.
- Forward-thinking national transport **policies** are critical to country-level and regional competitiveness in a decarbonizing and increasingly connected world.
- The **route to decarbonization is clear:** electrify what can be electrified; what cannot be electrified in the near term should be switched to sustainable advanced biofuels; and prepare for hydrogen-based new fuels to scale through local and regional ecosystems to a global ecosystem from 2035.
- What electrifies will be **cheaper,** but hydrogen and sustainable biofuels cannot compete cost-wise with oil and thus need different policy levers to scale.

Fossil Fuels

Oil demand halves by 2050, but fossil fuels have staying power in aviation and maritime, and in road transport in regions with insufficient electric infrastructure

- Reduction of oil is strongest in road transport – from 85 EJ today to 42 EJ in 2050, reducing its share from 91% to 57%
- Aviation oil use is virtually flat to 2050; growth in air transport is covered by biofuels and e-fuels
- Oil benefits from high energy density and an established infrastructure, and only electricity outperforms fossil fuels on costs, owing to its superior efficiency

Electricity

Electricity will revolutionize road transport and is also gaining share in subsectors previously thought to be hard-to-electrify, like heavy trucking and short-haul aviation

- Electricity's share in transport will grow from 1% today to 4% in 2030 and will be 23% in 2050
- In 2050, electricity meets one third of energy demand in road transport, but powers nearly 80% of the global vehicle fleet
- Electricity powers just 2% of aviation and 4% of maritime transport by 2050

Biofuels

Biofuel is a ready-now drop-in fuel, but the challenge is to make it sustainable

- There is already intense competition for sustainable feedstock for advanced biofuels for **aviation and shipping**
- First-generation biofuel will be displaced by electricity in road transport
- Regulation and consumer-driven demand will push advanced biofuel development (i.e. from waste streams) and uptake. By 2050, it could cover a quarter of aviation energy demand and possibly a fifth of maritime energy demand

Hydrogen+

Hydrogen and e-fuels are **energy intensive** to produce and will scale in maritime and aviation only from the mid-2030s

- Renewable energy should be prioritized for direct use of electricity in the near term until sufficient surplus is available for hydrogen production at scale
- Use of e-fuel in aviation will start this decade, growing to a 13% share of the aviation fuel mix in 2050
- In maritime, where decarbonization alternatives for long-distance shipping are limited, hydrogen-based fuels (such as ammonia and methanol) could represent 50% of the fuel mix by 2050
- Hydrogen will be important for the heaviest long-distance road segments, but even there is already being challenged by electricity

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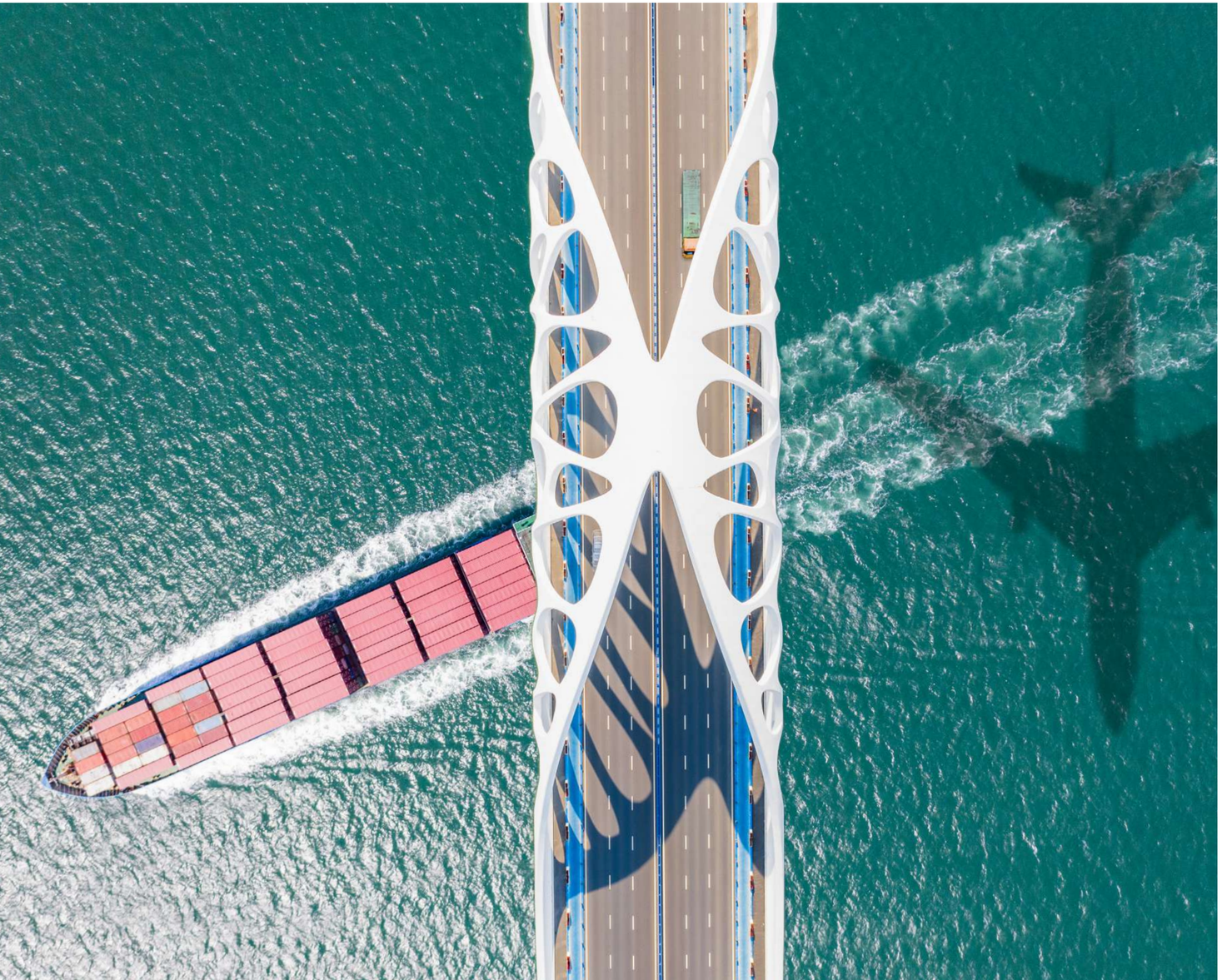


1 TRANSPORT IN TRANSITION A DEEP DIVE INTO FUELS, ELECTRICITY, AND INFRASTRUCTURE

Setting the scene

The transition in transport energy demand is by far the most dynamic among the energy demand sectors. DNV has quantified this consistently in our annual *Energy Transition Outlook*. This year, with this report, we take a deeper dive into the very large shifts in electrification, infrastructure, and fuel use that are set to take place in transport over the next three decades. Broadly speaking, we find that electrification of transport leads to a dramatic fall in operating costs which will increasingly offset associated capital spending. In contrast, those transport subsectors reliant on synthetic electrofuels (e-fuels) and biofuels or hydrogen for decarbonization face higher operating and capital costs that need to be absorbed into wider value chains and incentivized by wise policy choices.

Why we need to look at transport – now

Global GDP will more than double by 2050, with much of that value creation facilitated by growing volumes and increased efficiencies in the transportation of freight and people. The correlation between GDP growth and more and better transport is well-established (Gao et al., 2016; Choi, J.-H., 2023). The higher the level of economic activity, the greater the need for efficient transport. The contribution of transport to economic development is obvious: it creates jobs, promotes access to healthcare and education, and acts as an important source of government revenue. Less well-known is the fact that as transport decarbonizes in an era of rapid digitalization, it will become much more efficient as an economic factor of production of goods and services. As we detail in this report, while transport services will grow significantly in the next 30 years, overall energy demand in the transport sector will only expand from 105 EJ/yr in 2020 to 114 EJ/yr in 2050. Along the way, transport emissions will fall substantially, but will be far off course for net-zero by 2050.

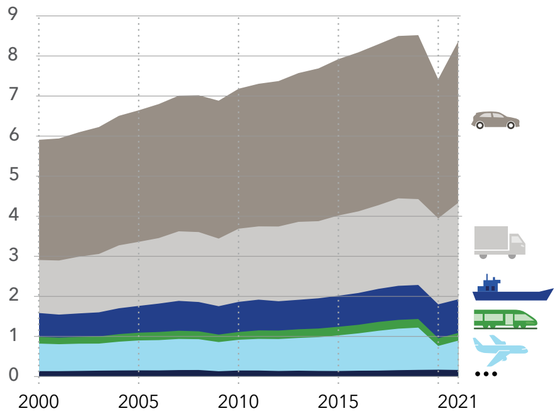
While transport services will grow significantly in the next 30 years, overall energy demand will only grow marginally. Transport emissions will fall but will be far off course for net-zero by 2050.

Hitherto, gains in energy efficiency have largely been neutralized by an expanding vehicle fleet, a steady growth in passenger flights, and an increase in the transport of freight on keel. Consequently, transport sector emissions have risen inexorably for many decades, with the singular exception of the years when COVID-19 held the world in its grip. During the pandemic, transport emissions fell by 14%, and aviation emissions more than halved. Emissions have now rebounded to pre-pandemic levels, except in aviation, which is still lagging somewhat (Figure 1.1).

FIGURE 1.1

Global transport sector CO_2 emissions in the last two decades

Units: Gt/yr



Dots represent category "others" such as emissions from pipeline transport.

With exception of the passenger vehicle segment, the transport sector is hard to electrify. Despite significant uptake of EVs in China, Europe, and North America, synthetic e- and biofuel blending mandates for road transport and aviation, and International Maritime Organization (IMO) ambitions for low- and zero-carbon fuels in shipping, the transport sector will decarbonize far too slowly – only reducing CO_2 emissions by 39% by mid-century.

Today, transport of passengers and goods accounts for about a fourth of global energy-related CO_2 emissions, and 37% of global CO_2 emissions from all end-use sectors. It is the sector with the highest dependence on fossil fuels, with more than 90% of energy stemming from crude oil.

Harmful emissions in vulnerable places

Beyond its large greenhouse gas (GHG) footprint, the transport of passengers and freight is also responsible for a considerable share of microplastics and fine particulate matter ($PM_{2.5+10}$) emissions, a leading and escalating cause of respiratory and cardiovascular illness and deaths globally (SLOCAT, 2021). A recent study estimates the transport sector's share of global $PM_{2.5}$ emissions to be around 11%, stemming from tailpipe emissions, evaporative emissions, resuspension of road dust, and particles from brakes and tyres (ICCT, 2019). $PM_{2.5}$ emissions are typically located in densely populated areas amplifying their hazardous impact. In Indian cities, for example, dramatic air quality improvements were recorded during COVID-19 lockdowns (Yadav et al., 2022).

Aircraft burning fossil fuel at high altitudes produce nitrogen oxide emissions, vapour trails, and cloud formations which have twice as much global warming contribution as their direct CO_2 emissions (EASA, 2020). Direct CO_2 emissions, sulfur oxides, $PM_{2.5}$ and nitrogen oxides from maritime shipping contribute to ocean acidification and eutrophication in sensitive ocean environments. Owing to its heavy reliance on fossil fuel, transport remains a highly problematic contributor to air pollution where it matters most, despite past and ongoing regulatory curbs.

Distributed and hard-to-decarbonize emission sources

Transportation is unique in having distributed GHG emissions. A single point source such as a steel plant can be equipped with carbon capture and storage (CCS) to reduce the emissions at the point of origin. Decarbonizing the transport sector is more challenging, if not impossible, in this regard. Although there are onboard CCS pilots for ships, it is not expected to be feasible to extend this to the entire maritime fleet. That said, it could be an important supplement to achieving GHG emissions reduction if there is a lack of other carbon-neutral fuels. CCS certainly does not apply to aircraft let alone the more than one billion vehicles on the road. A single solution for the decarbonization of transport can only be realized with liquid sustainable carbon fuels from biomass, renewable electricity, and sustainable CO_2 and water. However, feedstock availability and low value chain efficiencies significantly constrain their use. Thus, a variety of solutions are needed to tackle this huge challenge, such as battery electric vehicles, fuel cell electric vehicles, and synthetic low – or zero-carbon fuels that are bio- or hydrogen-based.

> Policy has to be sensitive to what technology can and cannot achieve.

Frontrunners in the race to decarbonize transport

Regions such as Europe, Greater China, North America, and OECD Pacific are frontrunners in the uptake of zero-carbon vehicles. In parallel, those regions are investing in hydrogen and hydrogen-based fuels as the most promising option for moving heavy goods over long distances. At the other end of the spectrum, regions like Sub Saharan Africa and North East Eurasia are very far away from producing the quantities of renewable electricity and the infrastructure required to decarbonize road transport. In the long run, however, a comprehensive transition of the transport sector must be inter-regional. The decarbonization of maritime and aviation requires corridors supplying non-fossil fuels reliably in the form of bio- and hydrogen-based sustainable aviation fuels, or biofuel blends, ammonia, or other e-fuels for maritime. The scale and timing of such corridors emerging, and the global adoption and rollout of optimal grid infrastructure for EV charging, depend largely on the rate at which frontrunner regions develop, pilot, and scale technologies, and hence manage down costs.

The policy and technology limits challenge

Policies and regulations both push and pull in varying degrees for a cost effective, safe, affordable, and accelerated transition. There are four ways for policymakers to transition the transport sectors, three on the supply side and one on the demand-side to ensure uptake:

Supply – infrastructure and fuels or electricity

1) Support electrification by strengthening the existing (grids) and new infrastructure for charging
2) Enable existing infrastructure with drop-in fuels, with low- or zero-carbon intensity, produced from scarce sustainable feedstocks (e.g. e-kerosene)
3) Facilitate new or repurposed infrastructure for new fuels (i.e. ammonia, e-methanol, and hydrogen)

All three of these strategies require a fourth corresponding action to create investment certainty for market deployment of new technologies and fuels:

Offtake – transport technologies and fuels

4) Stimulate the uptake of new or adapted drivetrain and propulsion technologies for vehicles, planes, and ships using new fuels, electric and hybrid modes. Accompany with policies stimulating or mandating the phase out of fossil-dependent transport through carbon pricing, tax disincentives, and bans.

When policy meets technology

Policy has to be sensitive to what technology can and cannot achieve. For example, EVs and associated infrastructure are now well established in some markets. However, driving adoption still requires incentives and attention should be paid to making charging infrastructure as future ready as possible – for example incentivizing home chargers that allow for bi-directional charging for eventual integration into vehicle-to-grid (V2G) systems, as well as connectivity to allow utilities to micro-manage smart charging. On the other hand, electrification has its limits and can power some heavy, long-distance trucking but not long-haul aviation and deep-sea shipping. There, policymakers need to work with industry to incentivize R&D, pilot projects, and commercial uptake, as well as commit to large public-private partnerships to deliver both zero-carbon fuel and associated infrastructure – for example green shipping corridors reliant on ammonia. One major challenge for hybrid, batteries, and new fuels, is the physical limits of these technologies regarding energy content per unit weight and volume which directly impact range and cargo options. Hence there is an intricate interrelationship between what policy can enable and technology options for short, medium, and long range transport.

Figure 1.2 illustrates that there must be different policy and technology solutions for different types of transport. It needs acknowledging that certain combinations of infrastructure, fuels and means of transport can only decarbonize parts of the short-, medium-, or long-range sub-segments within road, shipping, and aviation. As policymakers work in parallel to advance existing and emerging best available technologies, some long-term solutions may have to be prioritized for long-range and heavy-duty transport, since there are no other options in the short term to reach climate targets.

Action is needed now

The present pace of transition in the transport sector falls severely short of the goals of the Paris Agreement, and consequently all opportunities to accelerate change need to be seized as soon as possible. Electrification, the lowest-hanging fruit for the road transport sector, as a 'ready now' and least-cost option, is heading in the right direction, but with a regulatory framework that is far from ambitious enough. In parallel, intensive collaboration between all stakeholders is needed now in the hard-to-electrify transport subsectors to ensure that alternative low- and zero-carbon fuels needed in aviation and maritime will indeed be 'ready later'.

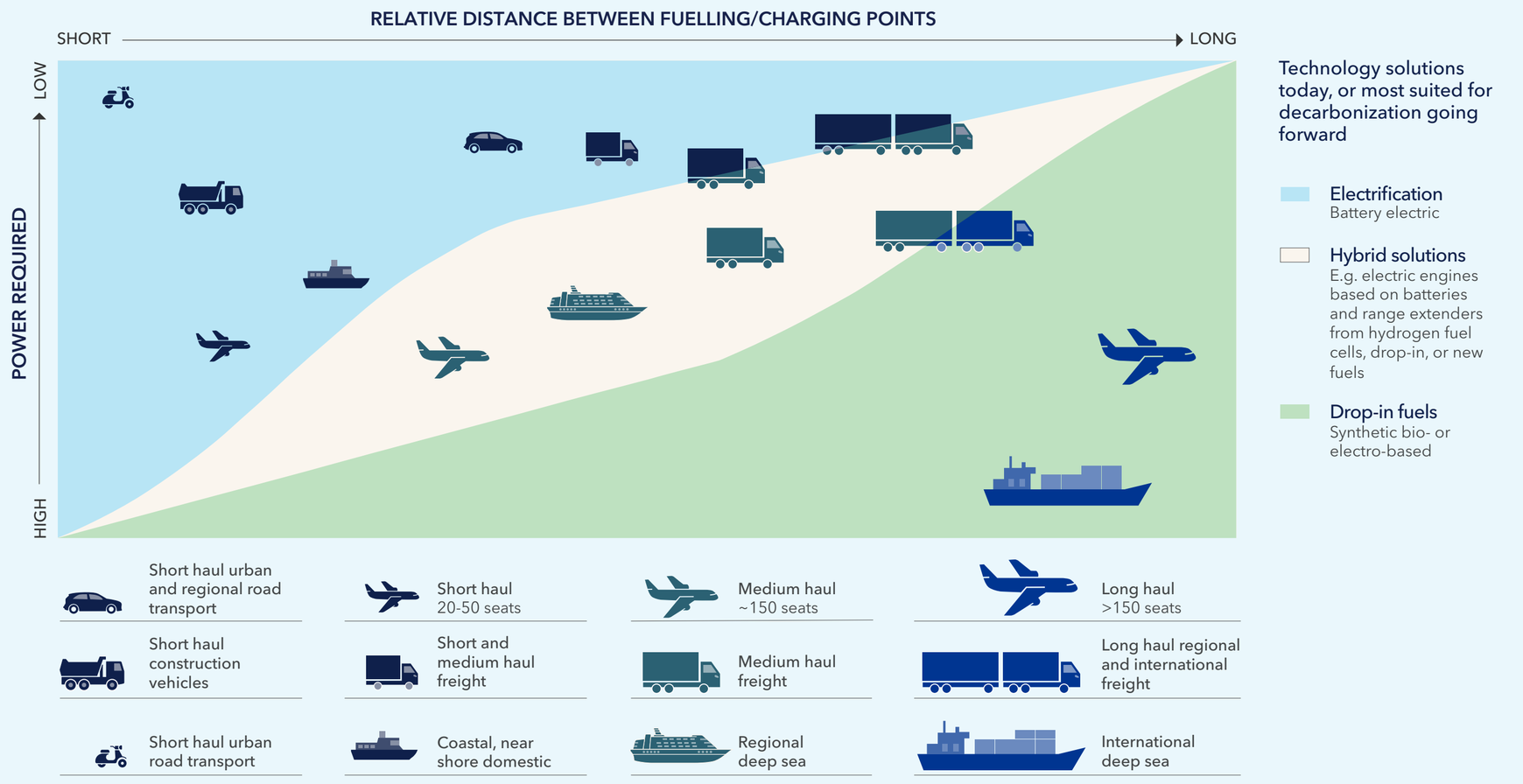
Any net-zero pathway demands that we should electrify everything that we feasibly can, and as quickly as possible. Where electrification is not a reasonable option then hydrogen-based fuels or biofuels are the best alternatives, and all attention should be devoted to accelerating the critical path to widespread availability.

About this report

This report draws on DNV's detailed, system-dynamics model of the global energy transition to 2050. It presents a deeper view than we have hitherto offered on the transport sector's transition to 2050, with a strong focus on the next decade regarding technological and infrastructure challenges and solutions. The policy landscape shaping the transition in road transport, maritime and aviation is laid out in detail and connected to ongoing and near-term developments. We have adopted a 'fuel-based' perspective, highlighting the synergies and interactions between the energy sources powering transport, rather than simply comparing and contrasting the transitions unfolding in the different transport sectors.

FIGURE 1.2

Electric, hybrid and alternative fuel solutions towards 2050



The easiest vehicles to electrify are those with shorter ranges and predictable routes, like buses, delivery vans, and small trucks. These vehicles typically have predictable routes, making it easier to plan and install charging infrastructure along their routes. Moreover, they can easily meet their energy demands with the current state of battery technology, while reducing their operating costs and carbon footprint.

Similarly, motorcycles and passenger vehicles fall in the easy-to-electrify category. While their shorter ranges and predictable routes make them viable candidates for electrification, the higher upfront cost of electric cars is a significant barrier to widespread adoption. However, as battery technology improves, and charging infrastructure expands, these vehicles will become increasingly viable options for electrification.

Heavy-duty trucks, ships, and planes require large amounts of energy to cover long distances, making electrification difficult with current battery technology. The higher upfront cost and low energy density of batteries are the main barriers to electrification in these transport segments. Ongoing research is exploring alternative technologies, such as new battery chemistries and fuel cells, to meet their energy needs.

While electrification of transportation is a crucial step towards a more sustainable future, it is essential to recognize that not all vehicles and sectors are equally easy to electrify. Therefore, a multifaceted approach that combines research, policy, and innovation should advance the technology and commercial readiness of feasible transition alternatives tailored to each transport segment.

The roundabout of wishful thinking

The global energy transition is too urgent and too important to accommodate wishful thinking.

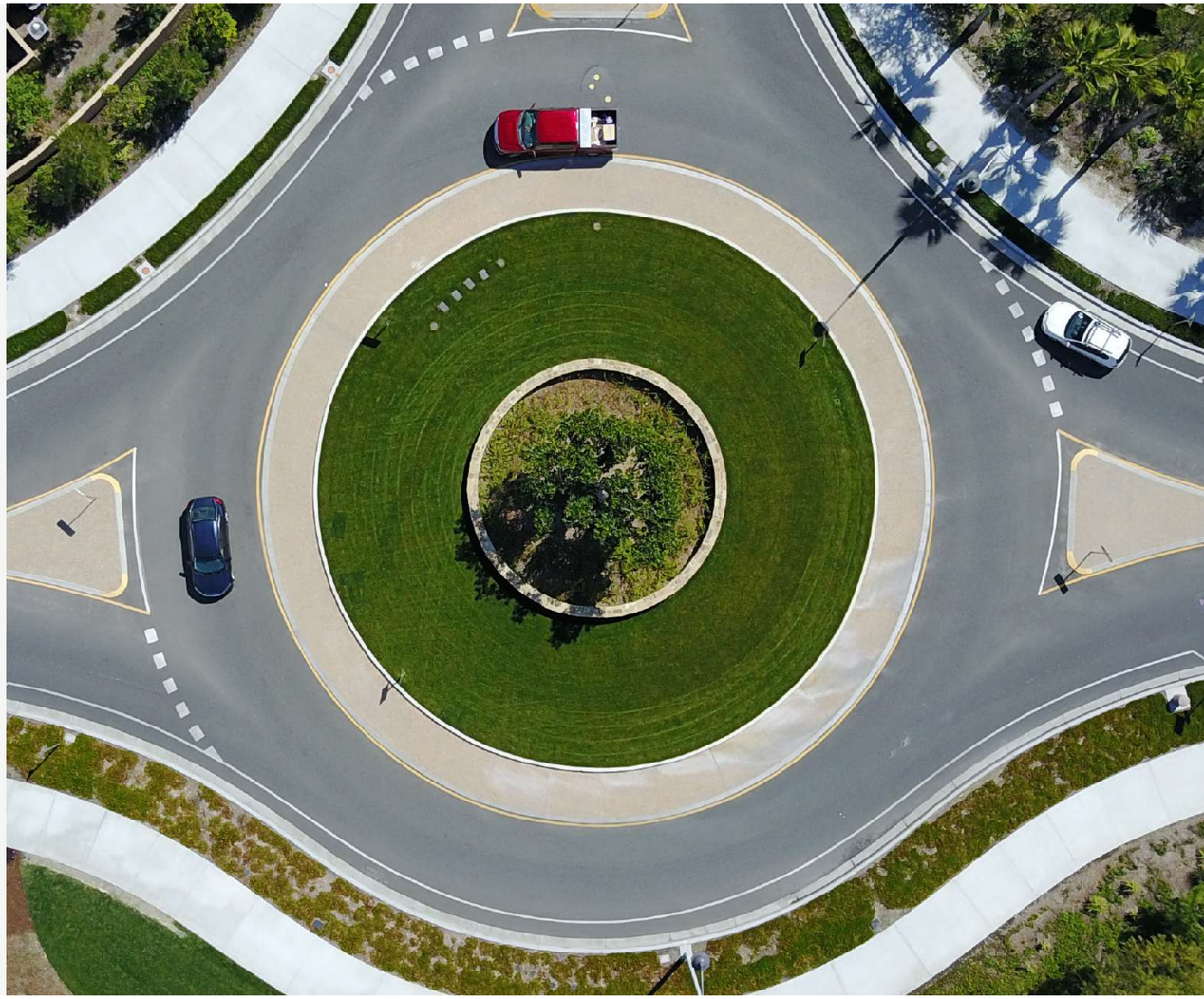
Wishful thinking is a common cognitive bias that affects people in all walks of life. It occurs when people believe in something simply because they want it to be true, rather than based on objective evidence. This can sometimes provide temporary comfort or optimism, but it can also be dangerous and lead to poor decision making.

As we will outline throughout this report, the transport sector needs a comprehensive transition to help achieving international climate goals. The tradeoffs, compromises and sheer costs involved in the transition demand the best possible grasp and scientific understanding of objective data and evidence.

Unfortunately, social media, professional network platforms, and public discussions are frequently marred by the wishful thinking of participants advocating transport solutions based on poor comparisons and often advancing one 'favoured' solution. For example, it may be true that, in an ideal world, a synthetic drop-in fuel may be the perfect fuel. But the world is far from ideal, the infrastructure needed to produce the green hydrogen needed for e-fuels is very far from scaling, and the energy losses in the value chain simply add up to prohibitive costs for all but very niche applications for many years to come.

Established research and adherence to quality standards, including data quality standards, are crucial to avoiding incorrect comparisons and for drawing valid conclusions.

Because road transport touches consumers lives more directly than aviation or maritime, and because the road transport is the most advanced in terms of viable decarbonization options, it is also in the road sector where myth-making is most advanced and egregious. Here, we set out a short guide on how to exit the roundabout of wishful thinking safely.



USE THE SAME PHYSICAL BASIS FOR COMPARISON

Using the same basis for a comparison is important to ensure that the comparison is fair, valid, and meaningful. If different bases are used, the comparison may not accurately reflect the true differences or similarities between the items being compared, leading to inaccurate or misleading conclusions.

Example:
To compare value chain efficiencies of battery electric vehicles, fuel-cell electric vehicles, and combustion vehicles using e-fuels, we used 100% renewable electricity for all of them.

USE THE SAME BASE YEAR FOR COMPARISON

Mixing time frames when making comparisons fails to account for the changes or trends over time. By using the same base year or time frame, researchers can accurately track and measure changes over time, allowing for fair and valid comparisons.

Example:
Current electricity grid mix should not be compared with imported green hydrogen available in the 2030s.

USE REASONABLE AND INDUSTRY-BACKED CONVERSION AND EFFICIENCY ASSUMPTIONS

Industry-backed conversion and efficiency assumptions are more reliable than values derived from lab studies because they consider real-world operating conditions and variations in equipment and systems. Lab studies can provide controlled environments and ideal conditions, which can result in overly optimistic results. Industry-backed assumptions provide a more realistic and accurate representation of actual system performance, leading to better decision-making and more efficient operations.

Example:
While Alkaline Electrolysis has an efficiency up to about 70-75%, Polymer Electrolyte Membrane (PEM) efficiency is usually slightly lower at about 60-65%. Recent lab- and prototype-based research finds efficiencies close to 100%. However, it will take decades until such values represent market average, and thus should not be used for value chain comparisons.

2 POLICY TO TRANSITION TRANSPORT

This chapter covers the policies required for the energy transition of transport and summarizes policy developments associated with the three transport subsectors covered in this report: road, aviation and maritime.

2.1 POLICY PRIORITIES

The transport sector relies heavily on fossil fuels. Policymaker interventions are to a large degree motivated by local air pollution and global climate change concerns as transport emissions continue to rise.

Based on our analysis and forecast, a clear and logical sequence of policy priorities emerges for policymakers:

- **Any form of transport** that can feasibly be electrified should be electrified. Of all the means of propulsion, electricity offers the highest benefits in terms of efficiency and emissions, including non-CO_2 pollutants.

- **Where electricity is constrained** – either by a lag in sufficient (renewable) generation capacity or through grid constraints, or due to the power and weight constraints of batteries – drop-in fuels should be promoted. The important caveat is that policies should encourage a switch to synthetic drop-in fuels, either biobased, e-fuels (RFNBOs) or other sustainable low-carbon drop-in alternatives. For biofuels, second- and third-generation has to be used, for reasons of sustainability and overall carbon accounting, as explained in Chapter 3.

- **In the longer term,** hydrogen and its derivatives, including ammonia and synthetic fuels such as Renewable Fuels of Non-biological Origin RFNBOs (e-fuels), recycled carbon fuels and more loosely defined "low-carbon" fuels should be made available for the hard-to-electrify sectors. While there are large energy losses in making green hydrogen and its derivatives, there are many advantages to these new fuels. However, policymakers should be aware that, owing to infrastructure constraints, these fuels will not be available at any meaningful scale until the late 2030s, as explained in Chapter 3.

Because policymaking generally proceeds in the interests of the greater public good, the sequence outlined here is the broad direction of the energy transition of transport. However, in the real world, an already-complex field of policymaking is further complicated by budgetary constraints and compromises as well as lobbying and special pleading on the part of fossil fuel, first-generation biofuel, and internal combustion engine incumbents.

First generation crop-based biofuels are increasingly being called into question due to their impact on biodiversity and from an overall carbon accounting perspective. There will likely be a shift to bio-waste based and algal biofuels in the medium term which will eventually be supplemented by synthetic e-fuels as a drop-in fuel option.

2.2 THE REGULATORY LANDSCAPE

Alternatives to decarbonize transport are presently at very different levels of maturity. Road transport has come the furthest in terms of the competitiveness of direct electrification options, and high-income countries have taken the lead in policymaking to transition their domestic road transport sectors. International aviation and maritime are much more complicated to decarbonize. Not only do they rely on non-electric forms of decarbonization and related infrastructure that are generally far from mature, but policymaking for these global sectors involves multilateral and supranational co-operation. Public-private partnerships and United Nations specialized agency organizations (IMO, ICAO) are the main catalysts of change in the transition of global transport.

Ways of transitioning transport sectors

For policymakers, there are four broad ways of transitioning the transport subsectors, three on the supply side (Table 2.1) and one on the demand side to ensure offtake:

Supply – infrastructure and fuels or electricity

1) Support electrification by strengthening the existing (grids) and new infrastructures for charging
2) Enable existing infrastructure with drop-in fuels, with low- or zero-carbon intensity, produced from scarce sustainable feedstocks (e.g. e-kerosene)
3) Facilitate new or repurposed infrastructure for new fuels (i.e. ammonia, e-methanol, and hydrogen)

All three of these supply-side options require a fourth corresponding action to create investment certainty for market deployment of new technologies and fuels:

Offtake – transport technologies and fuels

4) Stimulate the uptake of new or adapted drivetrain and propulsion technologies for vehicles, planes, and ships using new fuels, electric, and hybrid modes

Technical challenges and what is possible in the medium/long term

As Table 2.2 indicates, while renewable sources for electricity production are practically limitless, availability is constrained in terms of production and infrastructure. The application of electricity becomes more difficult and indeed impossible as vehicles or vessels become heavier and transport distances lengthen. In contrast, biobased drop-in fuels (e.g. 'green' gasoline) that are within the fuel specifications as their fossil-based counterparts, are not subject to weight/distance constraints. However, the availability of such fuel is severely limited by the lack of sustainable feedstock and, to some extent, by refinery capacity.

TABLE 2.1

Explanation of supply-side alternatives

	Transition alternative	Description
1	**Electrification and partially hybrid solutions** Examples: battery electric vehicles, aircraft, ships	**Battery electric** means of transport rely on new chassis designs and technology development for drivetrains and batteries with fast-charging solutions and on the strengthening of existing infrastructure such as power grids and components (e.g. directly, new cables, higher voltage, new transformer stations; or indirectly, distributed battery energy storage). Hybrid means of transport, electric engines and batteries, can partly charge by plug, and use drop-in fuels or hydrogen in fuel cells for electricity production for range extension. Relies on charging and new refuelling infrastructure for H_2 and new fuels or reusing existing infrastructure with drop-in qualities.
2	**Drop-in fuels** Examples: bio-based or non-biological such as RFNBOs (e-fuels), RCFs and low carbon alternatives, e.g. bio- or renewable diesel, biomethane upgraded from biogas, sustainable aviation fuels (Jet A-1 bio-kerosene)	**Production** relies mainly on new processing plants, but some co-processing. The distribution and supply rely on existing infrastructure and legacy equipment. Some biobased or hydrogen-based fuels with drop-in qualities can be blended up to 100%, but others are limited to lower ratios, depending on the standards and fuel specifications needed. Some fuels are blended at the last steps of the value chain, so parallel infrastructure is needed even though they are considered drop-in.
3	**New fuels, infrastructure, and value chains** Examples: hydrogen (H_2), ammonia (NH_3), e-methanol, multifuel hybrids	**New fuels** rely on new value chains from production to distribution, offtake in vehicles/ships/planes, and new supply chains from production to storage and refuelling. Involves new or modified fuel and drivetrain/engine technologies for end use, like combustion of new and non-drop-in fuels or electric conversion from hydrogen, ammonia, and batteries.

So-called new fuels are beset by constraints. These include temporal, feedstock, and production constraints (principally, the lack of green hydrogen) and permanent constraints in the form of the physical limits of some of these fuels (principally, H_2 and ammonia) related to energy content per unit of weight and volume.

Decarbonizing hard-to-electrify transport will need to proceed on a hybrid basis. Policymakers promoting biofuels prior to new fuels scaling sufficiently need to be fully aware of feedstock constraints, the high likelihood of sectoral competition for sustainable biofuel, and the fact that biofuel does not solve non-CO_2 emission challenges such as local particulate matter pollution ($PM_{2.5}$ and PM_{10}) causing respiratory diseases, and nitrogen oxides which contribute to smog and acid rain which affects the local ecosystems and human health.

A policy toolbox to promote the transition

Figure 2.1 presents a policy toolbox and its high-level categories. Policies and regulatory frameworks both push (foster technology development, fuels production) and pull (stimulate demand, deployment) to varying degrees to achieve a

TABLE 2.2

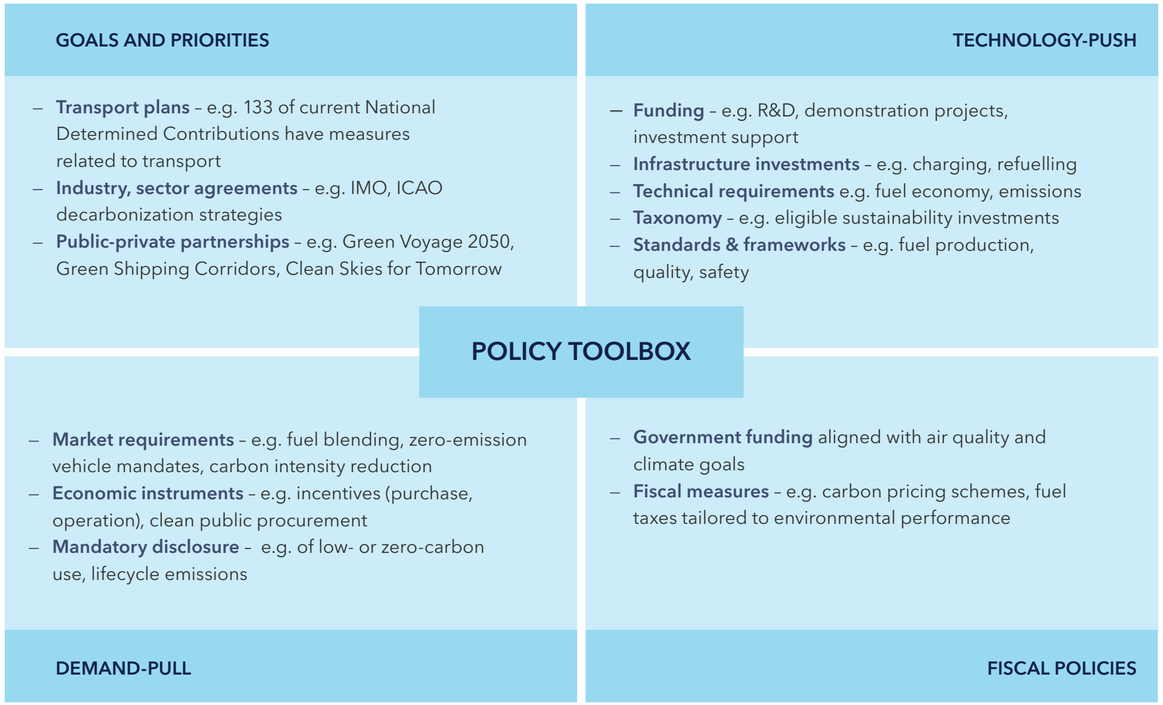
Technical challenges for policymakers

Value chain			Technology maturity and challenges		
Supply and demand	**Value chain steps**		**Electrification**	**Drop-in sustainable fuels reusing existing infrastructure**	**New fuel & new or retrofit infrastructure**
Supply infrastructure and fuel	Feedstock (sources)				
	Production				
	Logistics/Refuelling/Charging				
Demand vehicle/ship/plane	Road	Passenger vehicles			
		Commercial (light)			
		Commercial (heavy)			
	Maritime	Coastal/near-shore domestic			
		Regional short-sea			
		Deep-sea			
	Aviation	Short haul			
		Medium haul			
		Long haul			

Existing technology or infrastructure · Medium challenge · High challenge · Substantial challenge · "Impossible" (no known tech.)

FIGURE 2.1

A policy toolbox to transition transport



cost-effective, safe, affordable, and accelerated transition. The complexity of decision-making is high – the puzzle for policymakers is how to best transition existing or new infrastructure from the supply side and the offtake side, including means of transport technologies (cars, trucks, aircraft, ships), stepwise or simultaneously.

The policy toolbox linked to transition alternatives

To de-risk investments, policy support for new production and supply infrastructure must be matched with demand-side measures for offtake arrangements and market deployment of solutions, including support for investments in new or adapted drivetrain and propulsion technologies for vehicles, aircraft, and ships to be able to use the new fuels, and electric and/or hybrid means of transport. Technology and regulatory developments have to iterate quickly together to reach climate and sustainability targets: both bottom-up with new standards and industry best practice, and top-down with policies, directives, regulation and support measures.

As there is still uncertainty as to which fuels and technologies will achieve the required scale, governments face the challenge of balancing technology-specific and technology-neutral policies. While the latter are arguably more effective in finding the cheapest technology abatement options for decarbonization, the former are greatly needed to achieve technology and commercial readiness of alternatives needed for decarbonization goals.

Technology and regulatory developments have to iterate quickly together to reach climate and sustainability targets.

TABLE 2.3

Supply-side alternatives accompanied by policy examples

Alternative	Technology-Push policy	Demand-Pull policy

Electrification	– Government funding:
	  – R&D, e.g. electric aircraft full-scale testing
	  – Infrastructure rollout, e.g. fast chargers along highways and at harbours and airports, associated grid upgrades
	– Policy for renewable electricity buildout
	– Emission limits regulation
		– Domestic targets (e.g. Norway aviation)
		– ICE vehicles phase out policy
		– Market requirements through zero emission vehicle mandates
		– Uptake incentives to purchase (subsidies, tax credits) and operation (e.g. feebates)
		– Public procurement of EVs

Drop-in fuels	– Government funding: – R&D, technology roadmaps – Policy on sustainable bioenergy including limits on crop-based fuel, and risk assessment of indirect land use changes – Investment support for SAF production capacity, infrastructure repurposing, airport upgrades – Renewable and low-carbon fuel standards – Emission limits regulation	– Blending mandates for sustainable biofuels – Binding targets for sale and purchase and blending mandates – Carbon intensity reduction targets, technology neutral (e.g. IMO) – Investment support on technology upgrades – Fiscal measures incentivizing emission cuts, fuel levy, carbon price, offsetting (e.g. IMO carbon levy, EU ETS, ICAO's CORSIA scheme)

New fuels and infrastructure	– Government funding:
	  – R&D, e.g. HyShip project
	  – Investment support for fuel production, bunkering network and 'green corridors' (e.g. refuelling of new fuels, H_2, fast charging)
	– Contracts-for-difference scheme (i.e. strike price for difference between cost of conventional and new fuel)
	– Emission limits regulation
		– Policy to increase the share of renewable, low-carbon fuels
		– Mandates on fuel targets, minimum quotas on fuels
		– Increasingly stringent limits on carbon intensity of energy use (e.g. FuelEU Maritime regulation)
		– Investment support on technology upgrades, retrofitting (onboard end use, existing vessels)
		– Fiscal measures incentivizing emission cuts, fuel levy, carbon price (e.g. IMO carbon levy)

2.3 POLICIES IN ROAD TRANSPORT

Road transport has come the furthest in terms of competitiveness of cleaner alternatives, increasingly building confidence among policymakers to advance road transport transitions across the world. Regulatory frameworks have longstanding biofuel blend-in policies. However, electrification, emphasizing BEVs over FCEVs, is increasingly pursued to reduce ever-growing emissions.

The regulatory landscape addressing road transport-related emissions spans numerous levels of governance from national and global climate policy to the sub-national and city levels addressing carbon emissions and air pollution.

Two countries have the highest EV uptake rates, China in commercial vehicles, and Norway in passenger vehicles (see highlight). These nations have used a mixture of policies and preferential treatments.

EV support in Norway

Norway has succeeded in stimulating EV uptake. There is a goal of 'all new cars sold by 2025' being zero emission (electric or hydrogen). By the end of 2022, more than 20% of registered cars in Norway were BEVs, which also achieved a market share over 79% of new auto sales.

A detailed overview of the Norwegian approach to incentives, and their adjustments over time, is available from The Norwegian Electric Vehicle Association. The framework has provided EVs with exemptions (registration and VAT) to incentivize purchase and provide benefits to EV owners in terms of running costs. In the early phase, these included free parking, no road toll, free access to ferries connecting national roads, and the use of bus lanes. Enova, the government body providing funding to energy and climate projects, initially funded a EUR 7 million EV infrastructure programme providing 1,900 charging points by 2011. Norwegian government-supported investments helped establish fast-charging systems throughout the country. A 'polluter pays' approach at the same time has worked to deter internal combustion engine (ICE) ownership through CO_2-differentiated registration taxes and high fuel taxes.

In the promotion of EV adoption, it is to be expected that governments adjust support levels as time progress, following the effectiveness of a policy in terms of achieving its purpose or decreases in technology costs. This has also been the case in Norway. From January 2023, the 25% VAT exemption was removed for expensive EVs (> NOK 500,000) and some purchase-tax based on the electric car's weight was introduced. Toll road fees and ferry fares have also been adjusted and public parking fees are more in the hands of local authorities.

Ironically, the effectiveness of incentives and the increasing dominance of EVs in new car sales leaves fewer ICE cars to tax, meaning government tax revenues (cars/fuels) reduce over time. New fees will likely focus on 'tax per kilometre' and EVs paying a fair share to support road and infrastructure maintenance and to combat particulate matter.

For policy in well-established EV markets, the key issue, when making incentive adjustments, is to ensure that EVs remain the cheaper option to avoid reversal to petrol and diesel cars; and vehicle taxation based on environmental performance is paramount. For nascent markets, incentives continue to be needed to drive adoption and future-ready charging infrastructure.

Policies promoting the road sector's transition

While advancing biofuels through blend-in requirements is common, these fuels are not without challenges such as the food-fuel dilemma, feedstock availability, sustainability, costs, and their failure hitherto to limit emissions. We discuss this topic in more detail in the Biofuel Section 3.4. All regions, except for the Middle East and North Africa, have biofuel blend mandates in road transport, with Indonesia having the highest target (35%) around the mid-2020s. Some countries have recently reduced or frozen mandate ambitions e.g. in Europe due to rising food and fuel costs, and in China due to high corn prices.

Electrification policies are spreading worldwide. There are proven measures, especially for BEVs, building on experience from frontrunner regions (Europe, Greater China, North America, OECD Pacific). Follower regions are leveraging the benefits and developing their electrification strategies, for example, the Indian Subcontinent and incipient policy frameworks in the Middle East and North Africa regions.

Europe is taking further steps to curb emissions by introducing an explicit emissions trading scheme for road transport that will complement the tightening of vehicle emission standards and increase demand for low- or zero-emission vehicles. FCEVs are commonly on a par with BEVs in clean vehicle programmes, and while support schemes are becoming more technology neutral, BEV sales are vastly outstripping FCEVs. Battery-electric solutions are expanding into the bus and truck segments, given advances in batteries and battery costs.

Examples of recent key road transport policy from selected ETO regions – displaying a mix of technology-push and demand-pull measures – can be found in Appendix 1.1.

An overall takeaway from our assessment is that BEV policy is spreading worldwide, but with sustained hydrogen focus in for example Japan and South Korea. Globally, however, there is still a lack of BEV-related regulations such as ICE phase out policies, adoption incentives, and charging networks. Commercial vehicles, requiring much larger batteries will need sustained policy support with significantly higher and more-prolonged subsidy levels. Fast-charging infrastructure for fleets of commercial vehicles also needs support to achieve critical mass of locations to service fleet operations. There are inadequate levies on emissions and only a few frontrunner regions have requirements for CO_2 emission intensity reduction targets on vehicles or fuels. Only Europe appears to be setting stringent sustainability criteria on bioenergy and requirements on advanced biofuels and e-fuels.

Table 2.4 summarizes the technology challenges and adequacy of policies for road transport.

TABLE 2.4

Technology challenges and policy adequacy in road transport

Road	Electrification Batteries and charging infrastructure	Drop-in fuels Existing infrastructure	New fuels Retrofit or new infrastructure
Passenger	1 3 2 4	1 3 2 4	1 3 2 4
Commercial (light)	1 3 2 4	1 3 2 4	1 3 2 4
Commercial (heavy)	1 3 2 4	1 3 2 4	1 3 2 4

* Tiles 1 and 2 represent technology challenges. Tiles 3 and 4 represent adequacy of policies.

Technology maturity and challenges	Policies
1. **Supply** challenges and technology maturity for production and infrastructure	3. **Policy** push to address supply challenges for production and infrastructure
2. **Uptake** and demand challenges across all transport subsectors	4. **Policy** pull to address demand challenges across all transport subsectors

Technololgies		Policies
Existing technology or infrastructure		Well-defined policy, proven measures
Medium challenge		Defined policy, partial results
High challenge		Early policy, unclear results
Substantial challenge		Insufficient policy, no results
"Impossible" (no known tech.)		No defined policy

2.4 POLICIES IN AVIATION

From a technology standpoint, aviation has relatively limited options to replace conventional jet fuel, and, like international shipping, is frequently termed a hard-to-abate and hard-to-electrify sector.

International aviation has a global regulatory framework and standards for regional and international medium- to long-haul flights. The main catalyst for change in international aviation comes from the International Civil Aviation Organization (ICAO), funded and directed by 193 national governments to support cooperation in air transport. ICAO plays a role in aviation similar to that of the International Maritime Organization (IMO) in maritime transport.

In October 2022, ICAO adopted a long-term aspirational goal of net-zero emissions by 2050, moving beyond the goal of carbon-neutral growth from 2020 onwards – that is, ensuring that the net emissions from international aviation do not exceed the 2020 levels through the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). 302 airline members of the International Air Transport Association (IATA) have promised to reach net-zero carbon emissions by 2050.

Domestic short-haul aviation is within the reach of national governments in terms of creating the necessary enabling conditions for value chains 'at home'. As examples, Denmark and Sweden have announced goals to make domestic flights fossil-free by 2030, and Norway plans to electrify domestic flights by 2040. France on the other hand, is prohibiting some domestic short-haul flights where a train or bus alternative of 2.5 hours or less exists (effective 2022).

Policy will boost sustainable aviation fuels (SAF) through blending mandates, and their added fuel costs will be passed on to consumers through higher ticket prices. Beyond policy-compliance-driven change in aviation, the dynamics of behavioural change add a transition driver. Additional volumes of SAF will likely come through voluntary consumer demand for 'guilt-free' flying, enabled by ticket options promising investments/deployment of low- or zero-carbon fuels, offsetting emissions tailored to consumer willingness to pay. Such consumer-driven demand will provide funding and incentivize airlines to invest in clean fuels and lowering emissions. Some cargo and freight transport companies and several passenger airlines (e.g. American Airlines, Lufthansa Group, British Airways) have communicated net-zero 2050 targets. Companies, as part of net-zero pledges or corporate ESG targets, will add further motivation to address transport emissions in supply chains.

Sustainable aviation fuels from biological and non-biological pathways

Sustainable aviation fuels are subject to a variety of regulations, certifications, and criteria. Due to the high focus on safety in the aviation industry, testing and certification of physical and chemical properties for new SAFs are an important aspect. Certification of the environmental and GHG aspects will also be developed. The testing and certification of physical properties for aviation fuels is specified in the standards ASTM D7566 and DEF STAN 91-091. For Jet A-1 SAFs to be used in commercial flight, compliance with these standards is required.

Policy and regulatory frameworks in relation to SAF production and usage within the aviation industry are still developing within different markets, with the EU presently leading with initial legislative frameworks in place for both sustainable aviation biofuels and e-fuels. North America is a leading region for production of aviation biofuels, with the most ambitious fuel goals of 3 billion gallons per year in 2030. Several policies and instruments have been in place since 2005 (e.g. the US Renewable Fuel Standard (RFS), the US Sustainable Skies Act, and the Biden Administration announced SAF policies in 2021). Other countries' such as Australia also have ambitious SAF targets.

Recent moves by the European Commission to further restrict biomass of unsustainable origin or marginal GHG benefits have put more focus on waste materials and streams. This is evident in the EU Green Deal and Fit-for-55 legislative package. Other aspects that also need considering in the development of SAF legislation within the different jurisdictions is that while, within the EU, there is much focus on e-fuels and waste-based biofuels, North America has a greater focus on expanding its SAF production through its existing biomass production capacity (i.e. corn to biofuel) with considerably less emphasis on non-biological waste materials. Presently, there are no international definitions that cover all the aspects of sustainability.

Technical challenges – a question of time and timing

There are two central challenges in decarbonizing aviation: firstly, access to sufficient synthetic drop-in fuels with correct specifications from approved sustainable pathways; secondly, space limitations for less energy-dense new fuels on board planes. As illustrated in Table 2.2, these feedstock and technical challenges are likely to prevail over our forecast period to 2050. Due to the limited sustainable biomass, renewable or low-carbon hydrogen, biogenic CO_2, or CO waste streams available, policies are aiming (or should aim) at blending mandates for medium to long haul, and electrification with battery electric or hybrid solution for short haul flights. To overcome space limitations imposed by new, lower energy-content fuels, the fuselage or design has to be changed and that will be subject to lengthy approvals processes; interim solutions may involve sacrificing passenger seats or freight space.

Policies and regulation are likely to address specific fuel or propulsion categories as follows: 1) drop-in fuels, 2) hybrid electric (HFC or fuel), 3) battery electric, or 4) hydrogen for combustion in turbines.

The most obvious way to decarbonize aviation at present is with drop-in fuels, in the short term with biobased fuels, and from the 2030s on supplemented by e-fuels. However, sourcing and establishing large scale feedstock value chains for sustainable biomass, and hydrogen and sustainable biological or non-biological CO_2, takes time, as does approval of new production pathways of synthetic drop-in fuels. There are currently seven Jet A-1 approved biofuel pathways, of which two may be promising for e-fuels, and one has been lab-proven. Some aircraft manufacturers are modifying existing planes with hybrid solutions for new fuels (non-drop-in), rather than redesigning the fuselage, for a shorter route to commercialization. The challenge may still be less cargo and passenger space, and shorter range.

Policies promoting the aviation transition

Only seven of the current National Determined Contributions mention aviation, and this in vague terms (WRI, 2022). Nevertheless, we have seen enhanced focus in the last couple of years, driven by key countries and regions, emphasizing the stimulation of production of sustainable aviation fuels and infrastructure. Blending targets/mandates are emerging, and will be a key policy measure to increase SAF usage. Throughout the forecast period, fuel alternatives will have higher costs than conventional jet fuel. All changes in fuel and technology are therefore expected to come as the result of regulatory push and consumer-supported pull.

Examples of key aviation policies from regions and countries are given in Appendix 1.2. An overall takeaway from our assessment is that 'push' policies have accelerated for investments to increase SAF production capacity and R&D. However, 'pull' policies remain scarce in connecting supply and demand, and in guaranteeing offtake; while fiscal measures fall massively short (e.g. fuel levy, carbon price) of closing the cost differential between new and conventional fuels.

Table 2.5 summarizes the technology challenges and adequacy of policies for aviation.

TABLE 2.5

Technology challenges and policy adequacy in aviation

Aviation	Electrification Batteries and charging infrastructure	Drop-in fuels Existing infrastructure	New fuels Retrofit or new infrastructure
Short haul	1 3 2 4	1 3 2 4	1 3 2 4
Medium haul	1 3 2 4	1 3 2 4	1 3 2 4
Long haul	1 3 2 4	1 3 2 4	1 3 2 4

* Tiles 1 and 2 represent technology challenges. Tiles 3 and 4 represent adequacy of policies.

Technology maturity and challenges	Policies
1. **Supply** challenges and technology maturity for production and infrastructure	3. **Policy** push to address supply challenges for production and infrastructure
2. **Uptake** and demand challenges across all transport subsectors	4. **Policy** pull to address demand challenges across all transport subsectors

Technololgies		Policies
Existing technology or infrastructure		Well-defined policy, proven measures
Medium challenge		Defined policy, partial results
High challenge		Early policy, unclear results
Substantial challenge		Insufficient policy, no results
"Impossible" (no known tech.)		No defined policy

2.5 POLICIES IN MARITIME TRANSPORT

Like aviation, medium- (short-sea) and long-range (deep-sea) maritime transport will require sustainable drop-in and new low- or zero- emission fuels to decarbonize. Although efficiency enhancements will play a significant role, carbon-neutral fuels are needed to meet decarbonization goals, and shipping is expected to move from being almost entirely fossil-oil dominated today to increasingly use one or more alternative fuels such as methane, methanol, or ammonia that need associated new port bunkering infrastructures and changes in onboard technologies. Direct use of electricity is limited to shore power when ships are at berth, and to short-distance coastal shipping through the use of batteries (Figure 1.2).

Due to the international nature of shipping, maritime transport has a global regulatory framework and standards. Supported by both shipowners and governments, the International Maritime Organization's GHG strategy (2018) presently targets a 50% reduction in total annual GHG emissions (from 2008 levels) by 2050. The IMO strategy will be strengthened during 2023, possibly towards aiming for decarbonizing shipping by 2050 as well as addressing lifecycle GHG emissions. These developments will be covered in detail in the forthcoming *Maritime Forecast to 2050* (DNV, 2023b). To ensure that shipping achieves these ambitions, the IMO is expected to work on a GHG emission levy, with the revenues being used partly to provide direct rebate to zero-emission vessels and partly to support developing nations. The levy would be implemented in combination with a well-to-wake GHG emission fuel standard. The development of these measures continues, and we expect them to be adopted in 2025 and enter into force in 2027 at the earliest.

The EU is the only major regulator beside the IMO to impose GHG requirements on ships in international trade. The EU has agreed to a revision of its Emissions Trading System (EU ETS) which will include shipping from 2024. The revenue from 20 million European Emission Allowances (EUAs) – EUR 1.7 billion under current EUA prices – will go to the EU Innovation Fund and be earmarked for maritime-related projects.

The EU has also reached political agreement on the FuelEU Maritime regulation, which is designed to accelerate adoption of renewable

Investors and disclosure requirements boosting the maritime transition

Pressure and expectations from cargo owners, financial institutions, and other stakeholders continues to increase and is enabled by the establishment of a wide range of frameworks, standards, and requirements. The Poseidon Principles for Marine Insurance were launched in December 2021. The Science Based Targets Initiative (SBTi) launched its Net-Zero Standard in October 2021. SBTi enables companies to set net-zero targets in line with climate science, and covers the complete value chain. The US has proposed rules that mandate companies listed there to disclose direct and indirect GHG emissions and related climate risks, including material Scope 3 emissions. These requirements – combined with expectations on environmental, social, and corporate governance (ESG) reporting and disclosure of emissions in practice – mean shipping companies will need to provide more detailed reporting on emissions and ensure that future decarbonization requirements are met.

Investors looking to build robust portfolios of green assets are closely scrutinizing any investment opportunity to avoid future stranded assets, which may fail to reach decarbonization requirements because of making the wrong fuel and technology choices. The mounting pressure means shipowners need to see GHG emissions, both from their own activities and from fuel production, as a business-critical issue that needs their attention today, not in 2040 or 2050. Fuel flexibility remains a key strategic element in ship newbuilding to ensure that those built today can apply carbon-neutral technologies and fuels when they become available in the future.

and low-carbon fuels and technologies. The regulation sets well-to-wake GHG emissions standards per unit of energy used by the ship. The requirements take effect from 2025 and will over time require more stringent limits on such emissions.

Beyond direct requirements on ships in international trade, a wide range of policy exists. The US has several policy initiatives that aim to support development of infrastructure and renewable energy production that may impact shipping. Chinese national policy mainly addresses the green and low-carbon development of domestic shipping. For international shipping, it focuses on encouraging Chinese shipping and its shipbuilding industry to actively explore and promote decarbonization of the cross-industry value chain including shipping, shipbuilding, and energy sectors.

Beyond the IMO's global regulatory framework and regional policies, key stakeholder partnerships and investors are also catalysts for change (see highlight on previous page). On the margins of COP27, several high-level declarations underscored the continued push from a wide range of stakeholders in public-private partnerships working towards shipping decarbonization by 2050, including the establishment of green corridors to focus actions and resources. The green corridors concept will be transformed into actual actions through concrete projects such as the Nordic Roadmap for the introduction of sustainable zero-carbon fuels in shipping and the C40 Green Ports Forum.

Policies promoting the maritime transition

Policies promoting the maritime transition have spread and deepened over the last couple of years but remain scarce when it comes to guaranteeing offtake for clean fuels.

Examples of key policies and stakeholder initiatives are given in Appendix 1.3. Additional action will be needed to put shipping on track for a more ambitious decarbonization strategy to 2050. This will be covered in DNV's forthcoming *Maritime Forecast to 2050* (DNV, 2023b).

The major gap in maritime is between policies that aid the emergence of a fuel production and supply infrastructure enabling transitioning the deep-sea fleet to new fuels. Technologies are available or under development and ready for deployment when a firm demand can be established through policies. The expected strengthening of the IMO's ambitions in 2023, followed up by ship-specific requirements and fiscal policies nationally and internationally, is crucial to establish the required demand. At present, however, the relevant policies across almost all fuels, including electric propulsion are categorized as 'high challenge' in our summary in Table 2.6.

TABLE 2.6

Technology challenges and policy adequacy in maritime transport

Maritime	**Electrification** Batteries and charging infrastructure	**Drop-in fuels** Existing infrastructure	**New fuels** Retrofit or new infrastructure
Coastal/near-shore domestic	1 3 2 4	1 3 2 4	1 3 2 4
Regional short-sea	1 3 2 4	1 3 2 4	1 3 2 4
Deep-sea	1 3 2 4	1 3 2 4	1 3 2 4

* Tiles 1 and 2 represent technology challenges. Tiles 3 and 4 represent adequacy of policies.

Technology maturity and challenges	**Policies**
1. **Supply** challenges and technology maturity for production and infrastructure	3. **Policy** push to address supply challenges for production and infrastructure
2. **Uptake** and demand challenges across all transport subsectors	4. **Policy** pull to address demand challenges across all transport subsectors

Technololgies		**Policies**
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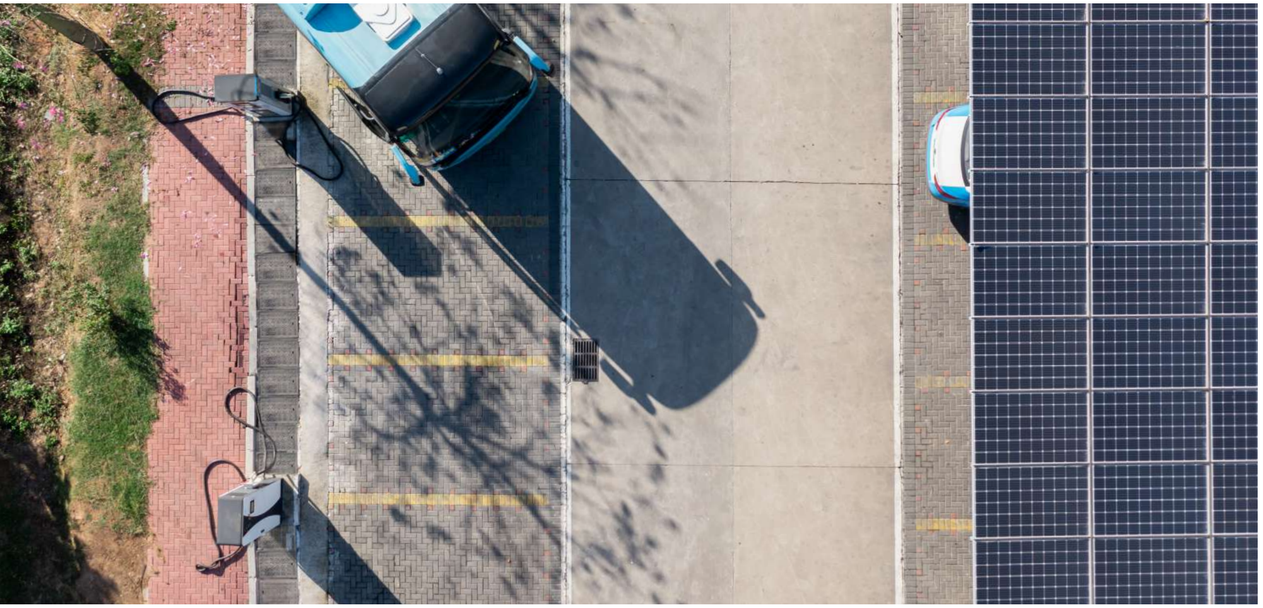
Substantial challenge		Insufficient policy, no results
"Impossible" (no known tech.)		No defined policy

2.6 MISSING PIECES FOR THE NEXT DECADE

A recent review of current National Determined Contributions (WRI, 2022) concluded: "Current NDCs have more transport sector targets … However, most transport measures lack specificity, accountability, quantitative targets, and ways to track progress. Stronger, more specific targets and plans to implement them will be needed … All nations can do more to strengthen transport measures". Our forecast confirms the need to do massively more.

The road, maritime, and aviation transport policy landscape is complex. The good intentions of actors in one transport subsector may jeopardize decarbonization opportunities for another (e.g. synthetic drop-in bio- and e-fuels use for road rather than for aviation or shipping). While regulators traditionally operate in silos, a systemic approach is required with comprehensive planning and regulatory frameworks that interlink energy carriers, fuels, and infrastructures with transport segments.



Road transport has longstanding policies and support measures advancing low- and zero-emission vehicles and related infrastructures coupled with announcements of conventional ICE phase out. Passenger EVs represent proven technology, but in most markets, EVs are still the more expensive option regarding upfront costs. Electrification will need continued support in regions to kick-start transitions, in the long-haul segment, for infrastructure, and because of inadequate pricing of socio-environmental costs (i.e. fuel taxes, carbon pricing). To spread globally in the coming decade, the Accelerating to Zero coalition (see Appendix 1.1) is expected to provide a promising platform that also supports efforts in emerging markets and low-income regions.

The aforementioned systemic approach is needed with the many overlaps in fuel alternatives for aviation and maritime transport. Both transport modes rely heavily on the commercial and technological readiness of sustainable drop-in fuels in the short term. A level of international coordination and prioritization would be well advised, given scarcities in both production capacity and feedstock. Government planning should also prioritize electrification in the range segments where it is technically feasible.

In both shipping and aviation, policy is picking up steam and ready for take-off. However, to be fit-for-purpose to make a meaningful contribution to Paris Agreement objectives within the 2030 and 2050 timeframes, the advancement of low- and zero-emission solutions needs significant fast-tracking in terms of requirements and support for new fuels' production capacity, logistics, and infrastructure build-out and offtake. Quantity-based policies, such as mandates stimulating demand and guaranteeing consumption are still uncommon and fall way short. Such obligations are needed to create certainty for investments. De-risking and improving the profitability of clean fuels through financial measures – such as carbon pricing – on the incumbent fossil-fuel counterparts (conventional marine fuel oil, aviation kerosene) is a necessity.

A detailed description of the policy factors included in our forecast can be found in our main publication – Energy Transition Outlook 2022. We emphasize that our forecast is a 'most likely' future, based on our system dynamics model which considers historical and most likely future technical, economic, and policy developments and the interplay between them. We caution that this 'most likely' future falls severely short of the goals of the Paris Agreement, and ultimately will lead to a global warming of 2.2 degrees above preindustrial levels by 2100 – in other words, climate catastrophe. We have also published a Pathway to Net-Zero Emissions report where the policy factors in our forecast are considerably deepened and strengthened as part of a back-cast framework that sees the world achieving net-zero emissions by 2050.

An all-electric refuse truck.
Image: courtesy Volvo Trucks.

3 POWER AND FUELS

This chapter dives deeply into how the energy transition will impact each of the main transport power and fuel sources: oil, electricity, biofuels, and new (hydrogen) fuels. There is a logic to that sequence: We begin with oil, currently responsible for almost 90% of transport energy, but halving by 2050. That halving is mainly due to the rapid electrification of road transport, which is also beginning to penetrate sectors hitherto considered 'hard-to-electrify'. There are absolute limits to what can be electrified, particularly in aviation and maritime, and that is where biofuels will play a critical decarbonization role in the near- and medium-term. There is already intense competition for sustainable feedstock for advanced biofuels. Over the next decade, ecosystems supplying hydrogen-based fuels (principally e-fuels and ammonia) will start to emerge locally and then slowly merge into a full-blown global ecosystem by the late 2030s.

3.1 DEMAND

In 2021, transport accounted for 26% of global final energy demand, supplied almost entirely by fossil fuels.

Figure 3.1 shows that, at present, 89% of transport energy use is oil, with natural gas and biofuels taking 6% and 4% shares, respectively, and electricity 1%. This mix is mirrored across the road, aviation, and maritime subsectors – with each today dependent on oil for roughly 90% of their energy requirements. By 2030, we will see increased growth of natural gas, electricity and biofuels, but oil will still be responsible for 82% of transport energy demand.

Changing mix

After 2030, electricity will grow significantly in the road sector, and direct electrification will also gain minor shares in aviation and shipping, such that, by 2050, electricity will represent almost a quarter of the transport sector's fuel mix. The share of biofuel rises to around 7% of the mix by 2030, and that share stays fairly constant through to 2050. From the end of 2020s, hydrogen and hydrogen-based fuels start to increase their share to mid-century, making a significant overall contribution of about 10% in total. By 2050, oil use will have almost halved to a 50% share – indicating its staying power in the transport energy mix despite the considerable, and in some cases very expensive, push for the decarbonization of the sector.

Road

Electricity punches considerably above its weight in the energy mix in terms of transport services provided. Thus, the expected growth in road transport services (passenger km and tonne-miles transported) over the next three decades will not result in growth in road-sector energy demand. In fact, quite the opposite: road-sector energy demand will be considerably lower in 2050 than it is today, principally because electric engines are three to four times more efficient than combustion engines. While over three quarters of all vehicles globally (78%) will be EVs in 2050, they will constitute only 30% or so of the road subsector's energy demand, with hydrogen FCEVs taking a further 3%. The smaller part of the vehicle fleet (less than 20%) still reliant on fossil-fuel combustion will be responsible for the lion's share of energy consumption. Fossil fuel oil constitutes close to 60% of the global road subsector's energy demand in 2050, with natural gas at 4%. Biofuels will make only a modest contribution to decarbonizing the road fleet, mostly through mandated blend rates, and will account for just 3% of this road transport energy demand.

Aviation

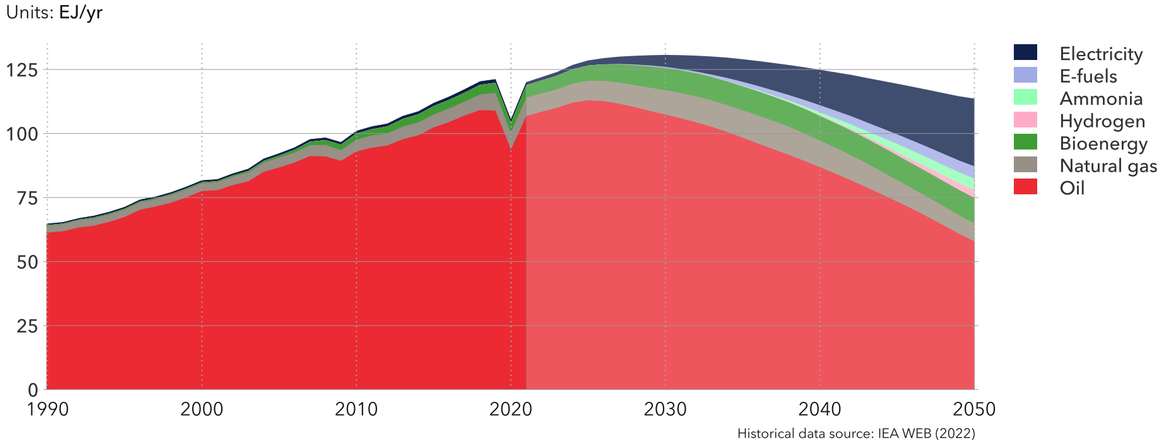
With minor exceptions, e-fuels will not be powering road transport, mainly due to inferior value chain efficiencies and high system costs. Instead, e-fuels will feature prominently in aviation. By 2050, we will see three times more e-fuels – a 13% share in the mix – than pure hydrogen in the aviation subsector, principally because as a drop-in option, e-fuels can serve most flights and engines, whereas pure hydrogen is limited to dedicated hydrogen aircraft, most likely for medium-haul flights. Battery-powered aircraft are suitable for short-haul flights only, and since short-haul accounts for only a minor part of aviation consumption, electricity will represent only 2% of the aviation fuel mix in 2050. In aviation, therefore, oil retains its dominant status – a 59% share in 2050, though in absolute terms aviation oil use will be 26% lower than today.

Maritime

Driven by the decarbonization push, the fuel mix in the maritime subsector will change significantly over the coming decades. By 2050, it will likely transition from being almost entirely oil-based to a mix dominated by the use of low- and zero-carbon fuels (50%), natural gas (19%, mostly liquefied natural gas) and biomass (18%). Electricity will have only a 4% share, from short-sea shipping and port stays for larger vessels. In this report, the base case maritime fuel mix is taken from our *Energy Transition Outlook* (DNV, 2022), which in turn uses a combination of several scenarios analysed in DNV's *Maritime Forecast to 2050*. That report details 24 scenarios across two maritime decarbonization pathways: IMO ambitions

FIGURE 3.1

World transport sector energy demand by carrier



complying with the current IMO GHG Strategy, and decarbonization by 2050 achieving net-zero shipping by then, and high and low values from these scenarios are included in the illustrations in the coming sections.

Demand growth across all sectors

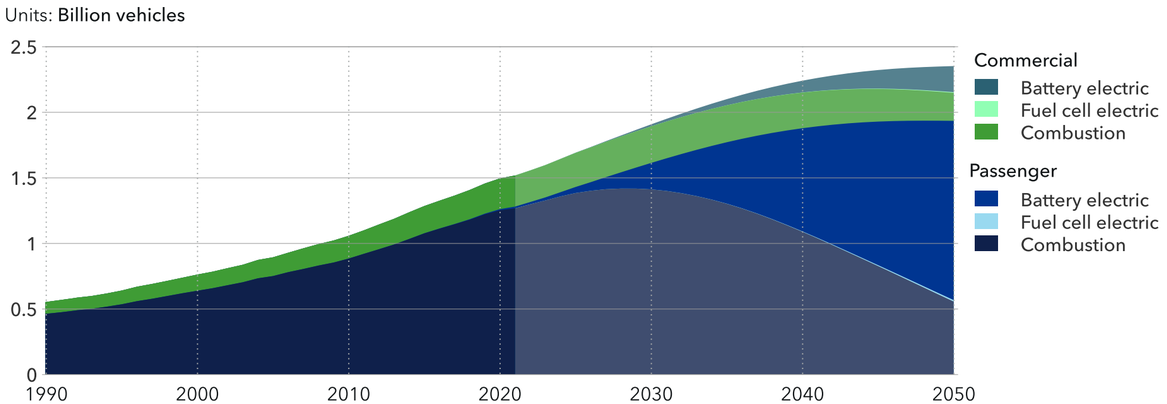
Figure 3.2 shows our forecast vehicle numbers, where the passenger vehicle fleet climbs from 1.2 billion cars today to slightly below 2 billion in 2050, with the ICEV share falling precipitously from 97% to less than 30% by mid-century. Almost the entire fleet of two- and three-wheelers will be electrified by 2040, while EV uptake in commercial vehicles clearly lags developments in the passenger vehicle category.

The size of the global passenger vehicle fleet will increase by about two thirds by 2050. As noted previously, vehicle-kilometres will also rise, more than doubling by mid-century. A similar dynamic is anticipated for commercial vehicles, though growth will be slightly lower, with the vehicle-km expanding about 50% towards 2050.

The rise in vehicle kilometres for the passenger segment is partly attributable to a growth in automation and in digitally-enabled ride sharing, both of which lead to more kilometres driven compared with privately-owned vehicles. The growing use of automation and ridesharing may to some extent happen at the expense of traditional public transportation,

FIGURE 3.2

World number of road vehicles by type and drivetrain



Combustion vehicles include ICEs and PHEVs
Historical data source: Marklines (2022), IEA EV Outlook (2022), EV Volumes (2022)

as well as walking and bicycle use, but the extent of these modal shifts is not included in our analysis.

Ride sharing will clearly affect the overall size of the vehicle fleet, but the main driver of car ownership remains GDP per capita: a rising standard of living increases vehicle density (vehicles per person). Regionally, this relationship is influenced by geographical, cultural, technological, infrastructure, and environmental factors, and by the availability of alternatives to road transport.

To predict future developments in vehicle density, we have fitted historical data to a Gompertz-curve (a type of S-shape curve). In some regions this is supplemented by expert opinion, enabling us, for example, to adjust for the effects of policy support for alternatives to road transportation. Detailed numbers for this can be found in our main ETO report.

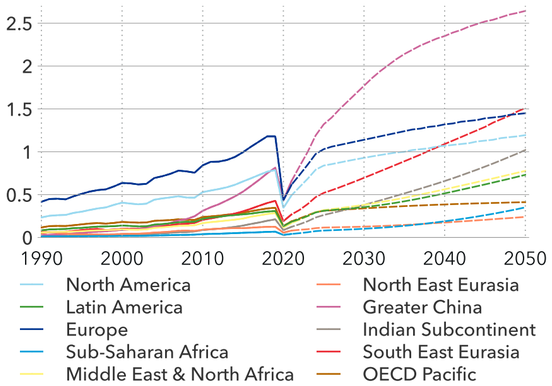
Driven by rising standards of living, global aviation has tripled in the first two decades of this century, demonstrating the relationship between GDP growth and the number of people that fly, and the number of flights they take. By 2050, we will see annual global passenger flights growing to 10.2 billion, 130% higher than pre-pandemic levels. The strongest growth will occur in Greater China, followed by South East Asia. The growth in passenger trips occurs despite COVID-19, which put the brakes on air travel. Aviation rebound has been slower than other sectors. While we do not foresee a permanent effect on leisure travel, the pandemic introduced new work patterns that will have a long-term impact – re-basing business travel 20% lower than pre-pandemic assumptions.

The size of the global passenger vehicle fleet will increase by about two thirds by 2050.

FIGURE 3.3

Air passenger demand by region of origin

Units: Billion passenger-trips/yr

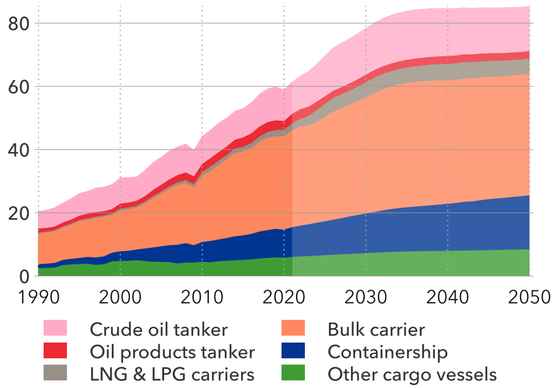


Historical data source: ICAO (2020), Airbus GMF (2018)

FIGURE 3.4

World seaborne trade in tonne-miles by vessel type

Units: Gt-nm/yr



Historical data source: IEA WEB (2022)

A world in which GDP doubles by 2050 will see cargo transportation needs considerably outweighing efficiency improvements such as improved load capacity or vessel efficiency itself. Cargo tonne-miles will therefore increase in almost all ship categories, with a total growth of 35% between 2020 and 2050. Most of the growth will come before 2030, after which global seaborne trade will stabilize. The later part of the forecast period will see growth in some categories such as gas carriers, containerships, and certain bulk segments, but also reductions in most segments as efficiency improvements equal a lower demand growth (e.g. for coal transports) and ongoing decarbonization is reflected in global trade patterns. Consequently, coal transport halves by 2050 in tonnes, and crude oil and oil products transport reduces by 20%.

A game of fuels – what will power transport in the coming decades?

Oil fuels 90% of transport today. This energy mix will change, but the nature and pace of change will vary across the different subsectors of the transport system. Future trends in fuel costs and supply-chain infrastructure availability are two main reasons for such differences.

Electricity will transform passenger road transport and also gain a share in segments previously thought to be hard-to-electrify, such as trucks and short-haul aviation. Oil-based fossil fuels will continue as a main source of fuel in aviation and maritime, where alternatives are energy-intensive and expensive. In some regions lacking electric infrastructure, oil use in road transport will also continue. Nevertheless, oil demand in transport will halve by 2050. Hydrogen and especially e-fuels are costly and energy-intensive to produce. They will require renewables-based electricity, competing with direct use of electricity to supplant fossil electricity production in the near term. Longer term, pure hydrogen and hydrogen derivates emerge as the most important options to decarbonize hard-to-electrify transport subsectors such as shipping and aviation. Biofuel – dependent on renewable sources such as waste oil, agricultural residues, and non-food crops – is suitable as drop-in fuel. Its share will grow this decade as sustainable feedstock in Europe and North America for advanced biofuels for aviation and maritime shipping increase in use, however in the longer term, cost and availability will limit its role in replacing today's fossil fuel use.

The following section focuses on how fuel costs will change in the coming decades in the three subsectors: road, maritime, and aviation.

Road transport

Battery electric vehicles (BEVs) account for about 2% of the global vehicle fleet today, but this share increases dramatically to 66% in 2050. BEVs will outcompete every other drivetrain because of their high efficiency and low cost of fuel per distance travelled compared with internal combustion engines. In addition, ongoing policy support such as emissions reduction targets and bans on sales of ICEVs will further drive BEV uptake which again contributes to reduce overall costs.

Using gasoline or diesel as reference cost, the cost of charging with electricity and driving the same distance will on average be about 60% lower in 2030 in Europe and OECD Pacific. E-fuels can be three to four times costlier than gasoline because of their low well-to-wheel efficiency (see Road Efficiency Infographic in the Electricity Section 3.3).

Consequently, for passenger transport, the transition is all about direct electrification. It is different for commercial vehicles, which can be classified as light, heavy-duty, and short-haul or long-haul. Light-duty commercial vehicles will mainly be powered by electricity because the same fuel cost and infrastructure advantages apply as for passenger vehicles. Electric charging infrastructure is easier to install than networks of hydrogen refuelling stations.

Heavy-duty transport, especially long-haul trucking, will have specific use-cases impacting the fuel choice. Certain subsegments of heavy and long-haul commercial vehicle transport present clear opportunities for hydrogen applications. Until recently, battery-electric options were not considered commercially feasible and able to cater for the range and transport loads necessary. This view is now changing, with battery-electric technology becoming more viable, and with charging-station density increasing compared with the still thin network of hydrogen refuelling stations. Also, longer ranges are now believed to be viable for electric trucks, while for the longest distances and heaviest loads diesel (including low-carbon options) and hydrogen are expected to be the main source of fuel.

Aviation

Aviation has few options to replace oil-based fuels in the short to medium term and is frequently termed a hard-to-abate transport subsector. However, it is strongly regulated and has a limited set of stakeholders, which in theory would enable a fast sector-wide change. It could be relatively easy to implement and monitor the uptake of technologies and fuels reducing GHG emissions. However, even if alternatives to fossil fuels progress in the future, they will still be much more expensive and less-readily available in terms of supply and infrastructure. Electricity-based aviation would be cheaper, but today`s batteries will not work for long-haul flights as the energy-to-weight ratio of them is not sufficient. Therefore, electrification is a realistic propulsion option only in the short-haul flight segment.

Considerable progress has been made in the development of sustainable aviation fuels (SAFs) from biomass or hydrogen (e-kerosene), and these are expected to play a key role in decarbonizing long-haul aviation. Biogenic SAFs are produced from sustainable feedstocks such as agricultural waste, non-edible plants, and municipal solid waste. The production process for these SAFs involves converting the feedstocks into liquid fuel that is chemically like traditional jet fuel but has a lower carbon footprint. SAFs can to a certain extent be blended with traditional jet fuel and used in existing aircraft engines without the need for modification.

E-kerosene, on the other hand, is produced by using renewable electricity to power the conversion of CO_2 and water into hydrocarbons that are then refined into kerosene. The process is known as power-to-liquid (PTL) and is considered a promising option for achieving zero-emission aviation in the long term. E-kerosene has equivalent properties to traditional kerosene and can be used in existing aircraft engines without any modifications.

However, the adoption of SAFs faces several challenges, not least cost. Biogenic SAFs are currently much more

expensive than traditional jet fuel due to the higher cost of feedstock and the limited production capacity. However, as production increases and economies of scale are realized, the cost is expected to decrease. In contrast, e-kerosene is still in R&D phase and its cost at scale, yet to be determined, is heavily dependent on the costs of CO_2.

Maritime transport

There is mounting pressure from regulators and parts of the maritime industry for the International Maritime Organization (IMO) to further strengthen its current ambition for reducing GHG emissions from international shipping which is currently a reduction of at least 50% by 2050 compared with levels in 2008. The main opportunity for decarbonization by 2050 will be fuel switching from oil to natural gas and further to low- and zero-carbon fuels such as ammonia, e-methanol, e-methane, and various forms of biofuel. Improved navigation, slower speed, increased fleet and ship utilization, wind-assisted propulsion, onboard carbon capture, and energy-efficiency improvements will also contribute to emission reductions.

The potential for electrification in maritime is limited to shore power when at berth and to short-sea shipping such as ferries and inland waterway transport. As with aviation, the energy density of batteries today and in the future is likely to remain too low to play any sizeable role in deep-sea shipping. Therefore, other low- and zero-carbon fuel options are needed.

Due to the low energy density of hydrogen in pure form, hydrogen derivatives are more likely to be a significant fuel in maritime. Hydrogen is the basis for fuels such as ammonia or e-methanol, and their widespread use in shipping will create a significant demand for low-carbon hydrogen. Ethanol can be produced from many feedstocks: from coal, natural gas, and biomass, to renewable electricity. However, e-methanol and bio-methanol are the most likely shipping options. Compared with using ammonia, methanol benefits from existing bunkering infrastructure and lower costs for storage tanks on newbuildings or retrofitted to existing vessels.

There are now 26 ships sailing that can use methanol as fuel (DNV, 2023), but availability of sufficient renewable electricity at a low cost will be a challenge to widespread uptake of both e-methanol and e-ammonia. Towards 2050, the availability of low-cost sustainable CO_2 needed to produce e-methanol may also be a challenge.

Low-carbon ammonia is another highly promising alternative fuel to decarbonize maritime shipping, but presents several challenges. Like e-methanol, ammonia can use large parts of the existing infrastructure for distribution to ports, but has the same challenges with significantly higher production costs than oil being used today. If produced from renewable electricity, the conversion losses are significant, and would need a massive ramp-up of renewable power generation. However, capturing CO_2 from natural gas during ammonia production is relatively simple, and the dominant share of ammonia being used in shipping in our forecast is likely to be blue ammonia.

Fuel prices

The future price of fuel is difficult to forecast, but we have reviewed the different fuel supply chains, which allows us to make realistic cost estimates in production and distribution by fuel source, and to understand what the most important cost drivers are. These prices are reflected in our forecast and show how the fuel mix and propulsion technologies develop through 2050. The price forecast includes the production steps for different processes and the regional costs for various kinds of biomass, electricity, fossil energy, and CCS.

Carbon-neutral fuels: Levelized cost of production and distribution are used as proxy for price. Bottom-up costs are estimated per carbon-neutral fuel supply chain, including:

- Production and processing steps
- Distribution
- Cost of CO_2 feedstock (as applicable)

Fossil fuels: Historical relationships between fossil fuel price and the price of crude oil or natural gas are used to estimate future fuel prices.

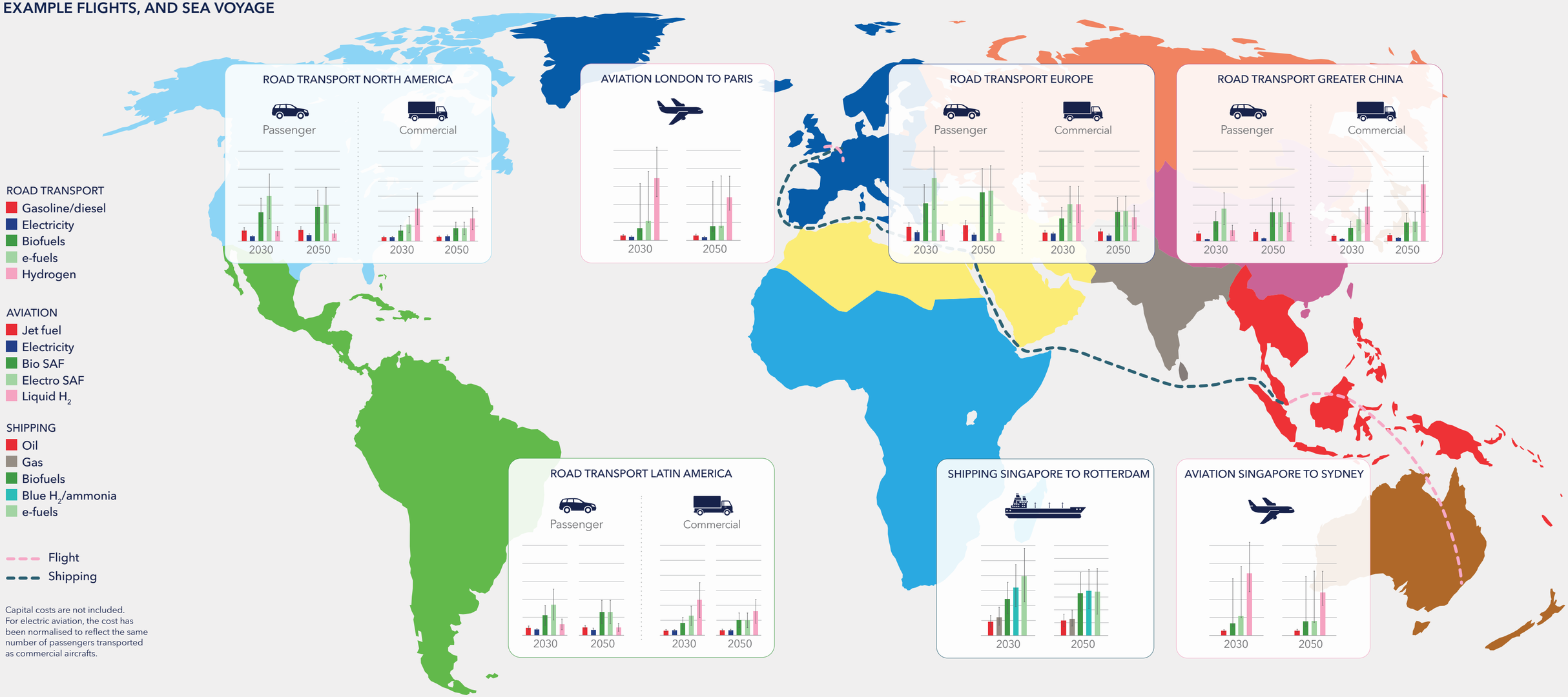
The infographic found on the next page reflects the costs for different competing fuels in 2030 and 2050.

The road transport subsector includes both passenger and commercial vehicles and shows the relative costs of transport per 10 km distance.

For aviation, two separate routes are shown using different fuel sources; the difference being that we expect to see electricity included for short-haul flights between London and Paris. However, by 2030 these routes will only be available at a pilot stage. Singapore – Sydney cannot be electrified with current battery technology and decarbonization of such routes is therefore dependent on biofuels in the years to come, supplemented by e-fuels in the 2030s.

For maritime transport, we show the relative fuel cost associated with a deep-sea route between Singapore and Rotterdam. The fuel costs are presented before any subsidies or carbon taxes have been added. In our modelling, we do however consider these factors in the forecast of the transport sector between now and 2050.

RELATIVE FUEL COSTS FOR ROAD TRANSPORT (10 KM), EXAMPLE FLIGHTS, AND SEA VOYAGE



Capital costs are not included. For electric aviation, the cost has been normalised to reflect the same number of passengers transported as commercial aircrafts.

3.2 FOSSIL FUELS

In 2021, 62% of oil supplied globally was for the transport sector. Of this, 80% was used to supply road vehicles, with the remainder supplying aviation and maritime in roughly equal shares. Among the main energy demand sectors, transport remains the dominant consumer of oil throughout our forecast period, still accounting for 50% of global oil primary supply in 2050 despite the accelerating shift to electricity, SAF, hydrogen, and ammonia in road, aviation, and maritime transport.

Table 3.1 shows the volume and share of world's oil demand in transport, and its subsectors: road, aviation and maritime. The road subsector will continue to have the largest share, but with ICEVs peaking at 1.4 billion vehicles in 2028, demand will halve in the next three decades. In 2050, demand is split equally between passenger and commercial vehicles.

Gas demand in transport in 2021 was about 5% of total gas supply. This share and the volume stay almost constant in the next decades. Maritime is responsible for almost all this demand due to growth of LNG-fuelled vessels, with the share of gas in maritime energy demand increasing from 6% to 19% in 2050. Compressed natural gas (CNG) use by road vehicles is negligible because, while cheaper than oil, it requires large storage tanks, provides limited range, and suffers from a near-absence of infrastructure (both engines and refuelling stations) relative to gasoline- and diesel-powered vehicles.

TABLE 3.1

Volume and share of world's oil demand in transport

	Total Oil Primary Supply (EJ/yr)	Oil Demand (EJ/yr)				Share of global oil supply			
Year		Transport	Road	Aviation	Maritime	Transport	Road	Aviation	Maritime
2021	173	107	85	10	11	62%	49%	6%	6%
2030	179	107	81	15	11	60%	45%	8%	6%
2050	118	58	42	14	2	49%	36%	12%	2%

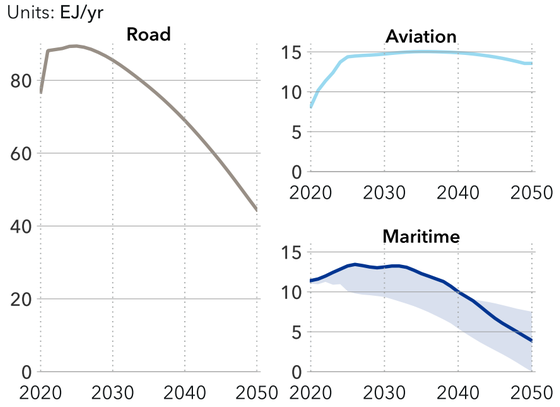
In aviation, natural gas use is non-existent owing to the incompatibility of its characteristics, such as energy density, flash point, and freezing point, with the current infrastructure. Figure 3.5 summarizes both oil and gas demand in road, aviation and maritime.

There is ongoing and mounting pressure to decarbonize transport for climate change, environmental, health, and energy security reasons. However, reducing oil demand for transport remains challenging for the following reasons:

- **Cost competitiveness:** Due to its large-scale production and availability, oil is relatively cheap. While it will steadily lose cost-competitiveness to electric propulsion, it remains much cheaper than alternative fuels (biofuels, hydrogen and its derivatives) in the next decade in the absence of much higher carbon prices or fuel taxes.
- **High-density energy:** Gasoline, diesel, and kerosene have energy densities more than three times that of liquid ammonia and liquid hydrogen.
- **Infrastructure:** The current transportation infrastructure, including tankers, pipelines, refineries, and gas stations, is established around oil-based fuels; establishing new or parallel infrastructure for new fuels is expensive, complex, and challenging.
- **Processing for transport:** Transporting oil requires no pre- or post-processing, unlike hydrogen and e-fuels which require energy-intensive conversion processes to transport them to their intended destinations.
- **Storage:** Crude oil can be stored almost indefinitely with virtually no loss in tanks or barrels. Global oil storage capacity in 2020 was about 9.2 billion barrels (15.6 PWh) (Forbes, 2020). As there is no special requirement for the storage temperature, the cost of storage is much lower compared with hydrogen and ammonia.

FIGURE 3.5

Fossil fuel demand in selected subsectors



Shaded area represents the range of expected uptake as outlined in DNV's Maritime Forecast to 2050

Reducing the carbon footprint of fossil fuel production

Owing to the staying power of oil and gas in end use, there are only two decarbonization options for oil and gas operators: decarbonize their own operations or repurpose their infrastructure to produce low- or zero-carbon fuels.

The list of decarbonization actions for upstream producers is relatively well-known: efficient production, changing power sources (e.g. to electricity), reducing fugitive emissions and flaring, and increasing CCUS. Downstream operators can turn to: energy efficiency, low-carbon and renewable hydrogen (instead of grey), synthetic fuels, and sustainable feedstocks (biomass, biological or atmospheric CO_2 for e-fuels).

One of the solutions for downstream operators is increasing production of drop-in fuels in the form of biofuels or e-fuels that can be used directly on existing engines and fuel systems. Many countries have implemented mandates for biofuel blending to both combat greenhouse gas emissions and reduce exposure to supply shocks in fossil fuel imports due to geopolitical tensions or other disruptions. Investment in e-fuel development and production has been increasing in recent years, while use of biofuels blended with fossil fuels, especially in road transportation has been increasing for decades.

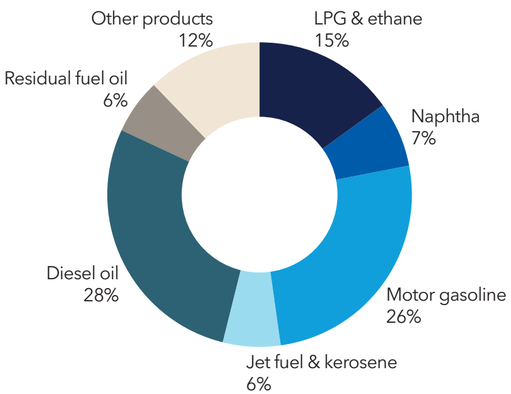
Refineries in particular are being caught in the crosshairs of change. As the volume of refined products decreases over the next decade and beyond, many risk becoming stranded assets (Bain, 2022). For those that continue to serve the still-considerable demand for refined fossil products in end use, there are a host of adaptation considerations, including:

- **Regulatory compliance:** Some refineries need upgrades to meet tightening environmental regulations related to air and water pollution, and GHG emissions. Refineries may need to develop CCS to conform to demands from national climate change policies and international competition.

- **Increased energy and carbon efficiency:** To reduce operating costs and emissions while increasing the final product volume and quality.

FIGURE 3.6

Current global share of refinery product



- **Biofuel compatibility:** Refineries are critical to the scaling of biofuel availability, as they allow the use of existing processing, storage, distribution, and dispensing infrastructure for biofuels. However, due to the high oxygen content and other contaminants in biofuels, they require an upgrading process in refineries for blending with fossil fuel. The potential risk to the refiner will play a significant role in the final selection of the biofuel insertion point. The blending point can be at pre-processing (highest risk), co-processing, or post-processing (lowest risk).

- **Changes in market demand:** Refineries need to keep pace with changing demand volumes of many different products, as summarized in Figure 3.6. This picture will change, especially in road transport, where demand for diesel and gasoline will decline while demand for kerosene (mainly used in aviation) grows. For example, in 2021, demand for diesel and gasoline was 9 times the demand for kerosene, but this ratio falls to 3:1 in 2050.

Depending on the market need, oil refineries have different configurations and product profiles. For example, in the US, fluid catalytic cracking (FCC) is more common because the demand for gasoline is higher, while Europe, Middle East and North Africa have high demand for diesel and kerosene, which can be satisfied with hydrocracking. So, most refineries are more-or-less suitable for insertion of bio-intermediates, depending on the nature of the intermediate and the desired products (NREL, 2019.)

Road

Road transport accounts for the lion's share of the world's oil demand (57% or 14 billion boe/yr in 2021). The global uptake of EVs will see oil demand in road transport fall to half of current demand (7 billion boe/yr) by 2050, or about 40% of the global oil demand by then.

The demand for fossil fuels in road transport varies greatly between regions. Figure 3.7 compares oil demand for transport per capita in 2021, 2030, and 2050 for all 10 ETO regions. Due to the rapid phase out of ICEV to the more efficient EVs, demand in North America, Europe, Greater China, and OECD Pacific falls by well over 80% by 2050. The reduction in demand accelerates after 2030 in line with EV uptake and electricity also scaling in the commercial vehicle segment. In contrast, across the Indian Subcontinent and Sub-Saharan Africa, oil transport demand increases by over 50% to 2050 because the growth in transport demand and the vehicle fleet outweighs the pace of electrification in those regions – which lags OECD and China by a decade or more. In Latin America, Middle East and North Africa, and South East Asia, oil demand for transport increases to 2030 and thereafter decreases toward 2050.

Figure 3.8 shows the absolute oil demand for road transport in different regions in 2021 and 2050. North America is a clear outlier as a major consumer of oil for transport. This is due to the following characteristics:

- The US and Canada have the highest rate of vehicle ownership in the world: in both cases approaching one vehicle per man, woman, and child.
- Both countries are very large and crisscrossed by extensive road networks, with both countries topping the list of annual miles driven per vehicle.
- Relatively underserved by public transportation systems and hence a high reliance on private vehicles for mobility.
- Historically, fuel prices in the US and Canada have been relatively low compared to other countries.
- SUV market leader: The US tops the list of SUV ownership per capita, with a recent survey (Volkswagen, 2021) showing high commitment to continued ownership of such vehicles.

While these characteristics persist through to 2050, the rate of electrification is steep and relatively early in both countries. Among the 10 world regions, North America's share of global oil demand in transport more than halves from 30% to 10%. In contrast, the two regions with the slowest EV uptake (Indian Subcontinent and Sub-Saharan Africa) increase their share of oil global demand by a factor of four.

Aviation

Aviation is a hard-to-abate sector with relatively few options to replace fossil fuel owing to technological, production cost, and infrastructure constraints. In 2019, oil constituted close to 100% of aviation energy demand (about 14.5 EJ/yr) – almost 8% of the global oil supply. Global aviation traffic will grow by 130% (from pre-pandemic levels) by 2050, leading to a

FIGURE 3.7

Oil demand per capita for road transport

Units: barrel/yr

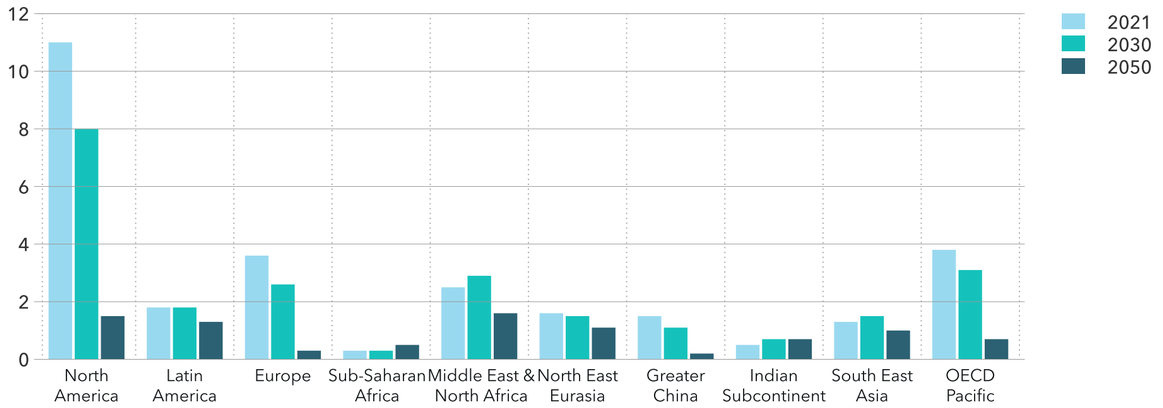


FIGURE 3.8

Oil demand, road transport, all regions, 2021 vs 2050

Units: Million barrels/yr

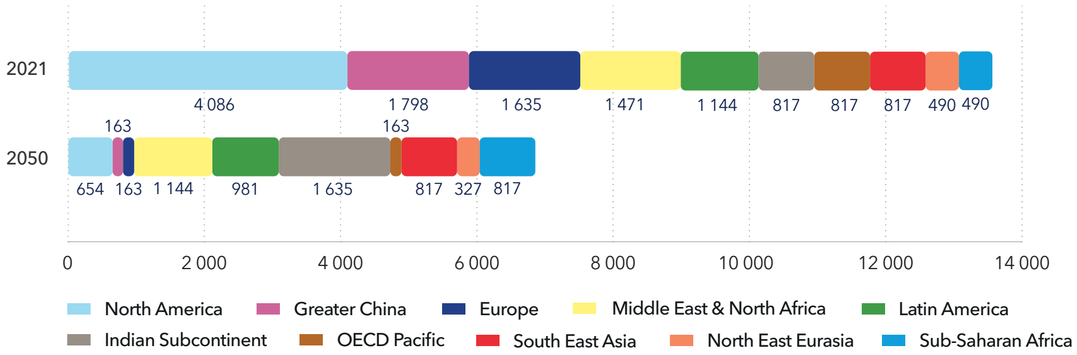


FIGURE 3.9

Oil demand per capita for aviation

Units: barrel/yr

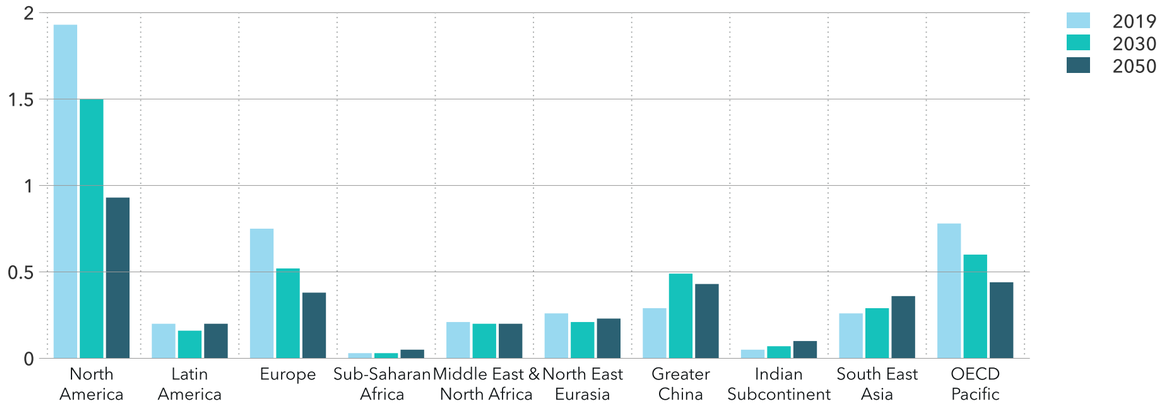
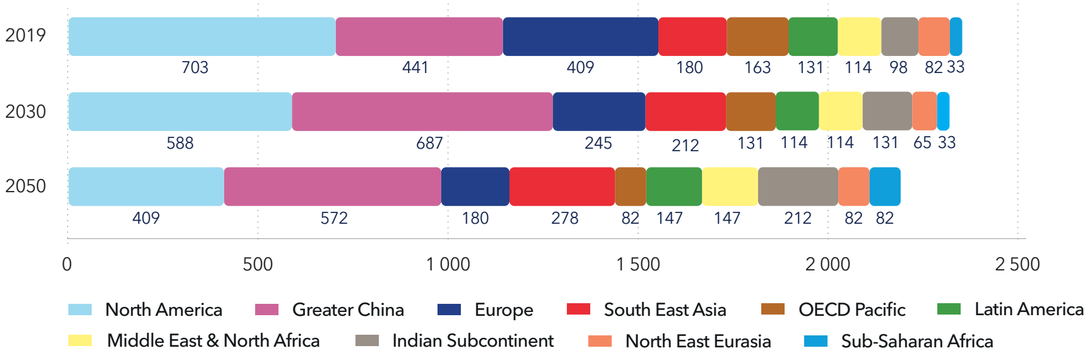


FIGURE 3.10

Oil demand, aviation, all regions, 2019, 2030 & 2050

Units: Million barrels/yr



near-doubling of energy demand from the subsector, indicating some efficiency gains. By mid-century, oil will remain the dominant energy source, about 60% of the fuel mix, despite extensive efforts to develop alternative fuels for aviation, including biofuels, e-fuels, and hydrogen.

Figures 3.9 and 3.10 show oil demand per capita for aviation in different regions, as well as total aviation oil demand per region, in 2019 (2020 & 2021 data are impacted by COVID-19), 2030 and 2050. On a per capita basis, the main delta is the peaking of aviation oil demand in 2019 in North America, Europe, and OECD Pacific, with Greater China peaking in the 2030s. In general, aviation is well correlated with GDP per capita, partly causing overrepresentation of North America throughout the forecast period relative to the size of its population. In terms of total oil demand per region, China is on track to eclipse North America as the largest consumer of aviation oil, with strong growth from the Indian Subcontinent and South East Asia.

The aviation industry is under intense pressure, directly from consumers, to reduce its carbon footprint (NATS, 2020). However, the technological solutions for doing so are expensive and difficult to scale. We forecast that biofuel will only replace about 10% of aviation oil demand by 2030. Blending biofuels with traditional jet fuel is complicated but manageable (see the Biofuels Section 3.4 – DHL Express case study). Changes in fuel properties, such as energy density, freezing points, and combustion characteristics can impact fuel and engine performance and safety, and may not comply with aviation regulatory standards. Additionally, we will see short-haul trips increasingly powered by electricity, medium-haul partly by hybrid battery-hydrogen solutions, and e-fuels used for medium- and long-haul. However, despite all the technical innovation and considerable investment in alternatives to oil-based aviation, the higher costs of these alternatives plus the significant additional investment in infrastructure they will need means that oil will continue to supply three fifths of aviation fuel needs in 2050.

Maritime

Nearly 3% of global final energy demand, including 7% of the world's oil (11 EJ/yr) in 2021, was consumed by ships, mainly by international cargo shipping. The IMO regulation capping the sulfur content of ship fuel came into force in 2020, dramatically changing the type of fuels being used. The main shift has been to a much larger share of lighter distillates in the overall fuel mix, or other variants of fuels with less sulfur. With the IMO targeting a 50% absolute reduction in CO_2 emissions between 2008 and 2050 and EU and other administrations increasing the pressure, the fuel mix in maritime transport will change significantly over the coming decades. It will transition from being almost entirely (92%) oil-based today to oil having only a small share of 11% (low case 0%, high case 41%) in 2050. Gas is growing in importance from 6% today to a 19% share (low case 0%, high case 36%) in 2050. Low-carbon fuels will have a large share, and biomass will be important. Electricity will have only 2% share as the energy density of batteries is not suitable for deep-sea shipping.

3.3 ELECTRICITY

Over the coming decades, electricity will gradually start to dominate road transport. The only exception is heavy, long-distance transport and areas with poor electricity infrastructure. As we discuss below, the boundaries limiting what electricity can power are shifting as battery costs and densities progress. However, direct electrification in maritime and aviation will remain limited; in those subsectors, indirect electrification via hybrid propulsion systems will play a much more significant role.

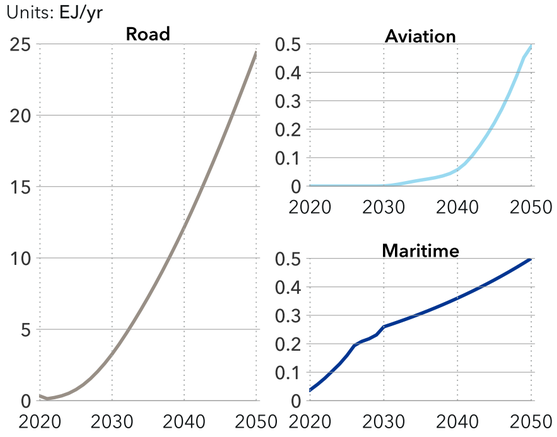
Pushing the boundaries

Ten years ago, 'range anxiety' was seen as the major problem that would limit the practicality of electric cars. Since then, the boundaries for electrification of road transport are stretching ever wider. Today, there are over 500 electric models worldwide and sales numbers passed 10 million in 2022 and are climbing rapidly. For many EV drivers, range anxiety is already a thing of the past or has morphed into fixable inconveniences like long waiting lines at a fast charger at the start of the holiday season.

Buses and trucks are now being electrified on a commercial scale in many countries, driven by legislation to reduce local emissions and other factors. With 70% of the trucks driving less than 250 km per journey in Europe, the only road vehicles that still seem difficult to electrify are the remaining portion of the fleet which are generally heavy trucks engaged in international long-distance transport. However, even in this segment, specific solutions, such as the Megawatt Charging System (MCS) or battery swapping stations on transit routes are being developed. Developments will continue to push the boundaries of electrification. However, in large parts of the world charging infrastructure will remain a major obstacle for decades to come. Hence, our forecast EV uptake varies significantly between regions (DNV, 2022a).

FIGURE 3.11

Electricity demand in selected subsectors



In the maritime and aviation sectors, electrification of propulsion was seen as impossible a few years ago. Now, however, in some niches such as water taxis and short distance ferries, electric ships are no longer an exception. In aviation, several companies are now offering light electric aircraft for sale. Although these are small single or 2-seater planes, 30-seater planes for short flights between cities are in development.

Despite the considerable media coverage given to these innovations, electricity is only set to play a minor role in aviation with about 2% of the overall energy mix, and in maritime with about 4% of the mix (Figure 3.12).

This section examines the drivers and challenges of emerging electricity-based solutions for (heavy) road, maritime, and air transport, and how these are being integrated into the electricity system.

FIGURE 3.12

The boundaries for what is possible to electrify are shifting. Road traffic is clearly leading.

Road transport

Passenger vehicles make up the largest segment of transport in terms of both number of vehicles and emissions. Cars and vans account for 46% of transportation CO_2 emissions and 10% of global CO_2 emissions. Passenger vehicles are also the most straightforward to electrify given the existing development of technology and charging infrastructure.

With government mandates to ban the sale of combustion engine vehicles running on fossil fuels within the next 10 to 15 years (e.g. countries in the Accelerating to Zero Coalition, see Appendix 1.1), it may seem inevitable that EVs will dominate the future market. DNV projects that 50% of global passenger vehicle sales will be electric by 2033, with the market moving fastest in Europe and China.

To realize these projections, challenges such as a complimentary charging infrastructure build-out supplying different EV driver's needs (fast charging, destination charging, charging-at-home with vehicle-to-everything integration) associated with this deployment need to be addressed. If these challenges are not overcome through innovative development in EVs and their associated charging infrastructure, then this transition will be slower and more costly.

The innovations required to facilitate mass adoption of EVs need only to be incremental. Radical new technology is not likely, nor necessary.

Nevertheless, there are both big opportunities and challenges for all involved in the EV supply chain, from EV manufacturers and suppliers to financiers, energy companies and charging station operators.

DNV projects that 50% of global passenger vehicle sales will be electric by 2033, with the market moving fastest in Europe and China.

The transition to EVs will differ markedly from country to country: Norway is the prime example of how transportation can be electrified rapidly, with 79% of cars purchased in 2022 being electric (OFV, 2023). In addition to EV-friendly policies and state support (see highlight in Section 2.3), Norway has benefited from an already robust electricity infrastructure. As the majority of Norway's heating is already electrified, the average annual electricity demand is 23,000 kWh per capita vs 6,000 kWh per capita for the European Union. The grid impact is covered further below. However it should be noted that for countries with less capacity in their distribution and transmission networks, the transition will be more challenging. In Sub Saharan Africa, where just over half (54% of the population) has access to electricity, EV uptake will severely lag high-income regions.

INNOVATION TO ADDRESS REMAINING CHALLENGES

Cost

EVs currently have a higher initial cost than their combustion counterparts, and that is a barrier for many people, both financially as well as in perceived risk (one has to drive a minimum number of km in order to justify the higher investment). Few buyers are in a position to conduct a total cost of ownership (TCO) exercise which would reveal that on average EVs have already plunged through the fossil TCO line. This represents typically a high-income country perspective, and we acknowledge that this description is not valid in regions such as Latin America or Sub-Saharan Africa.

In the long term, it is expected that governments will need to replace lost revenue from fossil fuel duty. Governments may be tempted to introduce alternative taxation such as km driven, which would reduce the advantages of EVs. However, rather than slowing down the transition to EVs, regulators would be well advised to identify entirely separate new sources of revenue that recognize both the neutral externalities of EVs and the considerable system-wide and multiplier benefits of vehicle-to-grid (V2G) and vehicle-to-everything (V2X) technologies. Naturally, tax revenue required for road and infrastructure maintenance and to combat particulate matter from tyre wear is likely to be accepted as equitable by all stakeholders.

Owing to their relative novelty, prospective buyers have concerns about the resale value of EVs. A liquid second-hand car market not only allows for much cheaper second-hand cars, it also allows for a good estimation of the residual value of new cars (and their batteries), thus reducing the risk of buying a new car and the price of leasing. The example of the second-hand EV market in Norway shows significantly lower depreciation of EVs compared to combustion vehicles.

A key facilitator of this second-hand market will be the accurate evaluation of the remaining life of batteries. This is not only a function of the number of km driven but also of the charging profiles, battery temperature and drive cycle throughout the car's life.

Access to charging

Access to charging is not only an issue in countries with poor or little electricity infrastructure. With the cost of EVs declining, and their penetration increasing, the availability of charging infrastructure is rising in importance as a barrier to EV uptake.

> A total cost of ownership (TCO) exercise would reveal that on average EVs have already plunged through the fossil TCO line.

While first-generation EV buyers relied mainly on private charging (in 2020, 80% of EV buyers in Europe had access to private charging (McKinsey, 2021), the next generation will depend on public charging to a large degree. More than 50% of Europeans live in multifamily households without private charger access, and public chargers will ensure practicality of EVs for long-distance trips, which prospective EV buyers still consider a main concern.

Innovative business models and use of parking spaces and land are key to solving these challenges for EV owners. Novel solutions such as rapid-charging hubs, lamppost chargers, and bookable overnight parking are all being explored to allow drivers easier access to charging near their homes.

Charging infrastructure and EV purchases are sometimes seen as a "chicken and egg" situation where private investors need to see more guaranteed returns before investing in hardware. This is where governments mandating ICEV bans will send clear signals to markets. Direct subsidies will still be required in most regions to fix market failures where high grid connection costs and uncertain demand will lead to certain routes or communities with insufficient chargers.

Charging experience

In many countries the experience of using public charging infrastructure leaves a lot to be desired, with the notable exception of the Tesla supercharging network. Public charging suffers from availability issues, pricing transparency, and ease of use challenges with drivers needing a collection of apps to access all public chargers. New protocols such as ISO 15118 which will enable Plug & Charge functionality will be a step change in ease of use for non-Tesla drivers. Its implementation will require coordination and innovation from EV manufacturers and charging network operators.

Supply chain and batteries

The availability of battery-grade raw materials has been a much-reported concern in the media lately. However, DNV expects that the sustained high prices of critical minerals will incentivize investors to fast-track their mining and refining projects, and the gap between the supply and demand will diminish over the coming years. This will not alleviate all near-term shortages: for example, the production of lithium carbonate and nickel will increase considerably in the coming decade, but short-term supply imbalances will occur due to burgeoning EV demand. Traditionally, lead times for mining projects have been 8-10 years to production. However, time to market for lithium and similar projects will be accelerated by the massive infusion of capital for clean technology, advances in industrial digitalization, a ready market, and a relatively low break-even period for early producers.

The future of electric heavy road transport

Within the transport sector as a whole, arguably the most significant remaining frontier for innovation and market impact is the electrification of heavy road transport. However, even in this segment, progress in electrification has been much faster than progress in alternatives such as hydrogen powered heavy road transport, one reason why several sub-segments that a few years back were believed would be powered by hydrogen are now significantly electrified. Heavy road transport is not a homogeneous segment (Figure 3.13); its elements include municipal garbage collection, construction and mining, specialized city logistics, and long-haul delivery. Some segments will be easier to electrify due to the driving patterns, where transport distance and convenient, rapid charging are important determinants of total cost of ownership (TCO).

Despite considerable pressure in many markets for commercial logistics companies to reduce their Scope 1 emissions, TCO is a key indicator of which categories will be electrified first. Unlike private owners, logistics companies are likely to conduct detailed TCO analyses prior to switching to electrified vehicles. Clearly, with further development of EV truck technology and fast charging, the categories that can be electrified will continue to increase.

Charging infrastructure

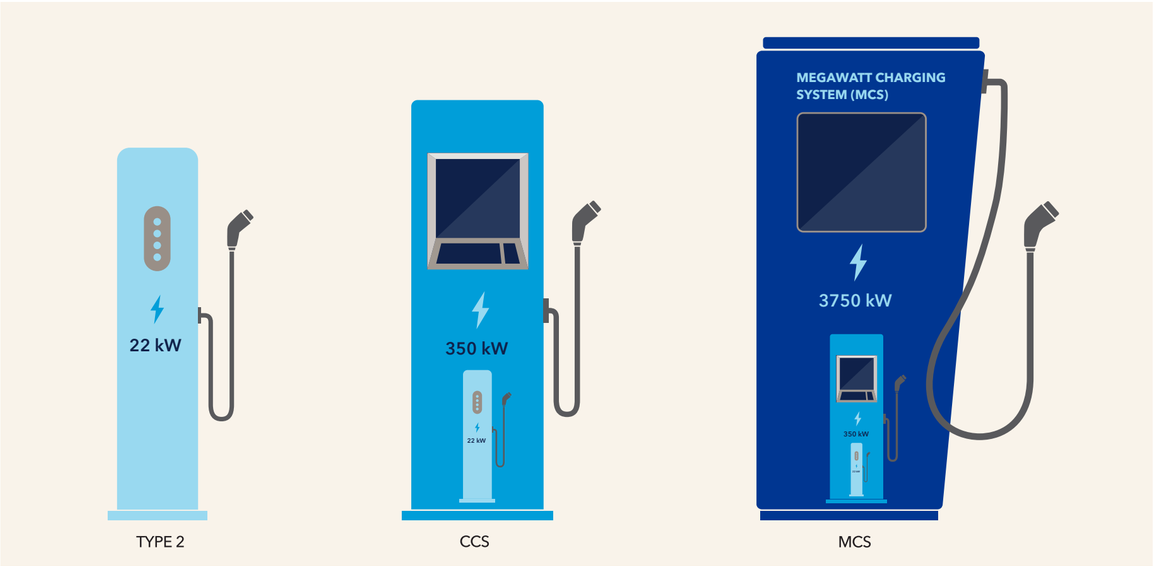
Over time, charging infrastructure has evolved from 11-22 kW (AC, type 2) used for public charging, towards fast chargers up to 350 kW (DC, CCS). The new international standard under development from CharIN for the Megawatt Charging System (MCS) will reach a maximum power of 3,750 kW DC (Figure 3.14). This standard is specially designed for safe fast charging of

FIGURE 3.13

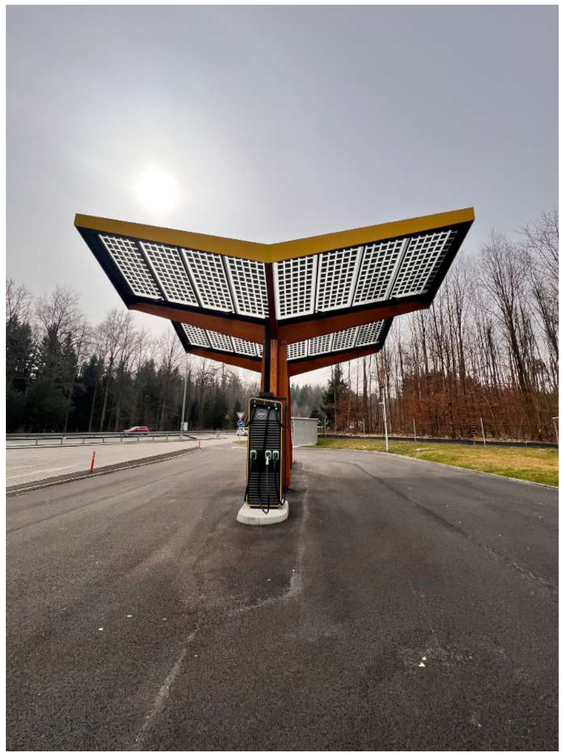
Categories of heavy-duty vehicles

FIGURE 3.14

Continuous development: Pushing chargers' boundaries (type 2, CCS, MCS), with 'Russian doll' inserts illustrating the magnitude of power rating differences



trucks and buses. Current electric trucks are not yet able to charge with this maximum power, due to voltage and power limitations on the truck side, but this standard will solve the range anxiety for trucks. With 1 MW fast charging, a lunch-stop of one hour would typically result in sufficiently charged batteries for the next 900 km. This broadly matches the average daily driving distance for long-haul



truckers, but does not quite satisfy, for example, the US Department of Transport maximum driving limit of 14 hours in a 24 hour period, and a mandatory 30 minute break after 8 hours of driving. Nevertheless, as MCS or similar fast charging technology rolls out, companies will likely adapt logistic solutions for efficient electric transport.

Charging requirements

With fast charging technology in place, it will be logistic patterns that will determine charging possibilities for different truck segments. In Europe, for instance, around 70% of heavy freight truck journeys are less than 250 km (Speth et al., 2022).

These distances indicate that overnight depot charging could solve large parts of national and state logistics, if necessary, in combination with opportunity charging at depots that are visited during the day. Day-time opportunity charging requires dispensers allowing high power ratings during short time intervals. For international freight transport and large countries, charging along highways, or designated truck logistic hubs will be required. Even though international freight transport does not represent the majority of freight transport, it will charge relatively large amounts of electricity due to the high number of operating hours. Logistic companies will add another component to their planning: making sure there will be chargers available.

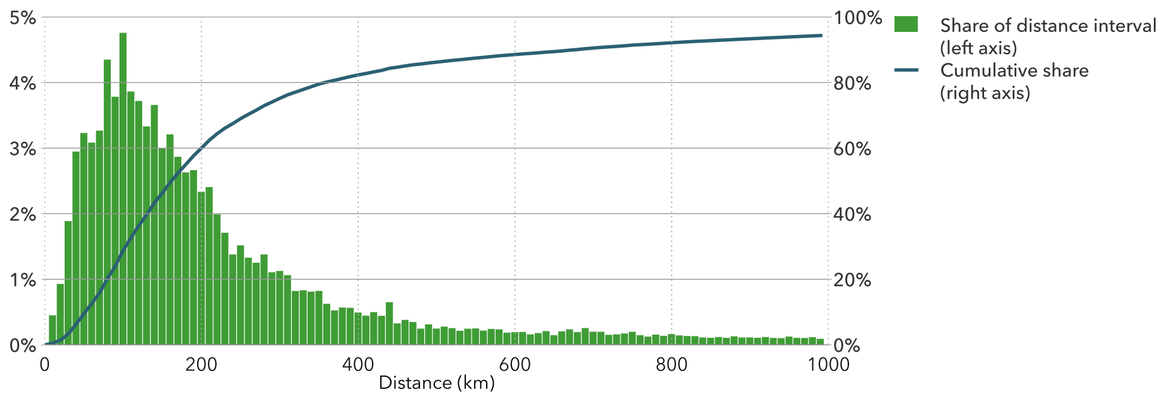
Various solutions emerging for depot charging include concepts for charging at the loading docks, for overnight charging of large numbers of trucks/buses, and combinations with shared infrastructure use for depot charging and (faster) opportunity charging (Heliox, 2023). Tesla, having pioneered its own charging infrastructure for cars, is implementing a proprietary fast charging solution (1 MW) for trucks. Other original equipment manufacturers (OEMs) or consortia look likely to be fast followers of this solution. A clear example is Milence (Milence, 2023), an EU company founded by major truck OEMs, that will roll out MW size fast-charging infrastructure for trucks in Europe. Several demonstration projects have started, underpinning the steep growth of electric road transport we expect in our forecast.

For international freight transport and large countries, charging along highways, or designated truck logistic hubs – effectively 'green corridors' – will be required. International freight transport is a modest percentage of overall freight, but it does require relatively large amounts of electricity due to the high number of operating hours. Planning ahead for sufficient charging will be an important activity for freight logistics companies.

FIGURE 3.15

Journey distance for European national and international freight transport

Units: Percentages



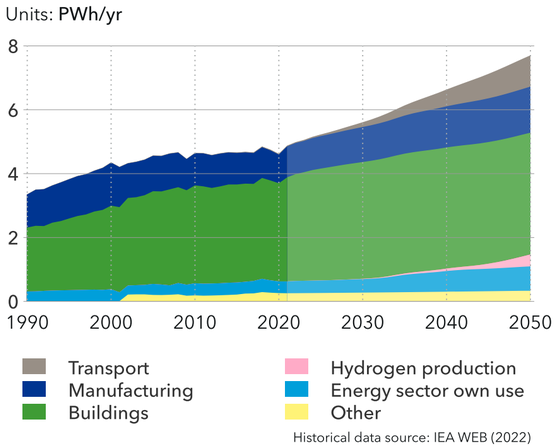
Historical data source: Speth et al., 2022

Integration into the electricity system

The integration of electric road transport into an electricity system needs to be considered at multiple levels. In this section, we will assess the energy needed for electrification of road transport and how this compares with the electricity system as a whole, the potential integration with variable renewable electricity generation, integration with regard to the capacity of the electricity network, and finally integration with public charging.

FIGURE 3.16

World electricity demand by sector



The electric capacity needed for electric road transport

The first question that needs to be answered is whether the electricity system can cope with the increase of volume of energy that is required to electrify road transport, especially considering that other sectors also need to electrify. Taking the EU as an example: at present, the entire transport sector represents about 2% of Europe's electricity use, and most of that is for rail transport. By 2050, the extensive electrification of road transport will see the share of transport, in what will then be a much larger electricity mix, rise to 17%. By mid-century, transport electricity demand will be marginally less than that from manufacturing and less than half the electricity demand from buildings. Accommodating this substantial rise in electricity demand across Europe will be challenging, but in our view is not unrealistic.

Electrification has significant efficiency advantages compared with internal combustion engines. Thus, despite the comprehensive transition of the road vehicle fleet to electricity, transport electricity demand will only rise by some 35–40% by 2050 compared with today. In fact, a much larger increase in electricity demand will come from the replacement of natural gas for heating with electrical heating, even considering the high efficiencies of modern heat pumps for space heating.

Renewable integration

The energy transition requires a huge increase in renewable generation from wind and sun. Because these sources are variable and follow weather

patterns instead of demand profiles, electricity storage, connectivity, demand-response and demand-following renewable generation (like biomass-based electricity generation) are required to make optimal use of these variable renewable energy sources.

EVs have the potential to provide a major and relatively cost-effective contribution to generation-following demand and electricity storage because of the inherent storage capacity of on-board batteries. This requires coordination with the electricity system to ensure that their charging – and possible discharging – will happen at times that are beneficial to the system. Discharging into the grid (vehicle-to-grid orV2G) is interesting, because it drastically increases the available storage capacity for the electricity system. Most EVs currently do not support V2G[1], and what is presently termed 'smart charging' only replenishes the energy that has been used for driving flexibly. With V2G, the whole capacity of the battery is available for the electricity system (considering energy reserved for driving and a safety margin to avoid excessive battery degradation). Properly configured for V2G, the storage volume EVs can offer to the electricity system is multiplied by a factor 4 to 5.

[1] Most EVs do not support V2G and/or are not optimized for this, resulting in low efficiency when discharging to the grid/building.

The expanded concept of 'vehicle-to-everything' (V2X) technologies, including V2G, vehicle-to-home (V2H), and vehicle-to-building (V2B), has the potential to revolutionize the way we use and manage energy in transportation and buildings. As DNV reported recently, a large-scale pilot has shown conclusively how V2X can bring very large benefits to grid operators and consumers alike (DNV, 2023c).

Figure 3.17 shows the variations of electricity demand and renewable generation in Germany for a week in May 2022. The demand that cannot be satisfied by renewable generation is called the residual load. The figure shows the effect on the residual load if the approximately 2 million EVs that are currently driving in Germany (4% of the total fleet) were to offer, on average, 20 kWh of storage capacity to the electricity system through V2G. This is the equivalent of a total battery capacity of between 20 GWh and 40 GWh. This graph shows that such a volume already would have a significant impact on the electricity system, allowing for a better integration of variable renewable electricity generation.

Integration in the electricity network

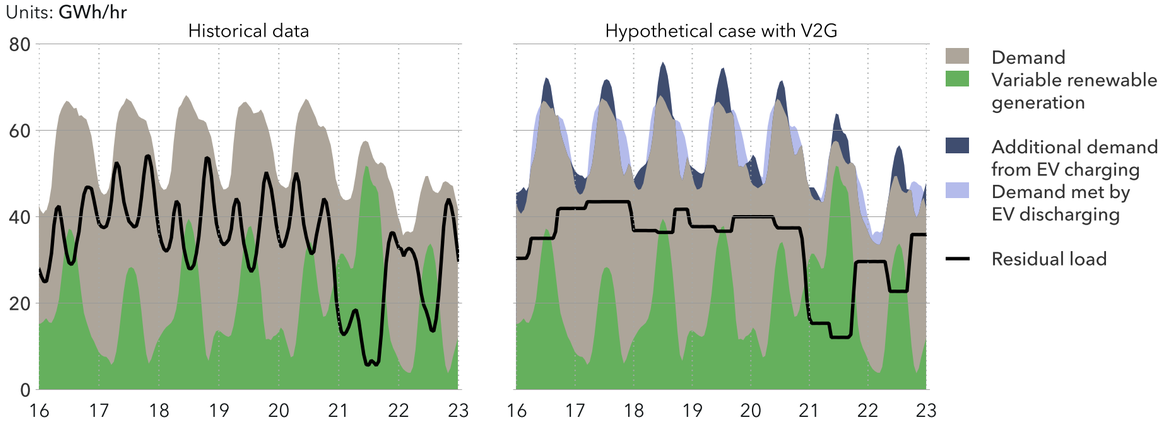
Figure 3.17 also shows that EVs will charge during the day to absorb solar energy, increasing peak demand. This can be positive for the grid, if this electricity is both generated and consumed locally, as it reduces the need to transport it out of the area. However, if the electricity needed to charge the vehicles needs to be transported from farther away, the network in between will require a significant expansion of capacity to accommodate the power flows.

A significant network reinforcement is required to facilitate the increasing and fluctuating energy flows caused by variable renewable generation and changing demand profiles, such as EV charging. However, reinforcement and associated investments can be greatly limited if flexible demand, such as smart charging and V2G take into account network constraints. Charging plazas can reduce the net impact of a fleet of EVs on the grid by distributing the scarce local network capacity among the vehicles in a smart way, reducing the otherwise required peak capacity by 80-90%. Obviously, this comes at the cost of not offering flexibility to the electricity system as a whole. Also, for fast charging at transit routes and logistic hubs, where a large charging capacity – and thus grid capacity – is required, in some cases continuously, charging plaza concepts can offer some relief, possibly combined with local storage to make sure the scarce grid capacity is fully utilized. For bus routes and for cargo, concepts like 'opportunity charging', where buses can charge at bus stops for a few minutes through a pantograph are competing with solutions using larger battery sizes.

With the cost reduction of batteries, concepts like opportunity charging for buses might be supplemented by stationary batteries used as a buffer to reduce the impact on the network or give way to concepts like battery swapping. Companies like Sany, SPIC, and CATL are implementing solutions in China for fleets of trucks for which standardization is easier to accomplish.

FIGURE 3.17

Daily variations in electricity demand for a week in May 2022 in Germany



Historical data source: ENTSO-E (2023) Transparency platform

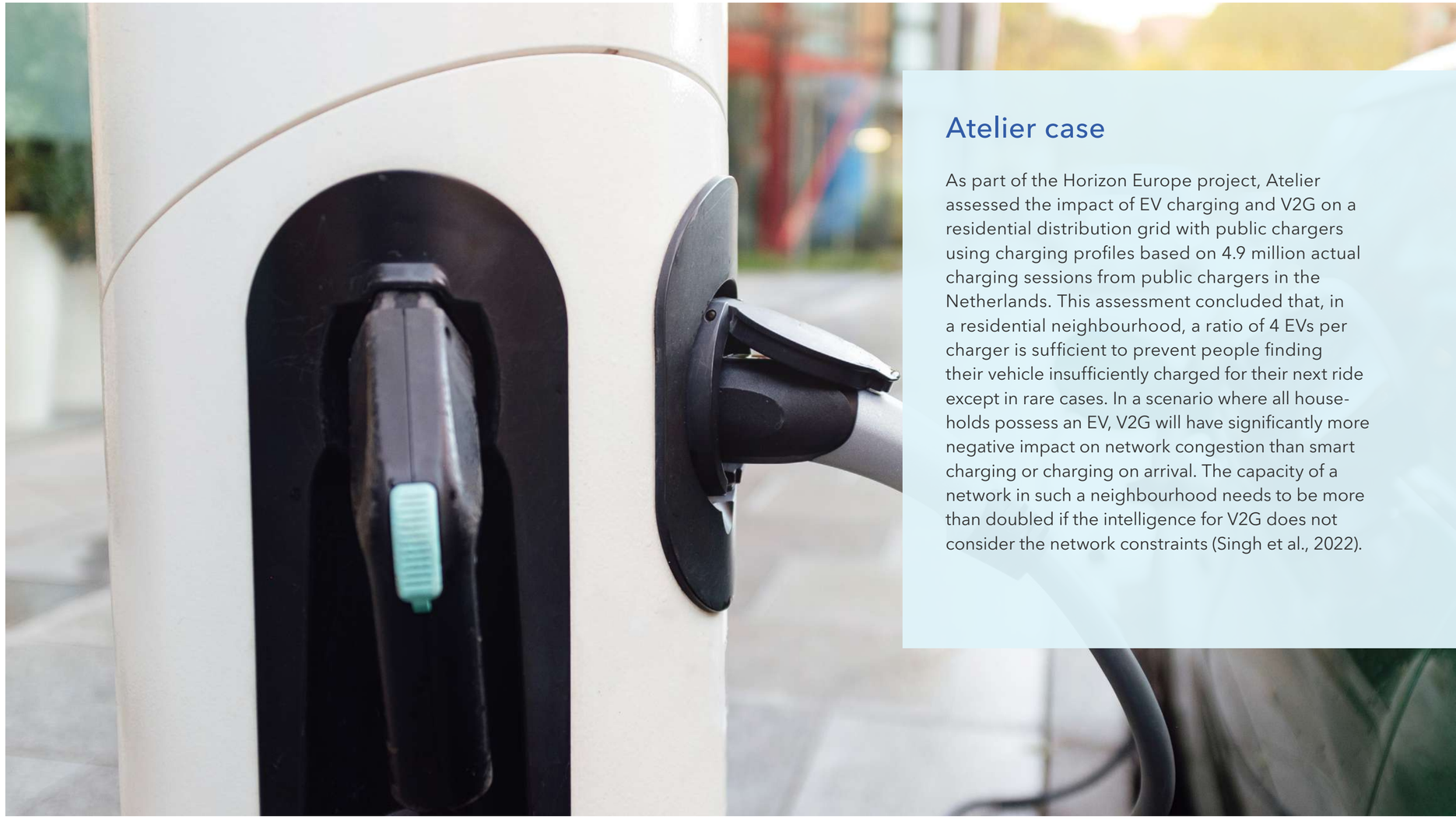
Opportunity charging of busses using a pantograph (photo: DNV)

Private vs public charging

For EV drivers, smartness takes yet another form. EV drivers with a private and suitable grid connection can reduce their energy bill through incentives from the grid operator that reflect the available grid capacity. However, an increasing number of EV drivers will rely on public chargers[2]. For them, access to a charging spot is the primary concern while smart charging and V2G, which requires a stable connection to the grid, will be less relevant. A key question is how to ensure that other vehicles occupy the scarce charging capacity for as short a time as possible?

Tesla, for example, levies 'idle' fees that apply when a car is fully charged and left at a busy supercharger location; the fee is waived if the car is moved within 5 minutes of reaching full charge. Many other solutions are being explored, such as chargers that make smart use of scarce shared network capacity, with insights gained from real world use of public charge points (see Atelier case).

As the electrification of road transport progresses, 'smartness' will mean different things to different stakeholders as a range of options emerges for both access to and optimal use of charging facilities.

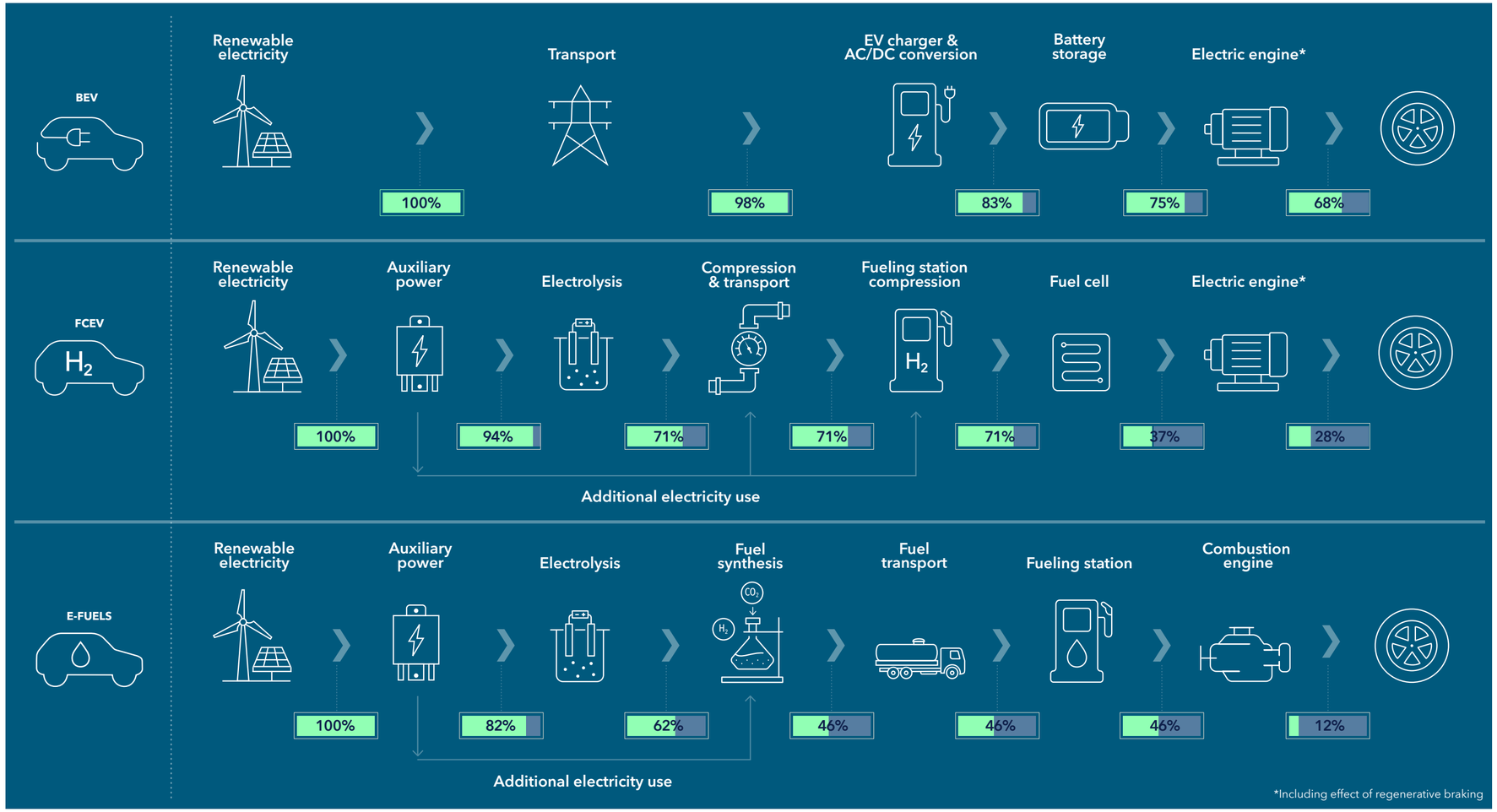


Atelier case

As part of the Horizon Europe project, Atelier assessed the impact of EV charging and V2G on a residential distribution grid with public chargers using charging profiles based on 4.9 million actual charging sessions from public chargers in the Netherlands. This assessment concluded that, in a residential neighbourhood, a ratio of 4 EVs per charger is sufficient to prevent people finding their vehicle insufficiently charged for their next ride except in rare cases. In a scenario where all households possess an EV, V2G will have significantly more negative impact on network congestion than smart charging or charging on arrival. The capacity of a network in such a neighbourhood needs to be more than doubled if the intelligence for V2G does not consider the network constraints (Singh et al., 2022).

[2] In 2021, about 42% of the EV drivers in the EU did not have a private parking place (Source: McKinsey 2022: Europe's EV opportunity – and the charging infrastructure needed to meet it). This will increase. As mentioned in 3.2.1, the access to charging is one of the challenges as more people that do not have a private parting space will switch to electric driving.

FIGURE 3.18



An energy penalty for producing pure CO_2 for the synthetic fuel production is not included

WELL-TO-WHEEL PERSPECTIVE OF ROAD TRANSPORT ALTERNATIVES

BEV registrations are growing at a CAGR of well over 30% in most large economies. FCEV registrations are already three orders of magnitude lower and will maintain only a marginal share of new passenger car sales. This is related to reasons of cost, refueling inconvenience, and the limited number of FCEV models available. But where BEVs really show their superiority over FCEVs is in energy efficiency, making BEVs the only reasonable choice of passenger road transport from an energy system perspective.

Our analyses shows that the less complicated value chain of BEVs is about three times more efficient than that of their FCEV counterparts on a well-to-wheel basis. The conclusions presented are for average mid-sized passenger vehicles but are not very different for commercial vehicles. However, we acknowledge use cases where long-range commercial FCEVs are the preferred option despite the drawbacks.

Curiously, e-fuels have been touted recently as an 'ideal' renewable fuel because they can be used in the existing vehicle fleet. However, this is tantamount to building castles in the air. E-fuel-powered vehicles are not only five times less efficient than BEVs on a well-to-wheel basis, but e-fuels as such are simply not available. They can only become a valid market once renewable energy penetration is very high and there is an abundance of over-supply hours – and that is not going to happen in any major economy within at least the next decade.

Aviation

Aviation emissions continue to climb in the wake of the pandemic. In 2021, aviation emissions grew by nearly a third after the 2020 low, accounting for over 2% of global energy-related CO_2 emissions. In 2022, emissions from oil use grew faster than emissions of coal, with aviation responsible for about half of that increase as the industry continued to rebound from the pandemic downturn.

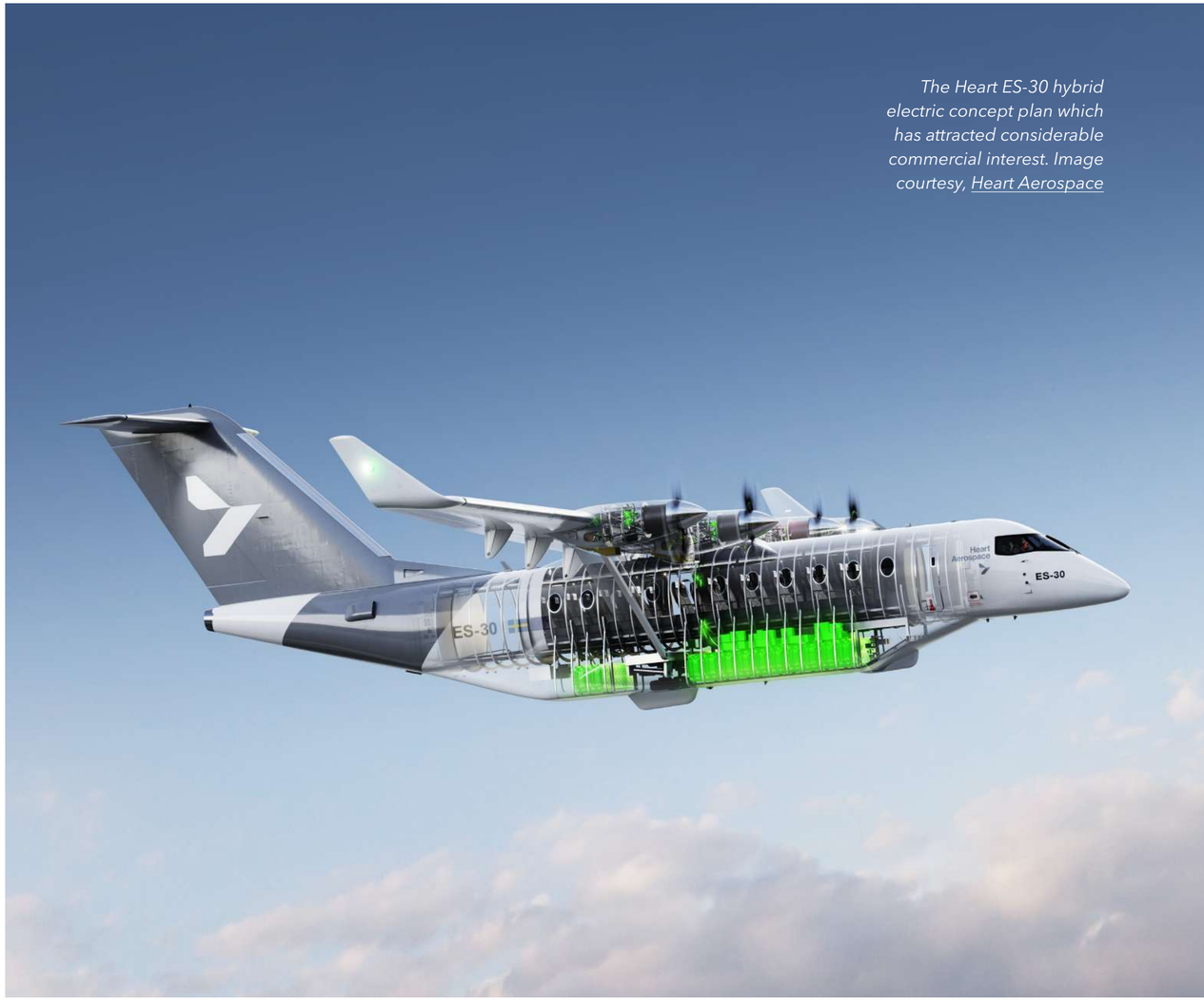
The aviation sector is a hard-to-abate sector. Kerosene is an easy to store, high-density fuel that is not easily replaced.

One alternative is electric flying, but this seems only an option for short distance flights with small airplanes. There are some micro electric airplanes operational and there are plans for small passenger airplanes, as pure electric or hybrid. In September 2022, the world's first all-electric passenger plane 'Alice' took flight from the Grant County airport in northwest US (CNN, 2022). Also shown opposite is an example of a concept hybrid electric airplane with a capacity of more than 25 passengers and an action radius of 200 km full electric and up to 800 km in hybrid operation (WEF, 2022).

The obvious limitation with electric flying is the weight of the batteries. Although the energy density of batteries significantly improved with the emergence of Li-batteries, the energy density is still a factor of 50 below that of kerosene. Moreover, aircraft greatly benefit from the decrease in weight due to the fuel consumption during the flight[3]. Batteries, charged or empty, do not change weight. Additionally, aircaft are obliged to always keep approximately 5% contingency fuel available, e.g. to be able to reach the nearest available airport in case of an emergency or circle an airport until it can touch down. The "dead weight" of this required contingency fuel is a burden for electric airplanes. Additionally, on short-haul flights, there may be competition from much more energy-efficient high-velocity trains. While we will undoubtedly see a growing array of innovative electric and hybrid aircraft in the coming decades, these will be confined to short- and medium-haul duty, whereas it is long-haul flights that are responsible for the bulk of aviation energy use and hence emissions. Today, international aviation is responsible for 60% of aviation energy demand. Our *Energy Transition Outlook* forecasts a marginal role for electricity in aviation, reaching approximately 2% of the total energy consumption for aviation in 2050 (DNV, 2022, p. 200).

We will undoubtedly see a growing array of innovative electric and hybrid aircraft – but confined to short- and medium-haul flights.

[3] For an average-sized airplane with a maximum take-off weight of 80 tonnes, approximately 50% is airplane weight and 20% is fuel weight.



The Heart ES-30 hybrid electric concept plan which has attracted considerable commercial interest. Image courtesy, Heart Aerospace

Taxiing, low hanging fruit?

Despite the expected marginal role of battery-powered electric flying, there is another way to reduce the use of kerosene: electric taxiing. Almost all aircraft need to taxi to the runway to take off (taxi out) or taxi from the runway to the terminal after landing (taxi in). Currently, taxiing is done using the aircraft engines to move the airplane. This has several disadvantages:

1) The efficiency of the aircraft engines is much lower at this low power output than at nominal power. The fuel consumption and carbon emissions are therefore relatively high.
2) Taxiing with aircraft engines produces significant noise pollution.
3) Taxiing is also a source of particle and nitrous oxide emissions.

Depending on the type of aircraft, the flight duration, and the distance from and to the gate, kerosene use for taxiing takes 2-17% of the total kerosene consumption for the flight (OAG, 2022). This is a significant share, and it is therefore worth diving deeply into the options for electric taxiing.

There are options to electrify taxi-in and taxi-out, e.g. using a built-inn or attachable electric front wheel motor, powered by the airplane's more efficient auxiliary power unit (APU) or using an underground traction system that couples the front wheel of the airplane to an electric traction unit (AIR, 2021). This latter option has the advantage that it can be powered directly from the electricity grid. However, it would take a major overhaul of runways.

The option we will describe briefly here is electric taxiing using a battery-driven tractor. This option requires a tractor that can pull (accelerate and move) an airplane over the distance between the runway and the gate (typically up to 5 km) and all the logistics around it. This option can be implemented with relatively low impact on current flight arrival and departure logistics.

FIGURE 3.19

Electric towing could lead to average fuel savings of 8%

Potential of electric taxiing

There are four obvious decisive factors for the impact of electric taxiing:

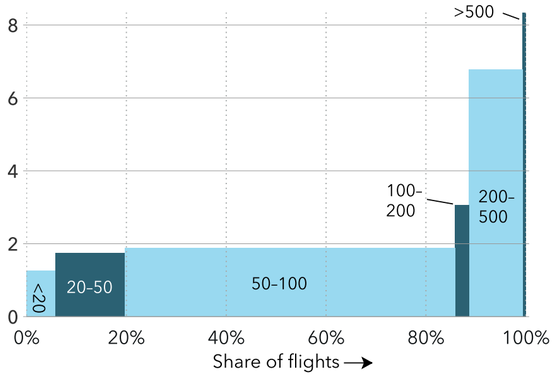
1) The duration of the flight
2) The taxi time/distance
3) The weight of the aircraft, and
4) The number of flights with the aircraft

Heavy airplanes that fly frequently over a relatively short distance offer the most potential for reducing kerosene use. Our research shows that most flights are made by aircraft in the weight class of 50-100 tonnes. The category above 500 tonnes is solely filled by the Airbus 380 (Eurocontrol, 2023)

FIGURE 3.20

Average flight time by airplane weight class (in tonne) in Europe

Units: hours of flight

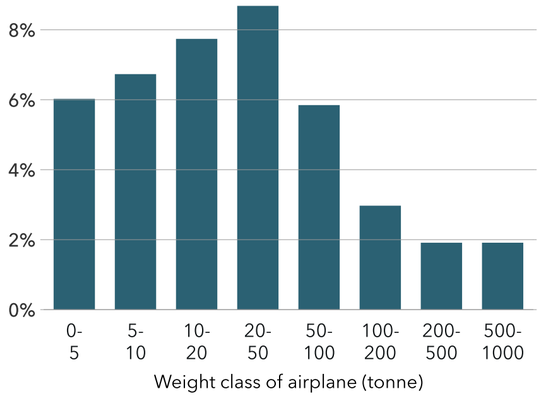


The specific fuel use for taxiing (in kg/min) is proportional to the weight of the aircraft. Based on literature values (Gollapudi, 2019; Airliners.net, 2017) for this specific fuel consumption, an estimate is made for the savings potential from electric taxiing. The result of this estimate is shown in Figure 3.21. It indicates that up to 8% average fuel savings can be realized. This is significant and an obvious decarbonization target with several co-benefits. However, as we have detailed elsewhere in this report, the heavy lifting in the decarbonization does not rely on direct electrification as such, but largely on a combination of indirect electrification (hydrogen and its derivates) and (sustainable) biofuel.

FIGURE 3.21

Potential for kerosene savings by electric taxiing compared to total trip fuel use, in Europe

Units: Percentages



Maritime transport

Similar to EVs, the evolution of electric maritime transport had a surprisingly early start. Reports of small electric boats and recreational crafts date back to the 1830s and reports on commercial operation and charging infrastructure (fixed and floating) date back the 1880s (ETHW, 2013). The age of oil in maritime from the early 20th century eclipsed these developments, although some pioneering work with electrification continued, particularly in Europe, where inland waterways are often calm and narrow.

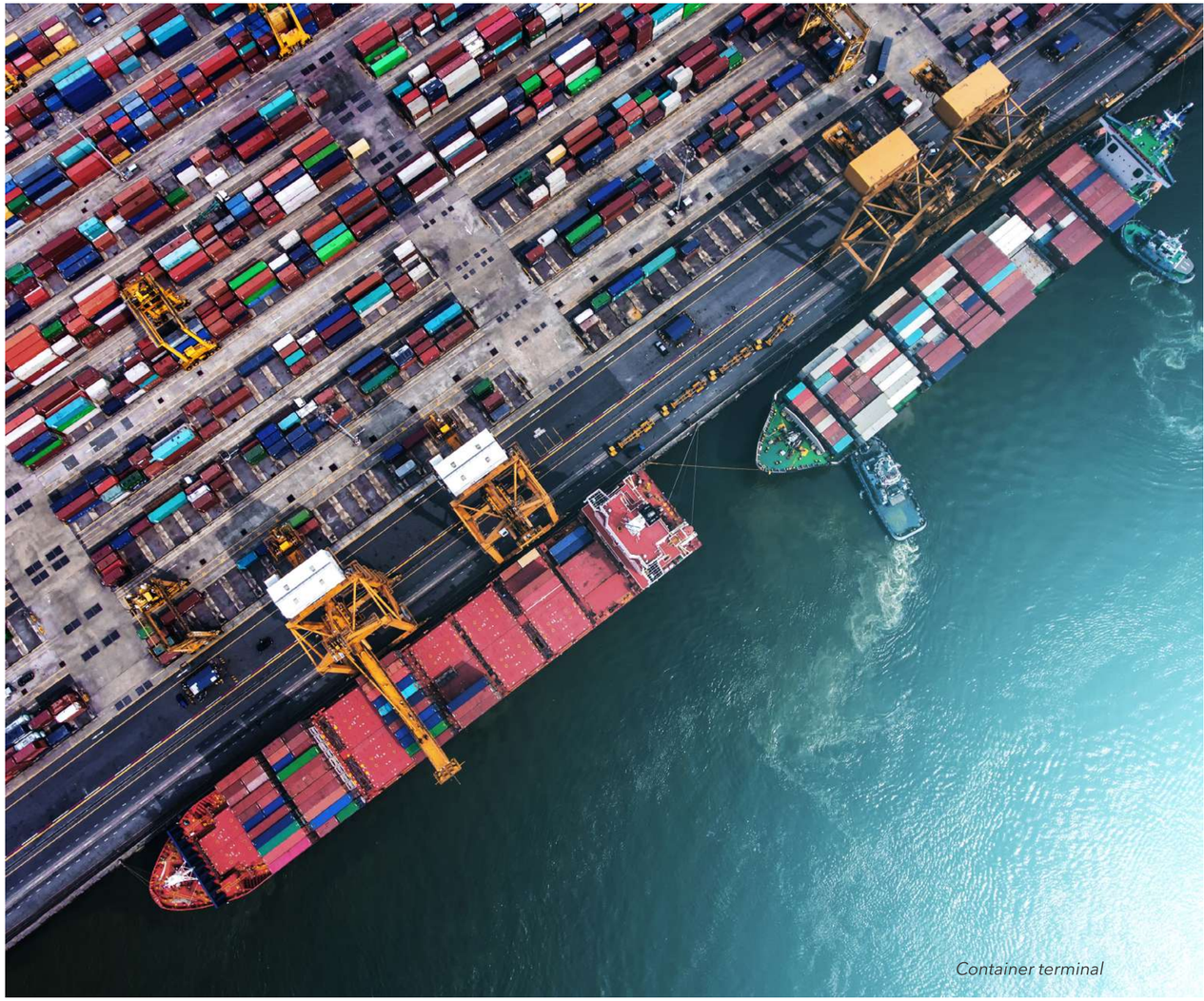
Electric inland shipping can help to reduce the strain on existing transportation infrastructure, such as roads and rail lines.

Modern electrification efforts, however, date to the early 2000s when battery technology (Li-ion) and electric propulsion technology improved rapidly. The first all-electric car-and-passenger ferry was launched in Norway in 2014. This vessel, the MS Ampere, can transport 120 cars and 360 passengers across the Sognefjord.

While attention automatically focuses on ferries, port operation tugs, or short sea ships like the Yara Birkeland 120 TEU container ship, inland shipping deserves similar attention as a candidate for electrification. The environmental benefits are important in ports and along inland routes. Fully electric vessels do not emit local harmful pollutants compared with traditional fossil fuel powered vessels. Moreover, the alternative is quite often road transportation and waterways can provide a convenient alternative route to destinations, avoiding traffic and congestion on the roads. In addition, electric inland shipping can help to reduce the strain on existing transportation infrastructure, such as roads, rail lines, highways, and bridges, and can be an important component of a sustainable and efficient transportation system.

To cater to the large power needs, battery swapping systems for inland waterways are under development, including the use of standardized batteries that can be quickly and easily swapped out of electric vessels at designated battery swapping stations. These swapping stations are located along the waterway network and allow vessels to quickly exchange their depleted battery for a fully charged one, thereby minimizing downtime.

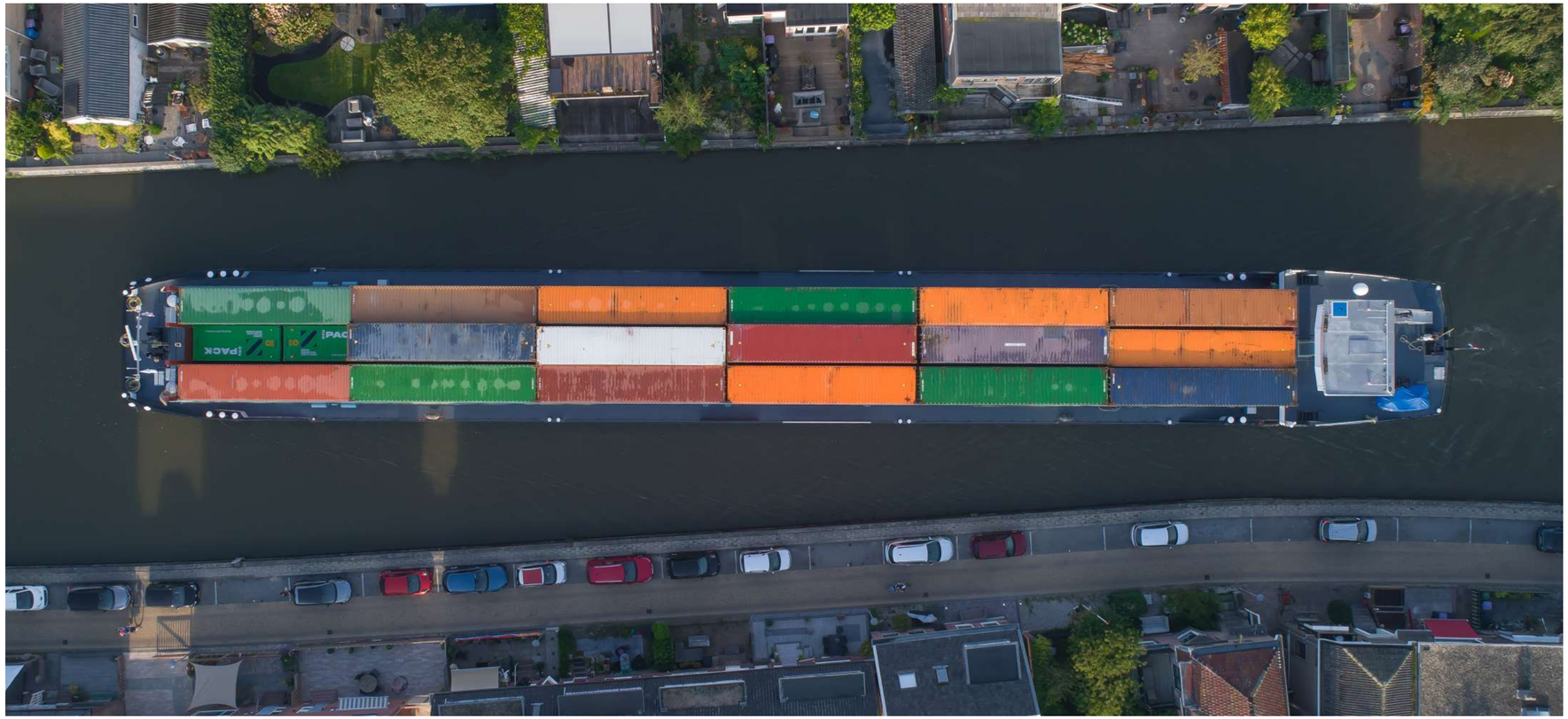
A good example is the Alphenaar, which started operation in 2021, the first Dutch inland vessel to use interchangeable energy containers for propulsion. The Alphenaar sails between Alphen aan den Rijn and Moerdijk and uses the ZES battery system (ZES, 2020).



Container terminal

The battery swapping process involves the use of (standard) cranes or hoists to lift the containerized battery out of the vessel and replace it with a fully charged one. The depleted battery is then recharged at the swapping station using renewable energy sources, such as solar and wind power, which helps to further reduce the environmental impact of inland waterway transportation. The use of a standardized battery swapping system can also help to reduce costs for vessel operators, as they no longer need to purchase and maintain their own battery systems. Instead, they can pay a fee for the use of the swapping system, which can be more cost-effective in the long run.

Overall, the containerized battery swapping system for inland waterways is a promising solution for sustainable and efficient river and canal transport and has the potential to significantly reduce emissions and improve the reliability and affordability of electric vessel operations.



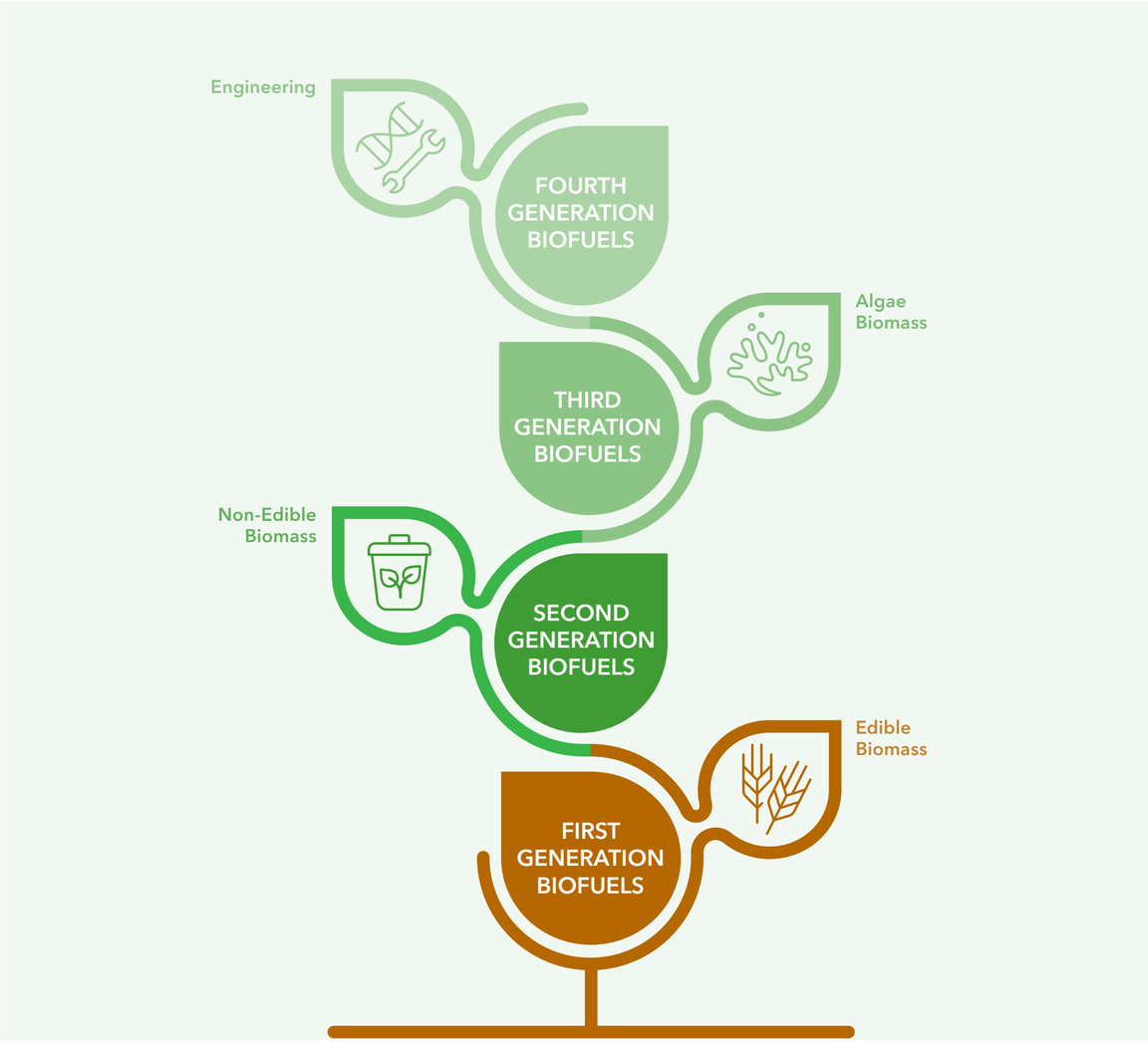
For ocean going vessels, battery swapping is likely not a big opportunity. Berthing time would normally be sufficient to charge a battery, and energy density and overall battery weight are the main challenge. Ferries are already doing MW charging with MW size batteries and the most optimistic present plans are for battery sizes up to 60-70 MW and charging of 30-40 MW (Ship Technology, 2021). Despite these and many other innovations, electric deep-sea shipping is not likely to ever constitute a sizeable share of overall energy use unless there is a radical, unforeseen revolution in battery energy density, which we do not factor into our forecast. DNV expects about 2% of maritime fuel use at sea to be electric by 2050 (DNV, 2022). Nevertheless, the potential to use electricity while berthing is significant. Cargo-carrying vessels have port stays of many hours, sometimes a day and more, and need to run auxiliary engines causing GHG emissions, local pollution, and noise. Providing these vessels with shore power is an obvious option, and although sometimes challenging from a power and capacity point of view, we expect that electricity use for shore power will increase significantly in the coming decades, representing typical 2-4% of global shipping energy use by 2050.

The Alphenaar, with the battery containers at the front of the ship. Image, courtesy Combined Cargo Terminals b.v., and Zero Emission Services (ZES).

3.4 BIOFUELS

Biofuels are already extensively used in transport – reducing local air pollution, energy imports, and (arguably) global emissions – and this role is poised to expand. Biofuels either in pure form or blended with gasoline, diesel, or natural gas were introduced decades ago. All regions, except the Middle East and North Africa, have biofuel-blend mandates or give biofuels preferential treatment, a prime example of the role of public policy in transport fuels. Biofuels represented about 4% of global transport energy demand in 2021, and were used almost exclusively for road transport. However, sustainable biofuels will make their way into aviation and maritime shipping very substantially in the coming decades.

Today's biofuel production is dominated by first generation biofuels, biodiesel, and ethanol, and is largely concentrated in 4 main regions (Figure 3.23). First generation biofuels are produced from edible crops such as corn, sugarcane, and soybeans, and can be used as a substitute for conventional fossil fuels in transportation. While first generation biofuels are considered renewable and can help reduce GHG emissions, they have several sustainability issues. A further increase in traditional biofuel production from crops or forests is being met with a chorus of criticism citing concerns about the sustainability of energy crop farming and extensive forestry use (Jeswani et al., 2020; Mather-Gratton et al., 2021). Diesel-powered tractors and fertilizers from natural gas that gives off powerful GHGs like nitrous oxide render much of the present biofuel production a climate net disbenefit. It is also very difficult to make the case for dedicating land to biofuel crop farming given that restoring the same land to forest or native grasses almost always offers a greater net carbon reduction (Fairley, 2022). Additionally, the use of fertilizers, pesticides, and other chemicals in crop production can lead to environmental damage, soil degradation, and water pollution. There are also concerns about the energy balance of biofuels, as the production and processing of the crops and fuels require significant amounts of energy which may outweigh the energy benefits of the fuel. The policies and incentives in place in the US and Europe have helped to drive demand and maintain their use in the transport sector. Very recent cost developments however, are putting pressure on biofuel use in Europe while the US at the same time is looking to increase biofuel use in road transport.



In recent months, biodiesel costs in Europe have ranged 70% to 130% higher than fossil diesel, depending on the feedstock used. Ethanol prices are currently about 50% to 100% higher than gasoline prices on the European wholesale market (Transport & Environment, 2022). Traditionally, biodiesel and ethanol price development has mainly followed diesel and gasoline wholesale prices. However, in the past two years, a partial decoupling has been observed in Europe, increasing the spread between biofuels and their fossil counterparts. Reasons for this can be found in the tense global food market as a consequence of the war in Ukraine. If this trend continues, it might lead to lower crop-based biofuel use to reduce prices at the pump which is a very political and consumer-sensitive topic. In contrast, US ethanol is now cheaper or sold at the same price as gasoline, due to the strong increase in US gasoline prices in the past three years, and a modest increase of US ethanol price in the same period (IEA, 2022). In the US, EPA-backed proposals seek to further increase the use of ethanol to lower the price at the pump further below gasoline (Reuters, 2022).

However, the use of first-generation biofuels is expected to decrease in the long-term as the industry shifts towards second- and third-generation biofuels that do not compete with food production and can be produced by using waste materials or non-arable land. Moreover, the widespread uptake of EVs will reduce the need for first generation biofuels blended in gasoline or diesel. Overall, while there are sustainability concerns associated with first-generation biofuels, the industry itself (e.g. aviation and maritime), nudged by market forces, is gradually shifting focus towards second-generation biofuels (see Figure 3.24), which have the potential to address most of these sustainability issues.

Tomorrow's picture – Second-generation biofuels to supply aviation and maritime

The next decade will see biofuel uptake in transport doubling, while global overall biomass demand rises by only 20%. On the one hand, a lot of traditional and inefficient use of biomass in low-income countries will be replaced by electricity. On the other hand, government and industry decarbonization targets will see heightened biofuel uptake in road transport, and, for the first time, biofuels used at scale in aviation and maritime.

While blending policies in numerous countries drove the demand for biodiesel and ethanol for road transport, maritime and aviation are only in a starting position for significant biomass uptake. However that uptake will be rapid because other immediate decarbonization options are limited, as outlined in the introduction. Because this is new biofuel use, and therefore not locked in to the controversies attached to first generation biofuels, aviation and maritime are likely to be largely supplied by second generation biofuels – that do not compete with food production and can be produced from waste materials or non-arable land, reducing the pressure on land use and natural resources. Additionally, the use of waste materials as feedstocks can reduce GHG emissions and provide economic benefits by reducing waste disposal costs. In the transportation sector, second-generation biofuels can be blended with conventional fuels or used as a standalone fuel.

One of the main challenges is the currently high cost of production compared with conventional fossil fuels and first-generation biofuels. The production processes for second-generation biofuels are still in the early stages of development, and the technology required to produce them at scale is not yet mature.

FIGURE 3.22

Global biofuel production by biofuel type

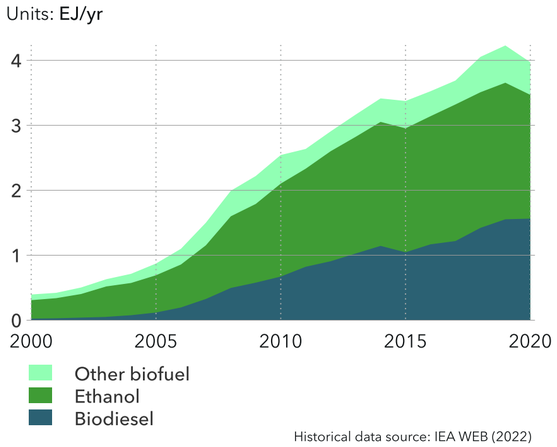


FIGURE 3.23

Biofuel production by region

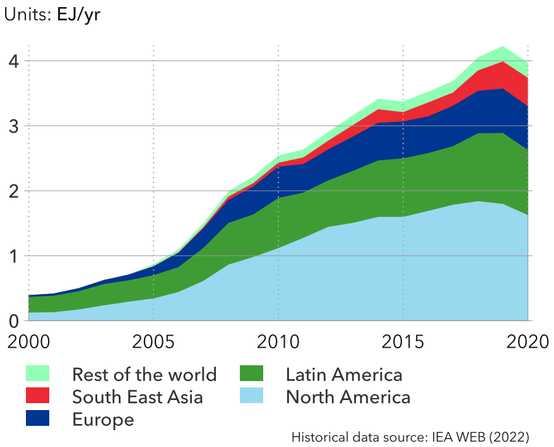
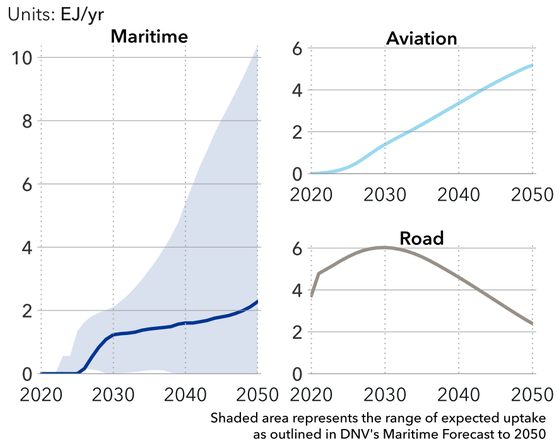


FIGURE 3.24

Biofuel demand in selected subsectors



Another challenge is the lack of infrastructure for the production and distribution of second-generation biofuels. Most of the existing infrastructure is geared towards the production and distribution of oil products and partly of first-generation biofuels. This means that there is a need for significant investment in new infrastructure to support the production and distribution of second-generation biofuels. With many of the technologies for advanced biofuel production being at relatively early stages of development and commercialization, there is considerable room for cost reduction in the medium to long term. A recent study from IEA Bioenergy indicates cost reduction of advanced biofuels in the range of 10-43% in the medium term through process improvement and lower cost of capital (IEA Bioenergy, 2020).

Assuming low-cost feedstock can be used and the factored-in technology improvement and lower cost of capital can be achieved, advanced biofuels would be cost competitive with fossil fuels in the medium term under optimal conditions, but not in general. In the coming decade, advanced biofuels for aviation and maritime are expected to be significantly more expensive than their fossil counterparts. Governmental and industry intervention can help reduce the price gap. An additional carbon price on top of the fossil fuel price will additionally impact the competitive situation favouring advanced biofuels. However, as any remaining cost gap would need to be covered by policy measures and by consumers willing to pay a premium, higher consumer prices for flights and significant government subsidies are the result.

Additionally, the regulatory environment for second-generation biofuels is still evolving, with different countries having different policies and regulations. This can make it difficult for companies to invest in the development of second-generation biofuels, as they may not be able to predict the future regulatory frameworks. Several large policy packages that are poised to boost biofuel uptake in the next decade are mainly in Europe, North America, and Asia, and include:

- Europe – Renewable Energy Directive, RED II
  - Sets the option to choose between a 14.5% reduction of GHG intensity in transport from the use of renewables, or at least a 29% renewable share in transport energy demand by 2030.
  - Includes a binding sub-target of 5.5% for advanced biofuels and renewable fuels (non-biological origin) by 2030.
- United States – Inflation Reduction Act
  - Provides tax breaks for SAFs, clean transportation fuels, and clean hydrogen.
  - Biofuels such as biodiesel and ethanol benefit from extension of existing tax credits.
- Asia`s blending mandates will significantly foster ethanol use in the coming years.
  - India's ethanol blending mandate is targeting 20% ethanol blending by 2025, originally targeted for 2030. This would mean a more than doubling of India`s current ethanol production volumes.

Alternatives from third- and fourth-generation biofuels?

Third-generation biofuels refer to biofuels produced from algae. Algae can produce a range of biofuels, including biodiesel, bioethanol, and biogas, depending on the type of algae and the processing method used. Moreover, algae can be cultivated in a wide range of environments, including non-arable lands and wastewater, which means that they do not compete with food crops for land or water resources. Algae can also be grown using a variety of cultivation systems, including open ponds, photobioreactors, and hybrid systems, which offer flexibility in terms of scale and production costs. Despite their potential, third-generation biofuels have not yet been adopted in the market. One of the main challenges is the high cost of production. The development of efficient and cost-effective processes for the cultivation, harvesting, and processing of algae into fuel is still in its early stages, despite decades of research and pilots aiming at upscaling. Additionally, the high capital investment required to build the necessary infrastructure for large-scale production is a barrier to entry for many companies.

The concept of fourth-generation biofuels is based on the idea that genetically engineering algae to optimize their photosynthetic efficiency and lipid or carbohydrate production could result in a highly efficient and cost-effective biofuel production system. This would enable the production of high-quality fuels with a low carbon footprint and a reduced environmental impact. However, those concepts of third- and fourth-generation biofuels will very likely not provide any significant amount of biofuel by mid-century due to the above-mentioned constraints and barriers.

Competition for feedstock increases

Biomass has been used as an energy source since the Stone Age. Biofuels used today are almost exclusively produced from crops (traditional biofuels) and represent a small portion of today`s biomass use. In light of the very serious sustainability concerns, advanced second-generation biofuels aiming at decarbonizing e.g. aviation and maritime will principally have to come from non-edible sources such as waste and residues. The next decade will therefore see a strong competition for non-food feedstock in North America and Europe, where regulatory frameworks will lead to a dramatic increase in use of both traditional and especially advanced biofuels. Hyper-competition will spark a quest for new and mostly untapped feedstock.

Based on our recent bottom-up analysis and a consideration of literature sources on land-use and sustainable feedstock sources, we estimate that the exploitable biomass potential for biofuels to supply maritime and aviation today is between 32–42 EJ. In the future, this potential could increase to 38–106 EJ. Comparing our sustainable biomass supply estimate to our forecast uptake in aviation and maritime illustrated in Figure 3.24, and our forecast uptake in other sectors outlined in our *Energy Transition Outlook* (DNV, 2022a), we see that the gap between forecast demand and estimated sustainable supply is set to decrease significantly as we approach 2035. Consequently, competition for sustainable biomass will significantly grow in the next ten years and continue to be high thereafter.

Regarding sustainability constraints, the estimate aims to be in line with the EU RED II directive on sustainable biofuels. It is important to note that this estimate does not include conversion of land for biofuel production purposes. The wide range in potential is due to the varying information found in research, such as the dry matter content of straw and the application of different economic and sustainability standards when sourcing biomass for biofuel production. Our 2023 update of the *Maritime Forecast to 2050* to be published in September 2023 will present a more detailed view on the availability of non-food feedstock to 2050 and implications for the maritime industry.

Advanced second-generation biofuels aiming at decarbonizing e.g. aviation and maritime will principally have to come from non-edible sources.

Biofuels in road transport

Biofuels have been the most important option in road transport decarbonization for many decades. Although usually seen independent from each other, the future of biofuels is highly connected to the uptake of EVs. The recent and widespread uptake of EVs will challenge the role of biofuels in road transport in many regions of the world, leading to a decreased use of biofuels in global road transport. While the EU biofuels market is dominated by biodiesel (80%) produced mainly from vegetable oils such as rapeseed, sunflower but also imported palm oil, the large US market is dominated by ethanol (70%) from corn. Those biofuels are highly controversial in terms of actual GHG reduction potential and their competition with food production. The EU made a landmark decision in their RED II limiting the use of crop-based biofuels to the 2020 use of each member state and thus freezes their contribution. At the same time, it is promoting advanced (non food-crop-based) biofuels. A move which is expected to be mirrored by other countries. The future of crop-based first-generation biofuel for road transport is clearly numbered. Production is likely to muddle along in the US until it is rendered uneconomic by EVs. Elsewhere, both electrification and legislation will drive crop-based biofuel out of the energy mix.

Biofuels in maritime transport

Sustainable biomass would be the preferred fuel for maritime transport as it easily can be converted to relatively energy-dense hydrocarbon fuels such as bio-MGO, bio-LNG, or bio-methanol. Sustainable biomass supply needs to be seen in light of demand from other hard-to-abate transport segments such as aviation, which has few decarbonization options.

Consequently, competition for feedstock increases if there is low availability of sustainable biomass. In this case, the prices of biofuels will increase making it unlikely that they will be competitive with e-fuels and other low-carbon fuels when those fuels become widely available. An updated and more detailed analysis of the role of biofuels for Maritime Shipping will be presented in DNV`s *Maritime Forecast to 2050* in September 2023.

Biofuels in aviation

SAFs, including biomass-based first- and second-generation fuels, will change the aviation fuel mix in the coming decade. Both in the short-term and all the way through to 2050, costs of such biofuels will be higher than current oil-based aviation fuel. Switches to these fuels are therefore expected to come as the result of regulatory and consumer-driven forces. Bio-based SAF is already implemented at small scale because of mandatory biofuel blend rates in certain countries and is expected to scale relatively fast given regulatory push and consumer pull. Providing large amounts of sustainably produced biofuel is a challenge, but aviation has fewer decarbonization options and a higher ability to pay. An example of how some industry players are running ahead of regulation in terms of decarbonization is included overleaf.

Industry Insight – DHL Express a frontrunner with SAF

As part of its mission to achieve net-zero emissions by 2050, Deutsche Post DHL Group has partnered with the Science-Based Target initiative (SBTi) to focus on "insetting" emissions within its own value chain rather than offsetting emissions through outsourced projects. One step in achieving this goal is a EUR 7bn investment, announced in 2021, to reduce corporate GHG emissions to below 29 million tonnes by 2030, mainly through:

- 30% sustainable aviation fuel (SAF) blending by 2030
- Electrification of 60% of last-mile delivery vehicles by 2030
- Carbon neutral newbuilds

More than 50% of the above-mentioned investment is dedicated to the direct purchase of biobased SAF. One of the largest such purchases to date involves Neste and BP committing to provide more than 800 million litres of SAF through to 2026. This helps the subsidiary company, DHL Express, to directly reduce emissions of its large aircraft fleet, responsible for over 90% of DHL Express emissions, and placing them at the forefront of biobased SAF use in the aviation industry. So far, DHL Express has sourced biobased SAF from vegetable oils, waste oils, or waste fat based HEFA (Hydroprocessed Esters and Fatty Acids).

This industry-leading initiative is underpinned by 'GoGreen Plus', a new and optional service enabling customers to tailor the level of carbon reduction they desire (for example, in line with their scope 3 corporate emissions reduction targets). While the initial investment helped to fund the securing of large volumes of biobased SAF in a tight market environment, the enrolled "GoGreen Plus" service makes it a business case for DHL Express.

> The initiative is directly targeting first-mover customers willing to co-fund decarbonization.

DHL Express has purchased 800 million litres of SAF, but it is not given that the fuel will be used in its fleet. Through a system called *book & claim*, airlines can purchase SAF without being physically connected to a supply side. The environmental benefits of SAF can be transferred between buyers and end-users via a dedicated trade registry. This mechanism, which is similar to the trade of renewable electricity through virtual power purchase agreements, is seen as an essential means of promoting the uptake of SAF in global aviation.

DHL Express is clearly an innovative frontrunner in tackling the decarbonization of a stubbornly hard-to-electrify transport subsector. The initiative is directly targeting first-mover customers willing to co-fund decarbonization. At the same, however, its substantial forward purchase of SAF over the next 4 years increases the pressure in the tight non-crop-based biofuel sector dramatically. This exemplifies DNV's view that competition for such feedstock for biofuel production will escalate in the medium term, placing early movers like DHL Express at a distinct advantage.

Image, courtesy: Deutsche Post DHL

3.5 HYDROGEN AND ITS DERIVATIVES

Hydrogen normally has significant cost, complexity, efficiency, and often safety disadvantages compared with the direct use of electricity. However, for hard-to-electrify transport sectors, hydrogen and its derivatives such as ammonia, e-methanol, and e-kerosene are the prime low-carbon contenders. But they are contenders in training and will not be available at scale until well into the 2030s. Before then, biofuel will fill an important role.

Hydrogen is combustible and gaseous at normal atmospheric pressure and temperature, but behaves differently to natural gas, requiring adaption or development of infrastructure and safety standards.

Hydrogen is the lightest element and has high energy density compared to weight, offering some advantages for applications where weight can be an issue, such as in heavy road transport. Overall, it is, however, more relevant to consider hydrogen's energy density compared with volume, which is very low compared with other fuels. This makes hydrogen more difficult to store and transport. Low energy density also reduces the feasibility of hydrogen, at least in its gaseous form, for use cases not connected regularly to the grid, such as shipping and aviation. The solution is to condense hydrogen to a liquid – which only partly solves the challenge – or convert it to derivatives such as ammonia, methanol, or synthetic fuels. Liquid hydrogen and derivatives can overcome limitations, but conversion is inefficient and costly.

The green challenge

Hydrogen markets today are mainly captive, with production taking place at or close to key industrial consumers. There are little to no open commodity markets for hydrogen, with the exception of markets for hydrogen derivatives such as ammonia and methanol. Hydrogen can be produced in several ways with varying efficiencies, GHG emissions and environmental impacts depending on the method and feedstock used. Currently it is almost exclusively produced from natural gas and coal without CCS. For hydrogen to be a viable option in the transportation sector, it needs to be decarbonized either through the production of blue hydrogen (i.e. CCS-based hydrogen production from fossil fuels) or from surplus or dedicated renewable energy for production of green hydrogen via electrolysis.

The production of 100% renewable carbon-based hydrogen derivatives is highly dependent on having access to renewable CO_2 sources. In this regard, CO_2 can be obtained from CCUS, DAC and BECCS.

Projected uptake

Figure 3.25 shows our projections for the uptake of hydrogen in both pure or derivative form for the maritime, road and aviation sectors.

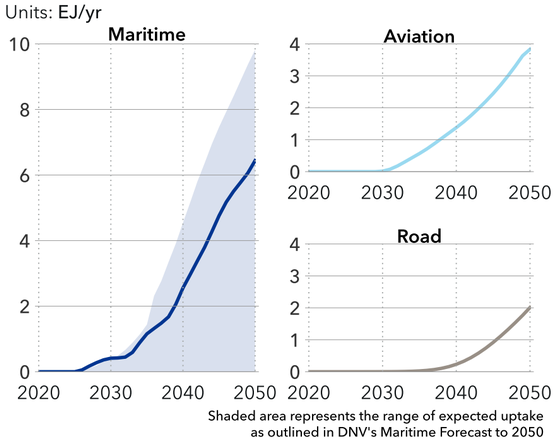
In the maritime subsector, uptake will start in the mid-2020s, but will take ten years to start scaling noticeably. Initially, some smaller vessels will be fuelled by pure hydrogen, but the vast majority of hydrogen use in maritime will be in the form of hydrogen derivatives as elaborated below. Our latest *Energy Transition Outlook* (DNV, 2022a) indicates an uptake of 6.4 EJ/yr in 2050. Due to the uncertainty in uptake in this subsector, we have also included the spread in uptake from DNV's *Maritime Forecast 2022*, where the different scenarios vary from negligible to 10 EJ/yr for hydrogen and hydrogen derivatives (DNV, 2022a and 2022c).

In the aviation subsector, the growth of hydrogen and hydrogen derivatives will start in the early 2030s and grow to about 3.9 EJ/yr in mid-century; some will be pure hydrogen, but the main share will be e-kerosene.

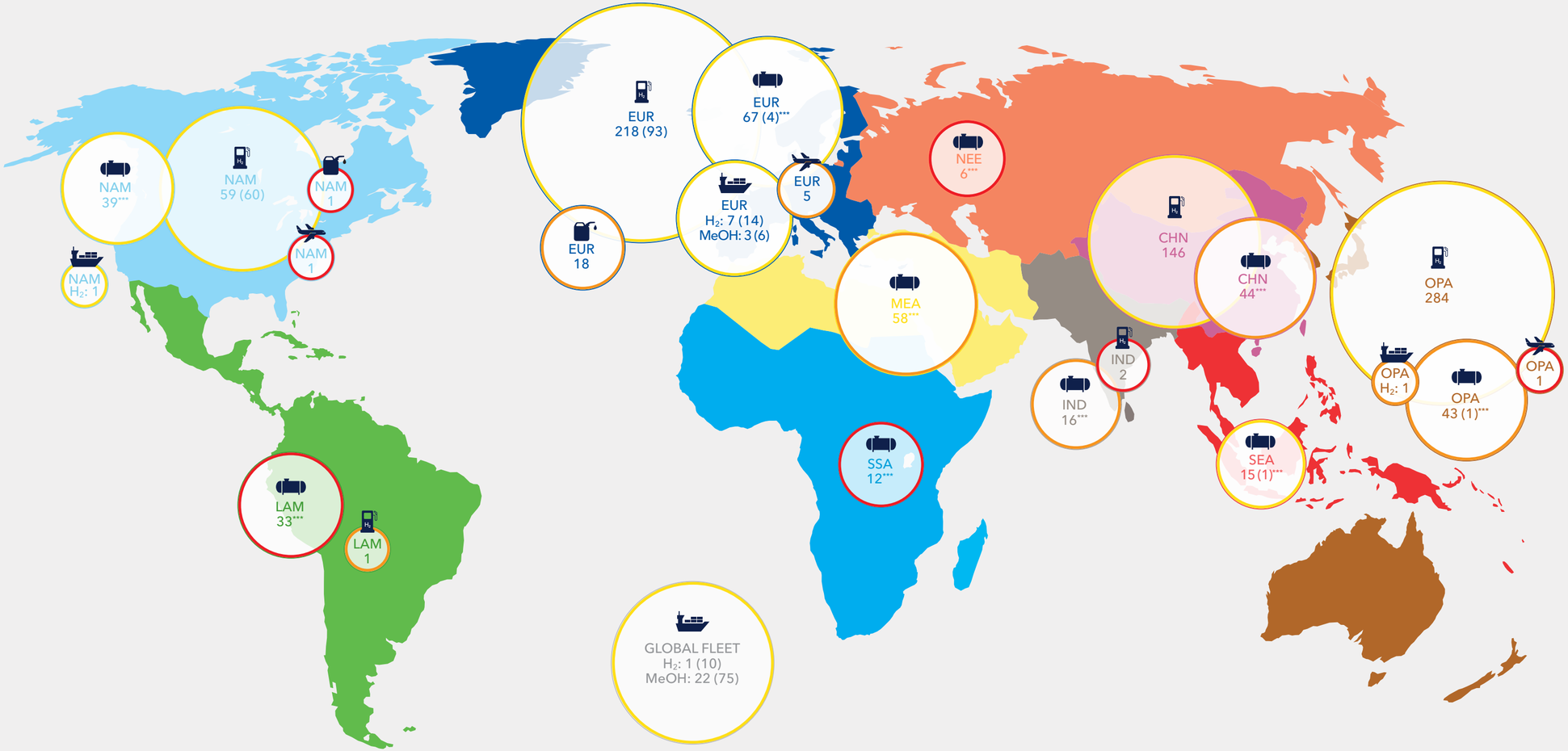
The road subsector will see negligible uptake of hydrogen until the mid 2030s. The uptake will then start to grow to 2 EJ/yr in 2050 and this represents pure hydrogen and no derivatives. Uptake will be dominated by the biggest trucks going long distances; smaller trucks, buses, and passenger vehicles will be only marginal users of hydrogen.

FIGURE 3.25

Hydrogen and derivatives demand in selected subsectors



HYDROGEN INFRASTRUCTURE AND POLICY LANDSCAPE STATUS QUO



Number of hydrogen derivative bunkering facilities for maritime transport*

Number of hydrogen refuelling stations for road transport*

Number of hydrogen and hydrogen derivative fuelled vessels

Number of demonstration projects for hydrogen fuelled aviation

Number of planned e-kerosene projects for aviation**

POLICIES

- Well-defined policy, proven measures
- Defined policy, partial results
- Early policy, no results
- Insufficient policy

For bunkering the assessment also include identified projects initiated by government, industry, or public-private partnership.

*Opened (planned/under implementation)

** Numbers are not exhaustive as e-kerosene projects are merged with bio-jet fuel as sustainable aviation fuels (SAF) projects.

*** Ammonia and methanol terminals for local storage in connection with ports. It is expected that all terminals could be used as a reload terminal for a bunker vessel or barge, with no or limited modifications to the terminal.

Based on publicly available data. This analysis does not include privately owned and run refueling stations for other vehicles than passenger cars, buses, and/or trucks. Check out the Alternative Fuels Insight database for updated information.

Road transport

Hydrogen is set to play a limited role in road transport, and one largely confined to the heaviest long-distance trucks. Fuel cell electric vehicle (FCEV) technology is relatively mature but is complicated by the fact that to power a vehicle, energy must move from wire to gas to wire, and, as shown in Figure 3.18, this results in significant energy losses. Hydrogen vehicles generally have a low well-to-wheel efficiency, at about 25-35%. They are also more expensive compared to BEVs, both in terms of fuel costs and purchase prices, with the limited number of models currently on the market now offered to buyers at very high discounts of 50% and beyond. This higher purchase cost can be partially attributed to the more complicated propulsion system in FCEVs when compared to their BEV counterparts (DNV, 2022b).

The challenge however is not so much the technology, but hydrogen itself. Neither green nor blue hydrogen is available in abundance, and when they do scale (from the mid-2030s) they will still not be cheap relative to direct electricity. Moreover, hydrogen refuelling infrastructure is only in its teething stages and will almost certainly only develop in favour of larger vehicles on designated routes once technical and vitally important safety standards are established.

While hydrogen navigates considerable obstacles to scaling, BEVs will be growing exponentially. BEVs already outnumber FCEVs by a ratio of 400 to one. For passenger vehicles, major vehicle manufacturers are moving in favour of BEVs, as typified by the following statement from Volkswagen: "In the case of the passenger car, everything speaks in favour of the battery and practically nothing speaks in favour of hydrogen" (Volkswagen, 2020).

In 2022, there were 42,000 passenger FCEVs globally, with the majority in Japan, Korea and US, and some in Europe. About 9,000 commercial FCEVs are currently operating, the vast majority of them in Greater China which as of today accounts for 90% and 95% of the world's fuel cell buses and trucks, respectively.

> Neither green nor blue hydrogen is available in abundance, and when they do scale (from the mid-2030s), they will still not be cheap.

Derivatives of hydrogen are not widely applied nor discussed as fuel in road transport. For example, current research on ammonia as fuel in road vehicles focuses mainly on using it as an additive in a mixture (Herbinet, 2022).

The challenging techno-economics of FCEV propulsion are well established and need no further elaboration here, with the exception of brief remarks on refuelling and safety.

Refuelling

Similarly to a gasoline car, an FCEV fills up with hydrogen from a dispenser at a hydrogen refuelling station (HRS). A HRS can either be supplied with hydrogen or produce hydrogen directly on site. There are around 730 such fuelling stations globally (IEA, 2022). Some provide hydrogen at a pressure of 350 bar, which is mostly used in buses, and others at 700 bar for passenger vehicles and trucks. The time for refuelling correlates with the pressure difference and can be an important part of the total cost of ownership, compared with battery plug-in charging. There is a need to develop efficient refuelling stations that can promptly dispense at 700 bar for hydrogen trucks. Otherwise, the fill times would be too long for trucks. The development of hydrogen refuelling stations and uptake of FCEVs is dependent on the users, standardization, and ambition levels in countries.

The strategy is often to create clusters in communities with a high number of potential early technology adopters. The next groups of fuelling stations are then often built as 'green corridors' between the clusters. This opens the market for new adopters in the connecting areas. This is demonstrated in California, the US, by the clusters in San Francisco and Los Angeles and some refuelling stations along the routes between the two metropolitan areas.

Standardization can help reduce costs by simplifying testing and approval schemes, and allowing for simpler scalability of the stations and enhanced customer experience.

There are varying ambition levels for hydrogen in road transport globally. These include, in our view, rather optimistic ambitions in Japan, the US, and South Korea. In the latter case, South Korea's Hydrogen Economy Roadmap aimed at 310 refuelling stations by 2022, only half of these have been built, calling into question further, ambitious targets for 2030 and beyond.

The Alternative Fuels Infrastructure Regulation (AFIR) for the EU reached a provisional agreement in March 2023. It notably paints a picture of infrastructure development favouring FCEV for heavy transport. It states that publicly accessible HRS should be deployed at least every 150 km along the Trans-European Network–Transport (TEN-T) core. This is now part of the TEN-T paragraphs in various legislation and directives. It also includes refuelling stations every 450 km for heavy duty transport. Every twentieth urban node must also have at least one hydrogen refuelling station to serve both cars and trucks to ensure adequate EU cross-border coverage. According to the European Parliament, by 2028 there should be HRS every 100 km along main EU roads.

Safety

Most people are aware of the basic risks and safety precautions at gasoline fuelling stations – for example, not smoking and not fuelling the car while the engine is running. A HRS can look similar to a gasoline station. However, FCEVs use pressurized hydrogen rather than liquid gasoline so, there are some safety aspects to be aware of, even though they do not affect the user much. The HRS and hydrogen vehicle tanks are

made to vent hydrogen to prevent accumulation and pressure build-up. Ventilation and detection are key principles in hydrogen safety.

The main challenge with hydrogen in FCEVs and refuelling stations is that hydrogen should not be kept in confined spaces where it can ignite. For example, garages and tunnels could be a problem area in this regard for hydrogen vehicles. Other challenges include leakage and emissions for both safety and environmental concerns and aggregated risk with local storage and other activities nearby.

However, it is also important to note that it is often believed that as long as you have an open area, the hydrogen will instantly disperse into the air. This is not entirely true, even though hydrogen does disperse quickly. With high pressure, there might also be a horizontal jet fire. Depending on the leak size and duration, a hydrogen cloud may form around and inside structures with turbulence from the depressurizing or wind, which represents an explosion or fire hazard.

Several HRS standards are in place, such as ISO-19880 Gaseous hydrogen – Fuelling stations, which covers the safety and requirements for hydrogen refuelling stations. There are several others, and more are being developed by the International Organization for Standardization's technical committee.

While safety standards and practices are developed and embedded in this nascent industry, other practical challenges abound, as we have briefly summarized in this overview.

FCEVs are more likely to take a role in heavy transport where hydrogen buses and heavy or long-distance trucks in large-scale deployment and in regional or interregional areas might be competitive.

However, for trucks, there are challenges relating to the diversity of vehicles. There is no standard truck configuration, meaning that every unique truck configuration needs to go through granting of approval in an official authorization process, and requires new testing. There is also a lack of regulation for hydrogen trucks. In the EU, for example, there is no Union-wide directive nor national regulation to maintain and repair FCEVs.

Maritime

In maritime, electrification will have limitations, especially for deep-sea shipping. Here hydrogen, and in particular hydrogen derivatives, are likely to play an important role in decarbonizing maritime fuel. Each alternative presents different opportunities and challenges as discussed in the following sections. More details on hydrogen-based fuels for the maritime sector can be found in the DNV *Maritime Forecast to 2050* (DNV, 2022c).

Hydrogen derivatives are likely to play an important role in decarbonizing maritime fuel.

Pure hydrogen
Given its low energy density and corresponding space demands, limited hydrogen uptake is expected in deep-sea ship segments where 2-stroke engines are a natural choice for propulsion. For the short-sea segment, however, 4-stroke engines are being developed. Hydrogen 4-stroke engines are also being projected with an estimated current technology readiness level (TRL) of 6–7 (DNV, 2022c). The proton-exchange membrane fuel cell (PEMFC) technology used to convert hydrogen to electricity is relatively mature with an estimated current TRL of 8 (DNV, 2022c).

For technology readiness level (TRL), the following definitions apply (EU)

TRL 1 – basic principles observed

TRL 2 – technology concept formulated

TRL 3 – experimental proof of concept

TRL 4 – technology validated in lab

TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 7 – system prototype demonstration in operational environment

TRL 8 – system complete and qualified

TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

To overcome low energy density as well as safety concerns, tests are underway to use a Liquid Organic Hydrogen Carrier (LOHC) to store the hydrogen aboard the ship and then extract the hydrogen before feeding it to the energy converter (Hydrogenius, 2023).

According to DNV's *Alternative Fuels Insight*, explained in more detail in Section 4.4, globally there are 10 smaller ships with hydrogen equipment installed, but not used, and another 24 ships on order as of March 2023 (DNV, 2023).

There are currently no bunkering facilities for hydrogen available (DNV, 2023). The hydrogen may be stored under pressure, liquefied (LH_2), or incorporated in LOHC, and hydrogen will not always be available in the temperature and pressure ranges and form that a ship can handle. Equipment for conversions will add cost and be a barrier in the roll out of a dedicated hydrogen infrastructure.

Based on its safety-related properties, hydrogen is considered a challenging fuel. On a ship, pure hydrogen will be stored either as a liquefied gas at very low temperature (-253°C) and a slight overpressure (typically 1–10 bar) or as a compressed gas at very-high pressure (typically 250–700 bar). As hydrogen is the smallest of all molecules, hydrogen gas is more challenging to contain than other gases; it has a wide flammability range, ignites easily, and may self-ignite. This combination of properties may lead to increased overall risk, unless applicable safety systems and practices concerning hydrogen are implemented. Since the 'equivalent safety' regime does not tolerate increased risks, it is expected that appropriate designs and more safety systems are needed compared with other gas fuel systems.

A key challenge is to avoid the chain of events that may lead to an accident if proper countermeasures are not in place and effective. Leaks associated with the bunkering operation and onboard fuel-storage system can potentially lead to high-risk events. DNV and partners have developed a Handbook for Hydrogen-fuelled Vessels as part of the Maritime Hydrogen Safety (MarHySafe) Joint Development Project (DNV, 2021).

Ammonia

Ammonia has attracted wide interest as a source of zero emission fuel for shipping as it is easier to store than hydrogen and the fuel itself does not contain any carbon. Engine technologies for ammonia are not yet mature, and neither 2-stroke nor 4-stroke engines using ammonia as fuel are currently commercially available. Given the large interest in ammonia for ship fuel, engine manufacturers have for some time developed their technologies to meet this demand, and the current TRL is estimated to be 5–6 (DNV, 2022c). Challenges include ammonia's combustion properties, nitrous oxide (N_2O) emissions, and potential ammonia slip. Significant development efforts are being made to get these engines to market within the next couple of years. However, the main challenge is related to safety due to the toxicity of ammonia.

Steam boilers running on ammonia are an immature technology. However, at least one boilermaker has begun concept development and testing is planned within the next couple of years, resulting in an estimated TRL of 2 (DNV, 2022c). In addition to the environmental benefits, having boilers able to burn ammonia could also contribute to solving issues related to operational discharges of toxic gases from the ammonia fuel installation.

Solid oxide fuel cells (SOFCs) are interesting for shipping due to their ability to use different fuels, including ammonia, and for their potentially higher energy efficiency compared with diesel engines. The current TRL is estimated to be 5–6 with a projected maturation longer than for internal combustion engines (DNV, 2022c).

> Ammonia has attracted wide interest as a source of zero emission fuel for shipping as it is easier to store than hydrogen and the fuel itself does not contain any carbon.

Ammonia is stored as a liquid, i.e. cooled to -33°C at around ambient pressure or pressurized to above 10 bar at room temperature. Onshore storage is typically pressurized below 5,000 tonnes ammonia and liquefied by cooling for larger storage units in combination with a reliquefaction plant (DNV, 2020).

There is currently no dedicated bunkering infrastructure for ammonia. However, as ammonia is a commonly traded product, there are 215 terminals for local storage in connection with ports (DNV, 2023a). On a general basis, it is expected that all ammonia terminals could be used as a reload terminal for an ammonia bunker vessel or barge, with no or limited modifications to the terminal. Loading and unloading from terminals to ammonia-carrying ships is currently handled safely with proper specialized training due to the safety issues with ammonia, and safety is believed to be improved by using a bunkering ship as an intermediate between the terminal and the ship using ammonia as fuel (DNV, 2020). Particular care should be taken when bunkering in densely populated areas.

The ammonia may be stored under pressure or refrigerated, and ammonia will not always be available in the temperature and pressure range that a ship can handle. Equipment for conversions will add cost and be a barrier in the roll out of a dedicated hydrogen infrastructure.

For ammonia, the main safety issue is toxicity, but also lowered temperatures as well as corrosion need to be considered (DNV, 2020). Mitigation options include designing fuel systems that prevent discharges. Alternatively, an ammonia recovery system could be considered, and leak detection and containment are important. Ammonia has been handled in various applications for over a century and its hazardous nature and safe handling are thus manageable challenges. DNV has published Class Rules for ammonia as a fuel since 2021. These rules are continuously updated as we learn by collaborating with technology developers.

Methanol

Methanol has seen rising interest in recent years. Methanol can be handled and transported under normal temperatures and pressure. This alcohol has one of the lowest carbon and highest H_2 contents compared to other fuels. Furthermore, methanol reduces emissions of sulfur oxides (SOx), and NOx by up to 60% in comparison to HFO, including reductions in particulate matter emissions of 95%.

Importantly, only fossil-based methanol is currently available for bunkering. However, plants for producing e-methanol are currently under development and production volumes could reach up to 0.1 EJ/yr before the end of this decade (Ricardo and DNV, 2023). This is essential for gaining any GHG-reduction benefits from methanol. E-methanol can then be added as a drop-in fuel in the existing infrastructure.

Tankers carrying methanol as cargo have successfully been using dual-fuel 2-stroke methanol engines for propulsion since 2017. With increased interest in methanol as fuel for other deep-sea ship applications as well, the commercially available product range is expected to increase, and we also foresee other makers entering this market. Retrofit options for a range of 2-stroke engines are also available, resulting in a current assessment of TRL 9 for 2-stroke dual-fuel engines (DNV, 2022c).

We also see an increased interest in methanol as fuel from shipowners operating in segments where 4-stroke engines are the preferred choice. This has triggered a technology development from manufacturers aiming to serve both the newbuilding market and potential retrofits. The current TRL is estimated to be 6, though we expect to see a rapid increase in technological maturity level for 4-stroke engines (DNV, 2022c). In the cruise segment there is interest in methanol as fuel and alternative energy converters. This drive can be expected to accelerate the development in fuel-cell technologies using methanol as an energy carrier, also benefiting other segments. The current TRL is estimated to be 5 with an expected maturation time longer than for internal combustion engines (DNV, 2022c).

Only fossil-based methanol is currently available for bunkering. However, plants for producing e-methanol are currently under development.

According to DNV's *Alternative Fuels Insight*, there are currently 25 methanol ships in operation and another 81 ships on order as of March 2023 (DNV, 2023a). Further insight into e-methanol and DNV's role as world's leading classification society regarding the uptake of methanol as maritime fuel is provided in Section 4.3 of this report.

There is currently no dedicated bunkering infrastructure for methanol. However, since methanol is a commonly traded product, there are 118 terminals for local storage in connection with ports, (DNV, 2023a). On a general basis it is expected that all methanol terminals could be used as a reload terminal for a methanol bunker vessel or barge, with no or limited modifications to the terminal.

Methanol is a low-flashpoint fuel (11°C, compared to 60°C for conventional fuels) and this is a key risk that is addressed in DNV Class Rules with measures such as double-wall piping and nitrogen systems. In addition, fire detection systems are required, because when methanol is ignited, its invisible flame poses a possible risk (IRENA, 2021).

Aviation

Aircraft are more weight sensitive compared with other transport modes and therefore require a fuel with higher energy density. This presents two alternatives for hydrogen in aviation i.e. in its pure form as or as e-kerosene.

E-Kerosene

E-kerosene is an electrofuel that has identical fuel characteristics as conventional jet fuel and can be used as a drop-in fuel in airplanes. E-kerosene is compatible with conventional combustion engines. Also, existing transport, distribution, and fuel infrastructure can be used without major adjustments to deploy it as fuel for the existing airplane fleet.

Producing e-kerosene relies on hydrogen from water electrolysis and CO_2 captured from the atmosphere. Thus, e-kerosene has significant potential to sustainably lower lifecycle emissions of aviation fuels in carbon-neutral aviation growth to 2050. This is also indicated in our latest *Energy Transition Outlook* (DNV, 2022a) which suggested the share of e-kerosene to be three times more than pure hydrogen in the aviation subsector. Compared to biofuels, the main advantage of e-kerosene is that it is better scalable in line with aviation's needs. Advanced biofuels, sourced from wastes and residues are only available as much as their primary product is manufactured. The used cooking oil or animal fats have alternative use cases (TE, 2022).

However, there is no significant production of e-kerosene today. This is principally due to the higher production costs of e-kerosene compared to its fossil counterpart because of the low energy efficiencies of carbon capture and hydrogen production from electrolysis.

Challenges related to the uptake of e-kerosene in aviation

- **Cost of renewable energy:** The cost of renewable CO_2 and hydrogen for e-kerosene are highly dependent on the underlying cost of renewable energy needed to produce them. This means that the economic viability of large-scale projects for e-kerosene and other synthetic fuels is dependent on the availability of cheap renewable energy.

- **Availability of renewable hydrogen:** Production of e-kerosene requires renewable hydrogen which is going to be scarce in the near future. The competition between the hard-to-abate sectors for green hydrogen and the development of electrolyser technology are two major factors to be addressed for ensuring access to cheap green hydrogen.

- **Availability of fossil-free CO_2:** The cost and efficiency of DAC technologies remain high because of the low concentration of CO_2 in the atmosphere. Expressed in terms of new direct air capture (DAC) technologies available today, the Climeworks Orca units can reportedly capture 500 tonnes of CO_2 per year. Based on this, capturing total aviation emissions in 2019 (1,035 $MtCO_2$) would require 2 million units, equivalent to 80 units running 24/7 for each aircraft in operation in the global fleet. Hence, further improvements in DAC technology are needed to drive the production of e-kerosene at scale (ITF, 2023).

- **Incentivizing market ramp-up:** The ReFuelEU Aviation initiative, agreed in April 2023, sets blending mandates for sustainable aviation fuels (SAF) and sub-quotas for e-kerosene, with a proposed e-kerosene blending mandate of 0.7% (0.16 Mt) by 2030, increasing to a minimum of 28% in 2050. The ambitions of the ReFuelEU initiative fall short by a significant margin when compared to the overall pledged production (i.e. 1.83 Mt) by the e-kerosene manufacturers in Europe. It is feared that this would not incentivize swifter and wider production expansion. Hence, higher quotas and a stable policy horizon are required to support the bankability of large-scale e-kerosene production projects.

Pure Hydrogen

Hydrogen-powered planes are still in their infancy, and the challenge for the aviation industry is to adapt hydrogen to its commercial needs. Pure hydrogen's gravimetric density is three times greater than that of conventional jet fuel, but hydrogen's volumetric density is four times lower. This means that storing hydrogen in its gaseous state will require large onboard storage volumes, which is a major showstopper. Hence, hydrogen has to be used in liquid form to reduce the required storage volume for medium- or long-haul commercial aviation flights. Gaseous hydrogen, just like battery-powered systems,

can only serve as an option for short lights. However, for shortest segments, battery powered systems will likely to be more competitive than hydrogen.

Airplanes are weight-sensitive, so hydrogen needs to be adapted to an energy-dense fuel to meet the industry's commercial needs.

The aviation industry is now initiating extensive research to use hydrogen as a possible future fuel for short- (less than 1,400 km) to medium-haul flights (1,400–4,000 km) while maintaining the seating capacity of the airplane. For long-haul hydrogen-powered flights, significantly radical design changes would be required to accommodate the liquid hydrogen storage tanks in the aircraft. As well as aircraft design and infrastructure adjustments, handling and safety regulation would need to be adjusted, and will need to evolve in synchrony with technology developments. Hence, the entry into service of hydrogen-powered airplanes with ranges greater than 4,000 km is unlikely before mid-century. However, there are some exceptions with modified planes that can have a faster timeline for approval. Some sacrifices will be necessary, with less space for passengers and freight due to lower volumetric/gravimetric energy content for the whole drivetrain system.

Challenges to pure hydrogen uptake in aviation
Hydrogen is one pathway that can help to decarbonize aviation. However, this comes with challenges which require cross-industry and public-private research partnerships to realize the full potential for the hydrogen-based future of flying (FCH 2 JU, 2020).

- **Aircraft and engine redesign:** Unlike conventional jet fuel, LH_2 storage tanks cannot be stacked in the wings. The general configuration will most likely be LH_2 tanks placed in the tail cone behind the passenger cabin. This will change the centre of gravity for the aircraft and would require appropriate aerodynamic adaptions to the aircraft design. Hydrogen combustion solutions require modified conventional thrust systems that could be retrofitted or redesigned for the existing airplane fleet by the mid-2030s. Demonstration projects from Universal Hydrogen and ZeroAvia are designed to introduce hydrogen in aviation combustion by making changes to the existing airframe designs. The most popular commercial airplane designs (i.e. Boeing 737 and Airbus A320 families) are likely to undergo their next edition design upgrades in the mid-2030s. This is the most appropriate time for entry of the hydrogen-powered single-aisle airplane fleet in commercial aviation, and the industry is ramping up its efforts with projects like ZEROe to bring hydrogen combustion by the middle of the next decade. However, factoring in the likely delays and technology learning curves these plans are most probable to be materialized in 2040s.
- **Onboard hydrogen storage:** The liquid hydrogen requires cryogenic tanks to store it at –253°C . A major challenge is to test the materials for these LH_2 tanks and all fuel-related components under realistic operational conditions over a longer time.
- **Availability of low-carbon hydrogen:** Low carbon hydrogen is needed to decarbonize hard-to-abate sectors like steel, cement, and chemicals. Therefore, a significant ramp up of low-carbon hydrogen production is needed to have sufficient hydrogen available to fuel a growing aviation sector in the coming decades.
- **Cost of low-carbon hydrogen:** To compete with conventional jet fuel on a cost basis, a reduction in price for production of low-carbon hydrogen is desired.
- **Refuelling infrastructure at airports:** Trucks are the easiest option to supply LH_2 to airports. This solution could help enable early innovation. However, supplying hydrogen via trucks might not be optimal for larger airports where the related congestion might pose a safety concern. Hence, each airport would need to optimize its fuel supply chain to decide what could be the best solution for its operations. Key deciding factors would be proximity to urban areas, the feasibility of retrofitting old gas pipelines if available to carry hydrogen, and access to large amounts of water and electricity to produce hydrogen on site. New regulatory frameworks are needed to guarantee safety during distribution and refuelling operations, and to prove the safety case for the hydrogen. Furthermore, research in a LH_2-hydrant refuelling system can help to fully optimize LH_2 fuel supply to airports.
- **Green corridor requirements:** This concept involves having hydrogen and refueling capacities at a minimum of two airports, preferably at either ends of a corridor or within a region, to allow for alternative landing and some flexibility for routes, maintenance, and security of supply.

Safety
Hydrogen as fuel has its own unique safety concerns as leaks are odourless and hydrogen-fuelled flames are in most cases invisible. Hydrogen-fuelled planes therefore need updated safety requirements, with specialized sensors to detect and alert potentially dangerous leaks or fires. Critical questions concerning safety measures and parallel operations include:

- Scan of potential safety issues, including leakages during refuelling and the range of potential impacts.
- Leakage management and countermeasures that can allow parallel operations during turnaround; for example, nitrogen systems for venting and purging of systems, before repressurizing and operations.
- Regulatory framework to guarantee safe handling and refueling with LH_2.
- Required ignition-free zone around LH_2 refuelling equipment and a safety buffer zone to assess whether parallel operations (like passenger boarding) during turnaround can be allowed.

4 SECTOR INSIGHTS

The core model development and research behind DNV's Energy Transition Outlook, including this report, is conducted by a dedicated team in our Energy Transition research unit – part of the Group Research & Development division, based in Norway. Some 70% of DNV's business is related to the production, generation, transmission, and transport of energy. The core research team is therefore assisted with real world insights from our thousands of technical experts who, each day, are testing, verifying, certifying, and advising on the energy infrastructure being designed and installed now that will deliver the energy the world needs for decades to come.

This chapter presents snapshots of aspects of DNV's engagement with the world of transport energy, including:

- A Sustainable Aviation Fuel pilot with the Norwegian aviation authority, Avinor, involving fuel from municipal solid waste
- How distribution system operators (DSOs) can minimize risks and benefit from the load from the ever-expanding fleet of EVs
- How DNV works with a growing range of shipowners on methanol-fuelled vessels
- A description of DNV's Alternative Fuels Insight (AFI) platform for the maritime industry

4.1 AVINOR SAF PROJECT

Background: Sustainable synthetic drop-in fuels, biological or non-biological, will play an important role in meeting the expected growth in demand for sustainable aviation fuel (SAF). However, these new fuels face a number of technical and regulatory challenges and many collaborative efforts involving the aviation sector, industry actors, and government stakeholders are exploring ways to address these challenges at the national and regional levels. In Norway, DNV has supported the Norwegian aviation authority, Avinor, and the national development bank, Innovation Norway, to assess the feasibility of a production process for SAF based on non-biological feedstock.

Regulation

There are proposed and emerging regulations and certification schemes involved in the development of SAFs in the Europe. EU is developing legislation for biological and non-biological SAFs, with the European Green Deal and Fit for 55 as central policies. RePowerEU will also boost renewable power and hydrogen production. The European Commission has proposed targets for mandating the blending of biological and non-biological synthetic SAF, and amendments have been made by the European Parliament and the Council of the EU. The ReFuelEU Aviation initiative is therefore significant for the development of SAFs, mandating sustainable aviation fuel blending at European airports. The European Parliament and European Council reached a political agreement on April 25, 2023.

Norway as a location for SAF production

As SAF production from non-biological waste products is a relatively new concept, with immature technologies, processes, and frameworks, there are several barriers to the establishment of this industry worldwide. Many such barriers are common and not country-specific. They include, for example, those related to cost, certification and traceability, regulations, standards, and technological maturity. For Norway, the barriers are generally related to risk capital and investment, with uncertainty on subsidies or investment support.

The ZEG Power modular blue hydrogen pilot plant at Kollsnes, Norway. In producing synthetic SAF, there are synergies with projects like this in terms of emerging value chains for CO_2 transport and storage. Image, courtesy ZEG Power AS

Important drivers for SAF production in Norway include the high renewables share in the country's electricity generation mix, 'relatively low' power prices (in some regions), and high-quality power supply. In addition, further development of renewable power is planned. Norway is also a leader in CCS and CCU competence and is actively creating related value chains. Furthermore, it has high standards for gas and fuel value chains, and Avinor (with airlines) is an early mover in SAF sourcing and supply, with a blending mandate of 0.5% in place, and to increase to 2% in 2023.

SAF production from municipal solid waste in Mongstad

The analysis included a pre-feasibility assessment of a production process for SAF at Norway's largest oil refining cluster at Mongstad on the west coast. The process was based on municipal solid waste (MSW) as feedstock. It included the combination of gasification, blue hydrogen, and DAC to produce ethanol using proprietary technology to convert syngas to alcohol and alcohol to jet fuel and diesel. Synergies with an ongoing blue hydrogen project at Kollsnes in Øygarden, west of Bergen will be important to utilize the emerging value chains for CO_2 transport and storage. A specific supplier of DAC technology at Kollsnes, for CO_2 supply to the plant at Mongstad, was also included in the modelled production process.

DNV's analysis defined scenarios with varying inputs of MSW, blue hydrogen, and CO_2 from DAC. The process and scenarios were estimated to have direct emissions of 1.4–1.8 $kgCO_2/l$ of alcohol-to-jet (AtJ) kerosene, which is estimated to reduce GHG emissions by 70-77% per litre compared with the EU's fossil fuel comparator. These estimates are for the direct emissions and are high level and do not constitute a detailed Life Cycle Assessments (LCA). Nevertheless, the estimates indicate that the margin (greater than 70) for GHG reduction is likely to be reached.

The production process analysed shows potential, but significant barriers remain. Some are project-specific, like the sourcing of feedstock and the optimization of conceptual and technical designs. However, there are also commercial and regulatory barriers related specifically to uncertainties in the regulatory landscape and the current competitiveness of synthetic SAF compared with bio-based SAF and regular jet fuel. The main regulatory risks are related to if low carbon (blue) hydrogen can be used, as well as non-biological carbon from waste, to qualify as SAF and part of the blending mandates. The trialogue discussions with the vote on the final delegated act text will decide on this. To meet the growing demand for SAF, incentives must be adopted, and industry actors and investors need a more predictable regulatory regime.

Aviation fuel produced from municipal waste is likely to qualify as SAF, if the GHG emissions reduction threshold of 70%, compared to the fossil fuel comparator, is reached.

4.2 EVS AND DISTRIBUTION SYSTEM OPERATORS: RISKS AND BENEFITS

The ever-expanding fleet of EVs carries risks to distribution system operators (DSOs) as well as benefits. The early adopters of EVs are in high-income neighbourhoods where residents can afford new cars, and, for the time being, this is where vehicle charging activity is clustering geographically. Moreover, charging activity concentrates in relatively few hours of the day. Thus, DSOs will need to accelerate upgrading or replacement of selected circuits to meet EV charging loads. A recent study based on circuit-level data for Pacific Gas & Electric in the US estimated that 16% of all 2,215 distribution circuits in the company's service area would need accelerated upgrading due to increases in EV charging demand (Jenn & Highleyman, 2022). The costs of these upgrades can be high, and are ultimately paid by electricity customers.

DSOs wish to encourage BEV use to increase sales and are mindful of the associated benefits of reduced GHG emissions, improved air quality, and lower cost of transportation for their customers. However, they must manage this new load to minimize increased costs and maintain service reliability. Here are just a few examples of how DNV works with DSOs to meet these challenges.

Accelerating the build-out of EV charging infrastructure

The total cost of ownership for BEVs has fallen below that of ICEVs, despite the higher upfront costs of BEVs that currently prevail. Manufacturers are introducing lower-priced BEVs that will be accessible to a larger share of the market. However, 'range anxiety' continues to hamper the growth of BEVs. To reduce this barrier, many governments and DSOs are offering financial incentives and logistical support to households and businesses to install Level 2 and DC fast chargers.

DNV administers such programmes for Public Service of New Mexico (PNM) and other electric utilities which over the next 18 months will:

- **Build an online retail marketplace** and network of local electricians to sell, install, and administer financial incentives for 3,900 Level 2 car chargers
- **Manage installation** of 150 Level 2 chargers for low-income customers
- **Administer customer rebates** and project management for installation of 'make ready' electrical infrastructure for DC fast charging stations and for installation of Level 2 chargers in public sector, commercial, and multi-family facilities
- **Administer 'make ready'** programmes for mass transit operators
- **Deliver customer education** and outreach services

Adapting digital platforms developed to promote energy-efficiency improvements in buildings is helping PNM to achieve its transportation electrification goals at scale and speed.

Managed charging

DSOs have many tools available to reduce peak load impacts from EVs, and thus their potential to overload distribution circuits. These tools include time-of-use (TOU) tariffs and direct control of charging via electronics built into or retrofitted to EVs. DNV recently designed and managed a pilot programme for a US state energy agency to test the relative effectiveness of these tools. For this project, DNV:

- **Recruited and managed** randomized experimental cohorts of recent EV buyers for a TOU tariff, managed charging, and control
- **Worked with a telematics vendor** to instrument vehicles, collect charging and travel data, and analyse patterns of charging

The study found that both the TOU tariff and managed charging approaches were effective in moving charging activity to the off-peak period. The managed charging approach was more effective in driving load reductions for the full peak period. These findings are important. Studies in the Netherlands and the US find that effective implementation of EV load control can lead to savings of up to nearly a third (32%) in transformer and switch replacement costs compared with uncontrolled EV charging scenarios (Brinkel et al., 2020). Moreover, these smart charging programmes represent a necessary first step in developing vehicle-to-grid programmes, which will enable the use of EV batteries for grid balancing. Such programmes will unlock additional grid and social value from the proliferation of EVs.

4.3 METHANOL-FUELLED VESSELS BENEFIT FROM RELATIVELY SIMPLE TECHNOLOGY

Methanol has quickly attracted attention as a viable alternative ship fuel following the adoption of the IMO interim guidelines for ships using methyl or ethyl alcohol as fuel (MSC.1/Circ.1621). Together with the IMO's IGF Code for ships using low-flashpoint fuels, and DNV's mandatory class rules, specifically the LFL FUELLED and Methanol Ready class notations, a comprehensive regulatory framework for the use of methanol as ship fuel is now available to DNV customers.

Lindanger, the world's first dual-fuel, methanol-ready tanker, was built in 2016 to DNV class. A MAN-designed Hyundai-B&W 6G50ME-9.3 ME-LGI dual-fuel, two-stroke engine allows Lindanger and her sister vessels to run on methanol, fuel oil, marine diesel oil, or gasoil.

Looking for a shipping partner interested in taking methanol propulsion to the next level, Swiss-based company Proman, a leading producer of methanol and ammonia, found an experienced joint venture partner in Stena Bulk. Together they ordered six 49,900 dwt, state-of-the-art dual-fuel MR chemical tankers with a cargo capacity of about 54,000 cubic meters each, all built to DNV rules.

Ship-to-ship, berth-to-ship, and truck-to-ship methanol bunkering operations have since been carried out successfully.

Combustion of methanol as the main fuel requires about 3-5% marine gas oil (MGO) in the mix to act as pilot fuel for ignition. The ships could in theory operate on MGO alone if running out of methanol but, according to Stena Bulk, they run on methanol practically the entire time. The water injected for NO_x reduction is produced on board from sea water.

The plan is to blend-in increasing amounts of blue, and eventually, green methanol to remain compliant with the IMO trajectory towards zero carbon.

Guidance paper outlines important technical design considerations

A new chapter in DNV's *Alternative fuels for containerships* document discusses the properties and requirements of methanol in detail, providing comprehensive guidance on ship design arrangements, containment concepts, certification and training, essential steps before signing a contract, and cost considerations in the context of carbon trading. A business case for methanol will be added soon. Most of the insights presented in this new chapter can also be applied to other ship types.

With a flashpoint of 11°C to 12°C, methanol is flammable and evaporates easily. It is also indirectly toxic. Necessary safety and zoning considerations are extensively discussed in the paper, based on the four IMO-defined elements of a safety concept for methanol-fuelled vessels: segregation, double barriers, leakage detection and automatic isolation of leakages.

European regulations require specific certification for fuels to be accepted as 'green' and count towards the ETS and FuelEU Maritime. DNV's advisory, assurance, and certification services cover the entire grey, blue, or green methanol life cycle from production to consumption. Prospective producers of green methanol are asking DNV to certify their production plants and processes to demonstrate their credibility to fuel customers. Furthermore, DNV Approval in Principle (AiP) allows equipment suppliers to offer individual components or entire fuel systems with DNV credentials.

Provided that all safety requirements are addressed properly, methanol has significant potential as a technically viable ship fuel. It is certainly gaining ground: of the newbuild ship orders placed in the first three months of 2023, 6% were with menthanol, equaling the 6% ordered with LNG (excluding LNG carriers). More insights are available in our latest Maritime Impact update on methanol.

Proman Stena Bulk have successfully carried out ship-to-ship, berth-to-ship, and truck-to-ship methanol bunkering operations

Lindanger, the world's first dual-fuel, methanol-ready tanker, was built in 2016 to DNV class.

4.4 ALTERNATIVE FUELS INSIGHT PLATFORM

Background: DNV launched its Alternative Fuels Insight (AFI) platform in 2018 to make up-to-date information on bunker infrastructure (supply) and uptake (demand) for all types of alternative fuel more easily available to the shipping industry, particularly decision makers on the end-user side. Without such insights, resolving the chicken-and-egg situation for any new fuel will simply take longer, impeding progress towards decarbonization.

AFI is a widely recognized go-to place for decision-making support on alternative fuels in the maritime industry, with more than 12,000 registered users. Through the platform's interactive features, users can access information and insights on LNG, LPG, methanol, ammonia, hydrogen, fuel cell, scrubber, battery, and shore power in map format with statistics and fuel price modules.

Collaboration project and what's next (roadmap)
AFI is in continuous development and will expand with new insights and features to help navigate the energy transition.

Hosted on DNV's digital platform Veracity, with the initial ambition to match and show supply and demand between ships and bunkering units, AFI is in continuous developing, expanding to share insights on fuel production and supply, as well as CCS facilities.

Through DNV's experience with projects in Maritime, Energy, R&D, and the annual *Energy Transition Outlook* – and leveraging our presence in all global regions – we have established a joint project involving all our business areas to help give more insight into how the fuels are produced, and to which family they belong. This will communicate the status and location of facilities producing e-fuels, blue fuels, and biofuels, and will support the industry with relevant information for these projects. By helping users to navigate the landscape of alternative fuels, our AFI aims to aid optimal decision-making.

In working with our AFI partners and users in helping them to transition faster, we believe that the *fuel of the future is collaboration* and that it only flows best where there is abundant and timely information, and market transparency.

APPENDIX 1
SELECTED POLICY EXAMPLES FOR THE TRANSITION OF TRANSPORT

Listed below are selected national and international policies driving the energy transition of transport. The lists are not exhaustive, but are indicative of policy concreteness, emphasis, and maturity of policy actions. Policies covering road transport are the most mature and are listed geographically. For aviation and maritime, which rely on both national and supranational policymaking, selected policies are categorized thematically.

A 1.1

Selected road transport policies

Global	ICE phase out policy (COP27): > 40 country signatories + cities, manufacturers in Accelerating to Zero Coalition to transition towards zero-emission new cars and vans by 2040 globally, and no later than 2035 in leading markets.
North America	– US: No federal ICE phase out policy but a goal to achieve a 50% EV sales share by 2030. The Infrastructure Investment and Jobs Act (IIJA) includes USD 7.5bn to charging, and USD 9.5bn to the hydrogen economy (vehicles, refuelling stations). The Inflation Reduction Act (IRA) includes USD 2bn to EV/FCEV manufacturing and tax credits to purchase (USD 7 500 passenger and USD 40 000 to eligible commercial vehicles). The Environmental Protection Agency to advance more stringent GHG standards for trucks in 2023. Biofuel blending is set by the Renewable Fuel Standard with renewable volume obligations. – Canada targets 100% ZEV passenger vehicle sales by 2035 and 100% commercial (light) by 2040. It has ZEV sales mandates on automakers/importers (light duty vehicles) for 20% in 2026, 60% in 2030, 100% in 2035, also offering purchase rebates. The Clean Fuel Standard sets carbon intensity reduction requirements for liquid fossil fuels starting in 2023.
Europe	– EU-wide ICE phase out policy (exemption on e-fuels) with no new cars, vans by 2035. New proposal (2023) for stringent CO_2 emissions standard for heavy-duty vehicles with a 90% CO_2 reduction target by 2040. – Renewable Energy Directive (RED II) sets the option to choose between a 14.5% reduction of GHG intensity, or at least a 29% renewable share in final energy consumption in transport by 2030. It includes targets for advanced biofuels and renewable fuels (non-biological). – Purchase incentives are widespread but with commencement of subsidy declines in mature markets. – An EU emissions trading scheme includes transport with carbon price on upstream fuel suppliers from 2027.
Middle East and North Africa	– No phase out policy for ICEs. Israel the exception with a 100% EV target for passenger vehicles by 2030. – Increased efforts seen in EV promotion through introduction of generous uptake incentives (United Arab Emirates) and support to onshore EV manufacturing (Kingdom of Saudi Arabia).
Greater China	– China targets more than 50% of car sales being ZEVs or PHEV by 2035. – New Energy Vehicle Industry Development Plan (2020) with accelerated infrastructure rollout, refuelling station capacity. There are national, provincial, municipal requirements and funding to provide charging infrastructure. – The New Energy Vehicle (NEV) programme sets sales mandates on manufacturers. A long-haul truck subsidy is available under NEV. – City cluster demonstrations for FCEVs and infrastructure include CAPEX and OPEX support.
Indian Sub-continent	– India's central government is increasing allocations to domestic EV manufacturing (battery cells, EVs) such as through exemption for customs duty on EV parts and capital subsidies. There is government support to targeted infrastructure development, and the FAME scheme offers purchase incentives. – India's biofuel blending target (20%) has been advanced from 2030 to 2025-2026.
South East Asia	– There are EV policy developments for manufacturing positioning and uptake incentives, e.g. Malaysia's Low Carbon Mobility Blueprint 2021-2030. Thailand targets 30% of automobiles produced by 2030 to be EVs. Indonesia has EV manufacturing mandates and targets for EV uptake, e.g. a 100% EV fleet mandate on state-owned companies by 2025, and an incipient incentive scheme (2023). – Biofuel blending mandates have been increased, e.g. in Indonesia to 35% in 2023, in Malaysia to 20% in 2025.
OECD Pacific	– South Korea's announced a ban on all new ICE vehicle sales from 2035. The Green New Deal / Covid Recovery policy include USD 2.4bn to EV and FCEVs and its infrastructure programme supports infrastructure rollout. Purchase incentives are available. – Japan aims to increase the market share of Next Generation Vehicles among new car sales to between 50% and 70% by 2030. Purchase incentives are available. – Both Japan and South Korea have biofuel targets (~5%) 2020-2030. – New Zealand has introduced an emission intensity reduction target on fuel wholesalers for a 9% reduction by 2035. – Australia's 2022/2023 federal budget has introduced the first commonwealth-wide subsidy scheme for EVs.

A 1.2

Selected aviation transport policies

Global	– October 2022, ICAO member states adopted a long-term global aspirational goal (LTAG) for net-zero emissions by 2050. – ICAO's market-based Carbon Offsets and Reduction Scheme for International Aviation (CORSIA) scheme on aircraft operators (voluntary participation 2021-2026 phases, all in second phase 2027-2035) aims to ensure that the net emissions from international aviation do not exceed the 2020 levels.
North America	– The US Aviation Climate Action Plan (2021) has a net-zero goal by 2050. – US Congressional bills (Sustainable Skies Act, Sustainable Aviation Fuel Act) aim to increase the use of SAF. – The SAF Grand Challenge targets production of 3bn gallons per year (~11bn litres) of SAF by 2030, achieving a minimum 50% reduction in lifecycle GHG emissions by 2030. The Department of Energy has USD 65m funding for projects on cost-effective, low-carbon biofuels. – The Inflation Reduction Act (IRA) offers tax credit up to USD 1.75 per gallon through 2026. – The US Renewable Fuel Standard has a SAF 'opt-in' approach, allowing SAF to generate compliance credits (Renewable Fuel Identification Numbers (RINs) to meet the renewable volume obligation. California's Low Carbon Fuel Standard sets requirements for carbon intensity reductions on fuel providers /refineries and has SAF as an eligible fuel to generate credits, sellable to obligated parties. – Canada has a net-zero vision for the aviation sector and an aspirational target for SAF use by 2030. – In 2018, Canada launched a SAF competition – Sky's the Limit Challenge – and in 2022, the Council for Sustainable Aviation Fuels was created (government-industry partnership) to accelerate the commercial production and use of Canadian-made SAF. – The federal Clean Fuel Regulation sets lifecycle carbon intensity reduction requirements for gasoline and diesel used in Canada starting in 2023 in which the production or import of eligible and registered SAF and other low carbon intensity fuels will create credits. – Draft Fuel Charge Regulation (2022) would provide relief from the fuel charge for the portion of aviation gasoline or aviation turbo fuel that is bio-aviation fuel (i.e. SAF derived entirely from biological matter available on a renewable or recurring basis).
Europe	EU policy developments: – The EU Renewable Energy Directive, RED II, targets 5.5% from renewable fuels of non-biological origin (RFNBOs) with a multiplier for SAF. – The ReFuelEU Aviation initiative ('Fit for 55' package) sets as blending mandate on fuel suppliers and airlines to scale up the uptake of SAF from 2% in 2025, 34% in 2040, and 70% in 2050, of which a sub-mandate is for synthetic aviation fuels (e-fuel) to reach a minimum of 28% in 2050 (proposal agreed April 25, 2023). The requirements apply to jet fuel consumed by flights refuelling/departing from EU airports. – The European Hydrogen Bank (EUR 3bn) will support hydrogen producers or purchasers, including e-SAF projects, using a competitive bidding scheme for contracts covering the higher production costs of green hydrogen. – The EU emissions trading system (EU ETS) will phase out free allowances (2024–2026) with intra-Europe flights paying the carbon price. 20 million free allowances from the EU-ETS have been set aside to incentivize uptake of eligible SAF fuels. The EU revision of the Energy Tax Directive includes a kerosene tax with a phase-in period 2023–2033 for intra-EU flights. – The EU Innovation Fund (2022) supports large-scale clean-tech projects with capital costs greater than EUR 7.5mn e.g. Swedish HySkies project to produce synthetic SAF. – The R&D programme, Clean Aviation research programme, aims to accelerate hydrogen aircraft development, building on Clean Sky flagship demonstrators. National policy developments: – The UK has a goal of net-zero domestic flights by 2040. The Jet Zero Council (government-industry partnership) aims to deliver at least 10% SAF fuel mix blend by 2030. Government funding (GBP 180m) supports expansion of SAF production capacity and aims for at least five commercial-scale plants under construction by 2025. GBP 685m funding targets zero-carbon and low-emission aircraft technology. – There are country-level biofuel blending obligations. Finland, Norway and Sweden have SAF blending mandates for a gradual increase to ~30% by 2030. – Norway has the goal to electrify all domestic flights by 2040 with accompanying research and support. Denmark and Sweden have set goals of fossil-free domestic flights by 2030. Denmark is using a flat fee of EUR 1.75 per passenger on both domestic and international flights to finance the ambition. – In France, the 2030 investment plan from 2022 includes EUR 1.2bn to R&D for low-carbon airplane development. – Germany has a Power-to-liquid (PtL) roadmap for sustainable electricity-based fuels. Federal government funding (EUR 1.54bn) supports investments in renewable fuels (2021-2024), and targets 200 000 tonnes by 2030. It targets PtL kerosene to represent a third of fuel use for domestic flights by 2030, with binding targets for sale and purchase.
Greater China	In the Greater China region, planning has advanced significantly in recent years (Yiru et al., 2022). – The State Council issued (2021) the Action Plan for Peaking Carbon emission by 2030 with push for the substitution of advanced liquid biofuels and SAF for traditional fuels and improvement of fuel end-use efficiency. – The 14th Five-year plan (2021–25) for Green Civil Aviation Development (January 2022) sets expectation for the aviation sector to: achieve breakthroughs in promoting the commercial use of SAF, aiming to raise SAF consumption to over 20,000 tonnes in 2025 and cumulatively to 50,000 tonnes during the 14th FYP period; establish an expected goal for reducing fuel use per tonne-km for air transport fleet to 0.293 kg and reducing carbon emissions per tonne-km by 4.5% (to 0.886 kg) from 2020 levels. – The 14th FYP for Bioeconomy development encourages areas with good conditions to promote and pilot the use of biodiesel and advance the demonstrative use of aviation biofuels. – The 14th FYP for Renewable Energy Development (June 2022) aims to scale up efforts in non-food liquid biofuels, R&D and promotion of advanced technology and equipment for biodiesel and aviation biofuel production. – Domestic aviation is expected to be included in the national emissions trading scheme although the timeline is uncertain.

OECD Pacific	– Japan's Green Growth (2020) strategy for aviation focuses on electrification and e-fuels. Its Green Innovation Fund (JPY 2tn ~USD 16bn) supports value chain development and R&D for next-generation aircraft, including core technologies for hydrogen. The state-owned New Energy and Industrial Technology Development Organization (NEDO) was awarded JPY 113.5bn in grants to e.g. pilot projects, e-fuels, and SAF in April 2022. – South Korea plans to expand domestic biofuels production and SAF use by 2026 with increasing targets and mandates for biofuels in jet (and marine) fuels. The government has targeted annual funds to hydrogen projects (i.e. its Recovery package with USD 2.4bn (KRW 2.6trn), supporting hydrogen-focused companies through R&D subsidies, loans, and tax exemptions. In 2022, a MoU was signed for stakeholder collaboration investigating infrastructure requirements for use of hydrogen at Incheon International Airport, and support deployment of hydrogen-powered commercial aircrafts, to meet the government's goal of carbon neutrality by 2050. – Australia's SAF Council (government-industry partnership) was set up in 2022 to advise on policies for net-zero aviation emissions by 2050. Government funding (AUD ~110m) aims to co-fund R&D and support SAF production and airport upgrades. – In 2022, the Sustainable Aviation Fuels Alliance of Australia and New Zealand recommended an emissions intensity mandate benchmarked against jet A1 fuel with a 2.5% reduction in emissions intensity by 2025, 3% by 2030, 10% in 2040 and 50% in 2050.

A 1.3

Selected maritime transport policies

Global	– Initial IMO GHG Strategy (2018) aims for a 50% GHG reduction in international shipping GHG emissions by 2050 relative to 2008. The strategy will be revised in July 2023, strengthening the target, possibly to decarbonize by 2050. – Energy efficiency and carbon intensity regulations are in place. – Work ongoing to develop a GHG emission levy and a lifecycle GHG emission fuel standard, possibly in place from 2027 at the earliest. – Multiple public-private partnership (PPP) initiatives: GreenVoyage2050, Green Shipping Programme, Green Shipping Corridors initiatives.
North America	– Several programmes, providing funding for infrastructure development including fuel production, port infrastructure, ship technologies. – Inflation Reduction Act (IRA) provides clean fuel production incentives such as a tax credit of up to USD 1 per gallon (USD 0.26 per litre) to clean transportation fuel (with less than 47 gCO_2e/MJ of CO_2e lifecycle emissions).
Europe	– Several programmes and initiatives, e.g. Innovation Fund, Horizon programme providing funding. – Shipping to be included in EU ETS from 2024. – FuelEU Maritime setting a lifecycle GHG emission fuel standard from 2025 and shore power mandates for container and cruise ships from 2030. – Possible taxation of fuels for international shipping in the EU.
Greater China	– Draft amendment to the Marine Environment Protection Law providing financial support and implementing preferential policies to enable the upgrading and operation of shore power supply facilities, as well as the building of vessels powered by clean and new energies.

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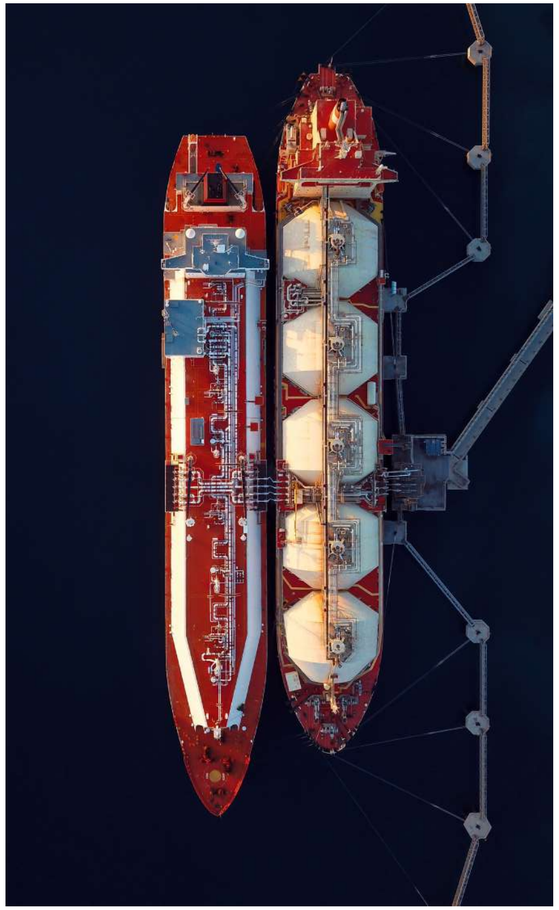

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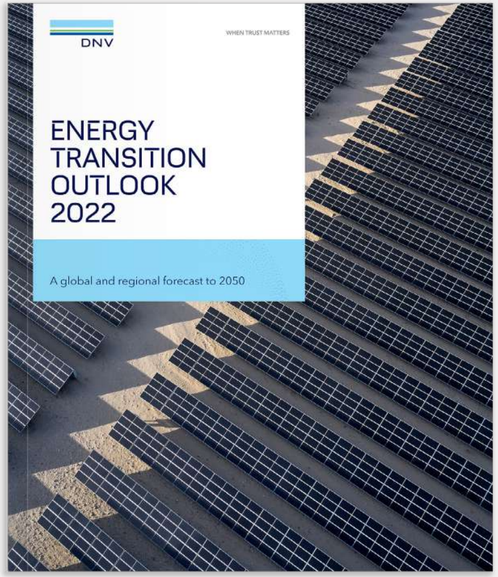

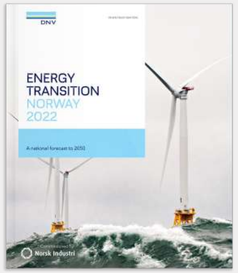

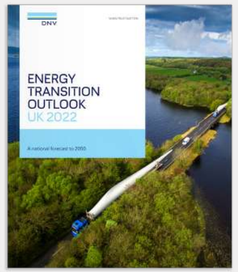

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