MIT Climate Grand Challenge: Tough to Decarbonize Transportation

Appendix D: Policy

Section Leader

Noelle Selin

Section Team

Florian Allroggen

Taylor Black

Christopher Knittel

Jing Li

Sergey Paltsev

Jessica Trancik

Ian Waitz

M. Emelia Williams

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D.1. Policy Directions and Themes

Policy considerations for the decarbonization of aviation, maritime shipping, and long-distance trucking vary widely between sectors. With maritime shipping and aviation taking a top-down approach that focuses on international regulators and trucking utilizing a national framework, each must be viewed within its own context.

D.1.1. Sustainability

Using the UN Sustainable Development Goals (UN SDGs) as a framework for sustainability planning, the proposed work applies a holistic approach to evaluate proposed solutions. The UN SDGs focus on the total impact of implementing a new technology, policy, or action plan and include aspects such as the protection of impoverished people, the effects on the health of people and the environment, economic growth, and furthering innovation. The decarbonization of aviation, maritime shipping, and long-distance trucking assists in reaching targets from the UN SDGs 1 (no poverty), 3 (good health and well-being), 7 (affordable and clean energy), 8 (decent work and economic growth), 9 (industry, innovation, and infrastructure), 12 (responsible consumption and production), 13 (climate action), 14 (life below water), 15 (life on land), and 17 (partnerships for the goals).

Table D 1. A list of project-relevant SDG targets for the team to focus on/consider throughout the research process.

UN Sustainable Development Goal	Target
1. No poverty	1.4. By 2030, ensure that all men and women, in particular the poor and the vulnerable, have equal rights to economic resources, as well as access to basic services, ownership and control over land and other forms of property, inheritance, natural resources, appropriate new technology and financial services, including microfinance
3. Good Health and Well-being	3.9. By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination 3.9.1. (indicator) Mortality rate attributed to household and ambient air pollution
7. Affordable and Clean Energy	7.1. By 2030, ensure universal access to affordable, reliable and modern energy services

	7.2. By 2030, increase substantially the share of renewable energy in the global energy mix 7.3. By 2030, double the global rate of improvement in energy efficiency 7.a By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology 7.b. By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programmes of support
8. Decent Work and Economic Growth	8.2 Achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labour-intensive sectors 8.4 Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-year framework of programmes on sustainable consumption and production, with developed countries taking the lead
9. Industry, Innovation, and Infrastructure	9.1 Develop quality, reliable, sustainable and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all 9.4 By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all

	countries taking action in accordance with their respective capabilities 9.5 Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, including, by 2030, encouraging innovation and substantially increasing the number of research and development workers per 1 million people and public and private research and development spending 9.a Facilitate sustainable and resilient infrastructure development in developing countries through enhanced financial, technological and technical support to African countries, least developed countries, landlocked developing countries and small island developing States
12. Responsible Consumption and Production	12.2 By 2030, achieve the sustainable management and efficient use of natural resources 12.c Rationalize inefficient fossil-fuel subsidies that encourage wasteful consumption by removing market distortions, in accordance with national circumstances, including by restructuring taxation and phasing out those harmful subsidies, where they exist, to reflect their environmental impacts, taking fully into account the specific needs and conditions of developing countries and minimizing the possible adverse impacts on their development in a manner that protects the poor and the affected communities 12.c.1 (indicator) Amount of fossil-fuel subsidies per unit of GDP (production and consumption) and as a proportion of total national expenditure on fossil fuels
13. Climate Action	13.2 Integrate climate change measures into national policies, strategies and planning

14. Life Below Water	14.a Increase scientific knowledge, develop research capacity and transfer marine technology, taking into account the Intergovernmental Oceanographic Commission Criteria and Guidelines on the Transfer of Marine Technology, in order to improve ocean health and to enhance the contribution of marine biodiversity to the development of developing countries, in particular small island developing States and least developed countries 14.c Enhance the conservation and sustainable use of oceans and their resources by implementing international law as reflected in UNCLOS, which provides the legal framework for the conservation and sustainable use of oceans and their resources, as recalled in paragraph 158 of The Future We Want
15. Life on Land	15.9 By 2020, integrate ecosystem and biodiversity values into national and local planning, development processes, poverty reduction strategies and accounts
17. Partnerships for the Goals	17.7 Promote the development, transfer, dissemination and diffusion of environmentally sound technologies to developing countries on favourable terms, including on concessional and preferential terms, as mutually agreed

D.2. Institutional Analysis

D.2.1. Stakeholder Analysis

D.2.1.1. Aviation

Due to the globalized nature and safety concerns related to aviation governance, aviation policy tends to take a top-down approach from an international level. This international governance is led by the International Civil Aviation Organization (ICAO). ICAO, though not an official regulator, oversees the collaboration and diplomatic relations of 193 countries to assist with policy development. On a national level, countries utilize their own transport safety authorities, oftentimes referred to as a Civil Aviation Administration (CAA). For example, in the United States there is the Federal Aviation Authority (FAA) that works in conjunction with the Environmental Protection Agency to form aviation and carbon emissions standards. Intergovernmental authorities such as the European Organisation for the Safety of Air Navigation regulate across a region and are considered to be invited members to ICAO. When considering the non-governmental players in aviation regulation, there are corporate, advocacy, research, and supply chain players (Wittmer et al., 2011) that can be seen in more detail in Figure D.1.

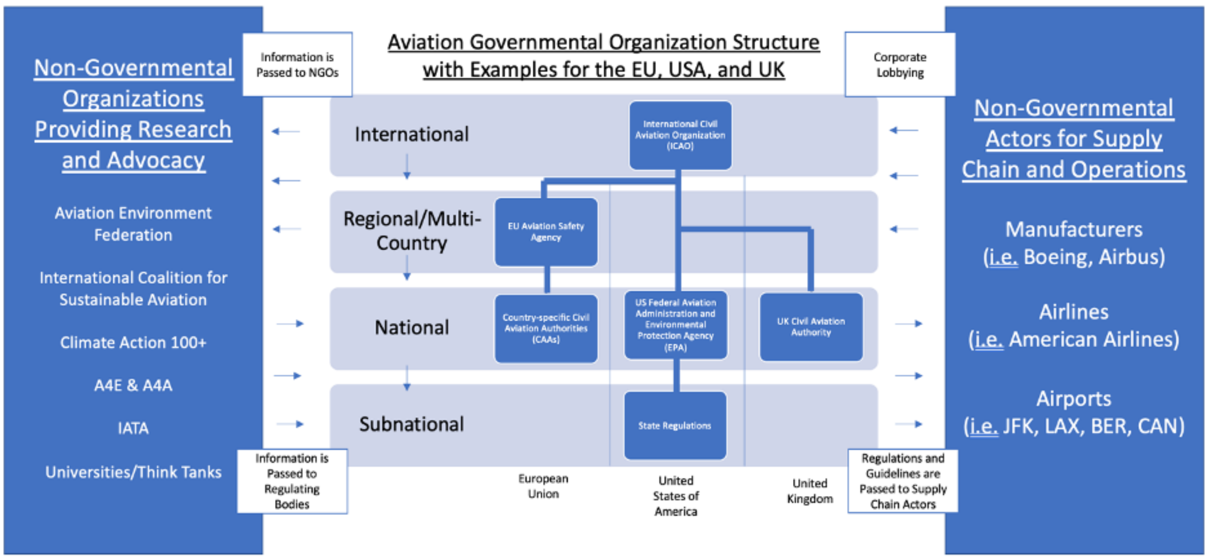

Figure D 1. Aviation Organizational Structure

D.2.1.2. Maritime Shipping

Though maritime shipping's institutional structure is similar to that of aviation (with a top-down approach), international regulators play a smaller role in policy implementation. The International Maritime Organization (IMO) performs the lead role in maritime shipping governance with individual countries adopting their own structure on the national or regional (i.e. European Union) level. One of the missions of the IMO is "to encourage and facilitate the general adoption of the highest practicable standards in matters concerning maritime safety, efficiency of navigation and prevention and control of marine pollution from ships," (United Nations, 1948) giving them jurisdiction over carbon emissions legislation. In reality, these regulations are typically implemented by national organizations and are loosely followed due to the "flags of convenience" practice. With "flags of convenience" ships can be registered to the nation that best suits a corporation's goals, often creating a "race to the bottom” for environmental and innovation regulations. (Hunter et al., 2010) Non-governmental organizations include, but are not limited to, ports, manufacturers, fuel suppliers, and advocacy/certification organizations.

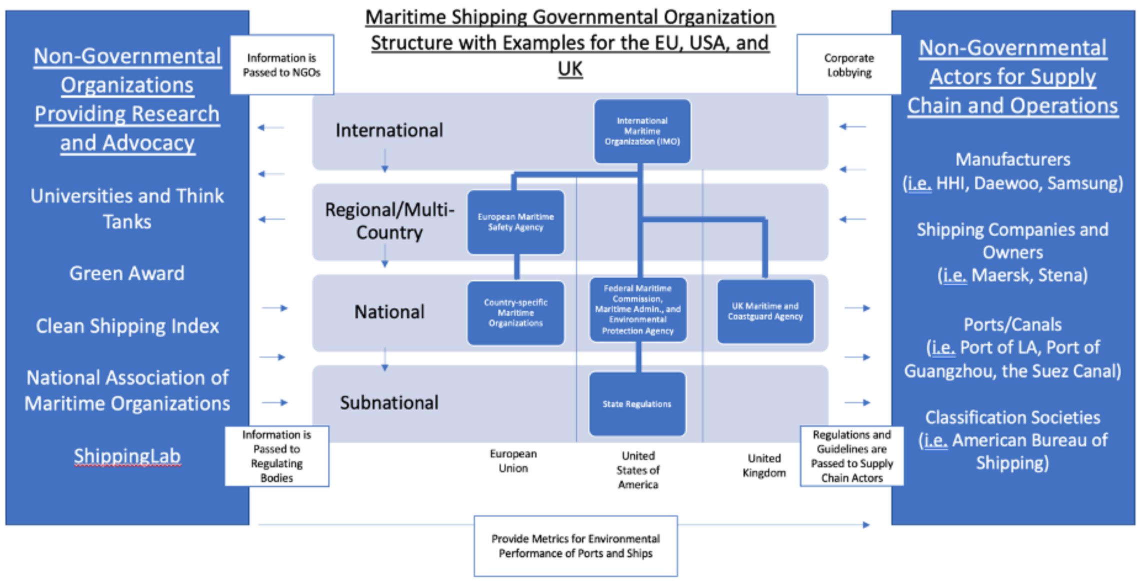

Figure D 2 Maritime Shipping Organizational Structure

D.2.1.3. Long-distance Trucking

Due to the fact that long-distance trucking is primarily a domestic issue, national regulators are the primary source of policies and guidelines. Each country has a unique structure for carbon emissions regulations in trucking but typically can be traced to a varied collaboration between the country’s environmental and transportation bodies. For example, in the United States the Environmental Protection Agency (EPA) and the Department of Transportation (DOT). Non-governmental actors vary by country, but include manufacturers, freight companies, and advocacy/safety groups.

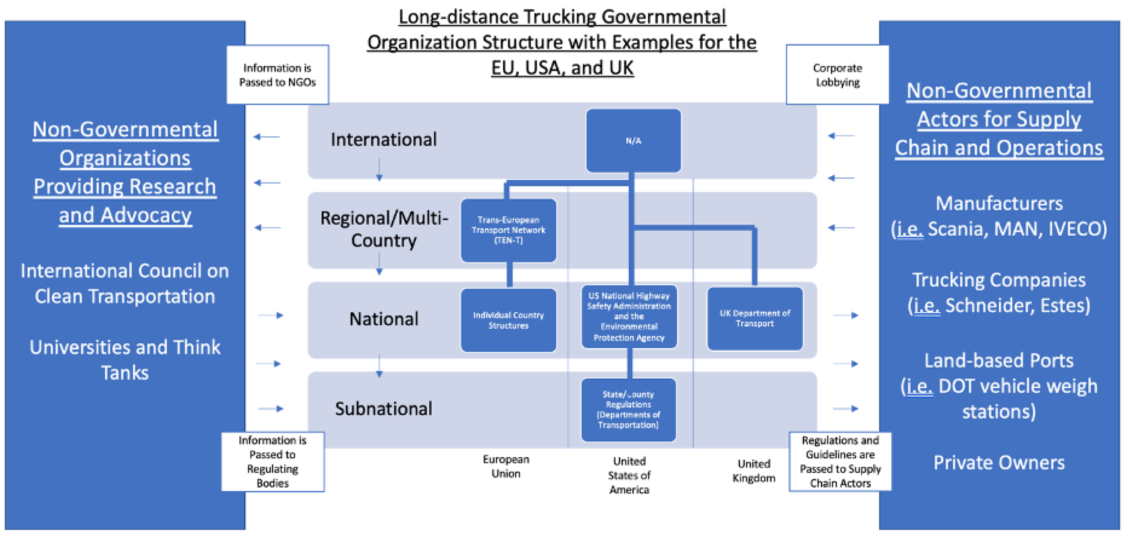

Figure D 3. Long-distance Trucking Organizational Structure

D.2.2. Policy Analysis

D.2.2.1. Climate Change

The decarbonization of tough to decarbonize forms of transportation will assist in reaching the Paris Agreement goals outlined in Article 2, "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change" (United Nations, 2016).

D.2.2.2. Aviation

The Chicago Convention led to the establishment of the International Civil Aviation Organization in 1944. Annex 16 of the Chicago Convention focuses on Environmental Protection, specifically referring to air pollution and noise pollution from aircraft (ICAO, 2008).

Recent programs by ICAO to control carbon emissions and promote technology transfer between developed and developing countries include CORSIA, the 2050 ICAO Vision for Sustainable Aviation Fuels, and the ICAO Assistance, Capacity-building, and Training (ACT-CORSIA) Program. CORSIA, or the Carbon Offsetting and Reduction Scheme for International Aviation, utilizes carbon offsets to lower the impact of carbon emissions from aircraft. ACT-CORSIA works to promote equity for CORSIA implementation between developed and developing countries. The 2050 ICAO Vision for Sustainable Aviation Fuels is “a living inspirational path and calls on States, industry and other stakeholders, for a significant proportion of conventional aviation fuels (CAF) to be substituted with sustainable aviation fuels (SAF) by 2050, for international civil aviation to reduce carbon emissions significantly, and whilst pursuing all opportunities in the basket of mitigation measures to reduce emissions as necessary.”

D.2.2.3. Maritime Shipping

The United Nations Convention on the Law of the Sea (UNCLOS) is often referred to as the “constitution for ocean governance” (Hunter et al., 2010). In regards to environmental governance, Part XII: Protection of the Marine Environment, of the convention focuses on pollution, protection of marine ecosystems, seaworthiness of vessels, and technology to reduce pollution (United Nations, 1994).

The International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) developed guidelines for shipping pollution in 1973. MARPOL was amended in 2011 to include carbon emissions control and energy efficiency for maritime shipping (United Nations, 1994). It was amended again in 2012 and 2014 to include NOx emissions from marine diesel.

D.2.2.4. Long-distance Trucking

In the United States of America, the Environmental Protection Agency (EPA) and the Department of Transportation (DOT) have put carbon emissions standards for recently manufactured heavy-duty trucks into place. In addition to carbon emissions standards, concerns over emissions have motivated reductions in speed limits nationwide and the requirement that heavy trucks are limited (by hardware) to a maximum speed of 65 mph. In California, increased NO_x standards (in comparison to federal standards) have been established and will be made mandatory in 2024.

D.3. Policy Storylines and Trends

Decarbonizing the tougher transport sectors requires both a change in demand, a change in technologies and infrastructure, and a change in governance and institutions. In each sector, there is a specific focus on increasing efficiency while catalyzing a transition toward low- and zero-carbon fuels. A number of policy storylines and trends have described pathways for such decarbonization, which are summarized here.

D.3.1. Aviation

Within existing aviation storylines, the largest focus has been on the deployment of sustainable aviation fuel (SAF), increases in operational efficiency, and policy measures that address demand reduction and incentivize alternative fuel sources.

The International Civil Aviation Organization (ICAO) has set out goals for governments on a 2035 and 2050 timeline to remain on a 1.5C pathway, including: well-to-wake greenhouse gas (GHG) emissions not exceeding 2020 levels in 2035 and well-to-wake GHG emissions reduced at least 50% from 2005 levels by 2050 with aspirations of achieving zero-climate impact by 2050 (ICAO, 2019). Their specific recommendations are included in the analysis below.

D.3.1.1. Technical Outlook

The technical outlook for aviation decarbonization lies in the development and deployment of SAF, exploring electric options for short-haul flights, and operational efficiency with improved aircraft technology. Biofuels have the least number of barriers compared to electric or hydrogen and can reduce emissions by up to 80% during its full lifecycle. They have the same fuel distribution infrastructure as aircraft engines already in use. According to the ICAO 2016 trends assessment, a 100% substitution of aviation fuel with SAF could reduce 63 per cent of the baseline CO_2 emissions from international flights in 2050 (ICAO, 2019). Several SAFs are bioenergy, which means that deployment needs to be planned sustainability as to avoid environmental and social risks. There are a considerable number of barriers documented in various storylines including feedstock supply readiness, the high costs and necessary funding, the overall sustainability of bio-sourced fuels, and consistency of different fuel types. Policy can be designed to solve many of the barriers, documented below.

Electric options for short-haul flights are reasonably popular within existing storylines, with the International Council on Clean Transportation (ICCT) estimating that up to 50% of emissions from regional flights could be reduced through electrification by mid-century, with net-zero lifecycle emissions (ICCT, 2020). They also estimate that electric aircraft used on short, regional flights could offset 10% of aircraft fuel use by 2050.

Operational efficiency improvements can be made on the in-service fleet and engineering and design innovations came be employed on new aircraft, including advanced wing tube technologies and alternative airframes can potentially reduce aircraft fuel burn by

30% by 2050 (ICCT, 2020). Research assembled by ICAO suggests that the fuel consumption of new aircraft/airframes can be reduced cost-effectively by approximately 25% by 2024 and 40% by 2034 compared to 2016 aircraft or an annual improvement of 2.2% (ICAO, 2019). New aircraft materials, improved control devices, and improved engines are all essential in making these comprehensive improvements. Operational improvements, such as maximizing load factors, traffic and descent optimization, weight management, and measures to reduce ground-level fuel burn can reduce aircraft fuel burn and CO_2 emission (ICAO, 2019). Many existing storylines, from academia and international organizations alike point to these measures as integral implements in the decarbonization of the sector.

D.3.1.2. Policy Outlook

The policy levers that have been identified by previous research on net-zero pathways have focused on demand reduction measures such as carbon pricing, SAF incentivization, and operational efficiency improvements incentivization.

Demand reduction policies are an included element of all of the storylines identified, with the most emphasis on carbon pricing in the form of a fuel tax. The storyline that presents the potentiality of the application of a fuel tax of 0.333 €/L indicated a 13% reduction of fuel burn and CO_2 produced in respect to the business-as-usual scenario (Valdés et al., 2021). These policies, however, do come with major political barriers: an aviation carbon tax would only be effective in reducing demand if it is common and equal among countries, especially the 20% of countries that generate 80% of the aviation emissions (Valdés et al., 2021). This would require massive movement in the international climate diplomacy space in the coming decade, which seems unlikely. In response to a fuel tax and the higher price of aviation, there is the possibility of larger scale modal shifts to less carbon intensive modes, such as rail travel. The storyline presented by Sharmina et al. (2021) points to the need to increase connectivity between land-based modes and the phasing out of short haul flights.

ICAO predicts that there will be an anticipated increase of a factor of 3.3 in international air traffic and fuel consumption is projected to increase by 2.2 to 3.1x compared to 2015 depending on the air traffic and potential carbon pricing schemes of the future (ICAO, 2019). This underscores the need for policy intervention to incentivize SAF, as demand reduction measures cannot feasibly alter the entire sector. Incentivization of SAF includes several policy pathways that will create effective market and demand mechanisms to foster the development deployment of SAF. The policy pathways that stand out in the storyline literature include market, regulatory, and innovation related policy. Purchase agreements and risk mitigation policies can influence the SAF market, including creating a differentiated tax regime and special financing lines, as they can reduce operational costs and investment in projects for SAF production and use (ICAO, 2019). Developing supporting mechanisms like a tax exemption or direct subsidy are other market-based ideas that could catalyze the early SAF market. The aviation storyline literature points to regulatory policies that would incentivize development and deployment of SAF, including mandatory blends or consumption targets, increasing feedstock yield and related agricultural policy, and implementing a national SAF program to coordinate between agriculture and transport sectors. Innovation policy packages include basic information and demonstration programs as well as increased funding for research and development of SAF, with special attention on assistance in studying processes and systems, and developing and implementing evaluation methodologies (ICAO, 2019).

D.3.2. Maritime Shipping

Within existing maritime shipping storylines, the largest focus is on the deployment of three central fuels (hydrogen, ammonia, and biofuels/HVO), increases in operational efficiency through physical improvements and voyage shifts, and policy measures that address incentivization of these two pathways to decarbonization. Prior research has not emphasized demand reduction, though one study mentions the potential impact of a shift to more localized product routes. However, there have been no attempts to quantify the impact of these shifts or their feasibility considering the global nature of shipping.

D.3.2.1. Technical Outlook

The technical outlook for maritime shipping relies on the opportunities for low or no carbon fuels and operational efficiency measures to decrease the impact of the ship as it sails, and the amount of fuel burned.

Currently, three fuels stand out as available candidates for a decarbonizing maritime shipping sector: advanced biofuel/HVO, hydrogen, and ammonia. As a drop-in fuel, advanced biofuel/HVO can provide a direct substitute but is expensive and there is currently limited production capacity and bunkering availability of HVO, which raises the question of whether this is a scalable fuel. Hydrogen could be a zero emissions fuel if produced from renewables and fits well with the anticipated energy transition to renewable power production on land. Hydrogen suffers from high costs and low applicability, limiting it to shortsea shipping in the near and medium term (Ryste, 2019). Ammonia is mentioned as a popular solution, and is seen by some as the chosen candidate for scaling up, and playing a role as a critical fuel for long-range transoceanic journeys that need fuel with high energy density (IEA, 2021). The effectiveness of ammonia as an alternative fuel depends on its rapid uptake, however; it could constitute the majority of the fuel mix (more than 70%) by 2035 (Halim et al., 2018). While still in mostly a demonstration phase tech-wise, many ports are "ammonia-ready" and the costs of retrofitting terminals to suit ammonia are drastically are relatively low.

The main technological barriers for the development and deployment of the fuels above include a key infrastructure issue: the main limitation to the shift from conventional fuels to alternative fuels is identified in the lack of availability of bunkering facilities at ports (Serra and Fancello, 2020). On the one hand, bunker suppliers are unwilling to invest in bunkering points until there is sufficient demand for alternative fuels as standard marine fuel, though on the other hand, ship-owners are unwilling to invest in alternative fuel vessels if refueling opportunities are not easy to obtain. There is also the question of storage capacity for gaseous fuels in comparison with liquid fuels. Storage tanks for gaseous fuels are more costly, space-consuming, and challenging to integrate onboard.

Electrification faces major technological barriers concerning efficiency and transportability to meet the needs of longer distance sea trips. Short sea trips and hybrid solutions are feasible though without increased shore-based facilities for charging, this will also be limited in deployment. One study predicted that electric ship penetration would be at about 10% by 2050, suggesting its limited applicability (Halim et al., 2018).

Operational efficiency upgrades and shifts were common in all storylines, with a focus on speed optimization/slow steaming, capacity and voyage optimization, hybrid power and propulsion, vessel size, and hull shape. Slow steaming minimizes the amount of fuel burned in transit, limiting greenhouse gas emissions and the CO_2 emissions reduction potential is projected to be up to 60% for this operational efficiency change (Bouman et al., 2017).

D.3.2.2. Policy Outlook

In terms of policy, there is widespread recognition that the two main types of policy strategies needed to reach net zero by 2050 include incentivizing a fuel shift and incentivizing operational efficiencies.

Within the 2018 IMO's Initial Strategy, there is a focus on addressing fuels in the mid- and long term, between 2023 and 2030, and 2030 and beyond - "pursuing zero-carbon or fossil-free fuels for the shipping sector and developing robust lifecycle GHG/carbon intensity guidelines for alternative fuels" (Rutherford and and Comer, 2018). From a regulatory perspective, some have suggested allocating carbon emissions from international shipping to countries in order to more effectively regulate them under Paris Agreement policies (Selin et al., 2021).

No market-based measure for international shipping has been applied on an international level thus far, and they seem unlikely in the short term. The EU attempted to include shipping in their 2019 ETS proposal and were met with strong opposition, which claimed "claimed it may create distortions for efficient trade and hinder the global decarbonization process started by the IMO" (Serra and Fancello, 2020). In the framework of the IMO's Strategy, the implementation of MBMs seem to be expected in the long-term for decarbonization to be realized.

Fiscally, there is a need for collaboration with financial institutions to create tailored financial instruments with low-interest loans for low-carbon shipping. There is also a need for the support of research for the commercial viability for alternative fuels and operational efficiencies.

Regarding incentivizing the use of ammonia, codes and regulations that have been long established in the refrigeration industry would need to be translated to the existing International Code of Safety for Ships using gas or other low-flashpoint fuels (ITF, 2019). Price on a $/GJ basis is comparable to other bunker fuels, at the high end but is not unaffordable. From 2016 to mid-2019, the global ammonia price corresponded to a range of about 10–20 USD/GJ and the cost of renewable ammonia production in 2040 amounts to approximately 20 and 25–35 USD/GJ for electrochemical ammonia production and electrolysis of water followed by the HB synthesis in large and small scale, respectively (Hansson et al., 2020). Global production needs to be increased from renewable sources; this will require large amounts of electricity, but the production is not constrained by any other raw materials (Hansson et al., 2020). The major issues are land-based, making sure that the fuel needs to be available in the right locations at the right volumes. The existing ammonia transport network connects production and storage locations that serve the industrial market and doesn't reach ports in a way that would be utilizable to ships. Incentivizing RD&D in ammonia infrastructure and ship demonstration will be key for development deployment. Fuel cells for ammonia will mainly be used in pilot and early applications for the next 5-10 years and it is uncertain when this fuel could become commercially viable (Ryste, 2019).

Concerning advanced biofuels/HVO, there are policy needs for development and deployment, including: environmental and societal constraints allow for large quantities of primary bioenergy and waste in 2050, prices or policies emphasize the production and use of that bioenergy and waste as feedstock (Staples et al., 2018). Policies must address the multiple barriers of cost and availability in that regard, seeing as currently, the cost of biofuels is roughly twice the price of their fossil counterparts (International Renewable Energy Agency, 2019). Though the cost of biofuels is expected to drop considerably, it will only become competitive by 2040 or so, considering the feedstock cost and competition with other fuel sectors. Second and third generation biofuels seem to be the most suitable option to avoid sustainability issues and increasing competition for land. To meet demand for the maritime sector alone, there would need to be a substantial increase in their production levels. Secure and long-term supplies of low-cost and sustainability sourced feedstock will be critical to the economics of biofuels (International Renewable Energy Agency, 2019). This points to the need for future policies that incorporate smart agricultural practices, and waste and residue policies.

The current regulatory landscape surrounding hydrogen is lacking: as a novel fuel, there are no existing federal regulations that specifically cover the design and operation of hydrogen-powered vessels, including hydrogen as a vessel fuel, use of fuel cells for vessel propulsion or hydrogen bunkering. Though, there are regulatory hurdles concerning safety, including International Code of Safety for Ships using gases or other low-flashpoint fuels (the "IGF code") (ITF, 2019) and Classification Society rules, which must be considered if hydrogen can be deployed and scaled. There is a dire need for R&D into the safety, efficacy, and viability of hydrogen applications to prove both the technical and business viability of new hydrogen market. The opportunity of future hydrogen production lies in the fact that its capacity fits well with the anticipated energy transition to renewable power production on land. Policies need to address the sourcing of hydrogen as most of the hydrogen is produced from fossil fuels without carbon capture. The addition of new infrastructure for hydrogen would imply prohibitive costs, although these could be assuaged by repurposing and adapting LNG infrastructure (International Renewable Energy Agency, 2019). Costs are expected to decrease and become competitive by 2030, reaching 37 − 77 USD/MWh (1,233 – 2,566 USD/ton) by 2050, but are currently not cost competitive with any fossil fuels at 108,275 USD/MWh (3,593 – 9,180 USD/ton) in 2019.

Incentivizing operational efficiency improvements is an integral part of many researched storylines in the maritime sector. Maritime shipping storylines assume massive increases in efficiency improvements, in line with the 2018 IMO Initial Strategy goals, but within this research, there is a recognition of the barriers to implementation. Within the 2018 IMO Initial Strategy, there are operational efficiency targets, the carbon intensity of international shipping would fall 40% by 2030 from 2008 levels and by up to 70% in 2050 (Rutherford and and Comer, 2018). The ICCT predicts that, based on trends in international shipping emissions and demand, combined with fleet renewal under the EEDI, shipping's carbon intensity is likely to fall by at least another 10 percentage points by 2030 without further policy interventions (Rutherford and and Comer, 2018).

Operational measures, such as slow steaming, can be easier to adopt at scale, as no major technological changes are needed. As the Energy Efficiency Design Index (EEDI) and SEEMP aim to increase the energy efficiency of new ships over time, there is a need to "to instill an energy-efficiency culture in international shipping, particularly with regard to effective implementation of the SEEMP and ensuring the inculcation of energy-efficiency measures" (Sekimizu, 2013). There are myriad barriers to implementation, including technological and commercial aspects. There is a question of the ability of energy efficiency technologies available on the market to provide the needed benefits in terms of emissions reductions in comparison to the benefits claimed by the manufacturers of those systems. Commercially, there is a barrier that is known as the "split incentive," which occurs when the ship owner, who controls capital spending, is not the same as the operator, who is responsible for fuel costs and therefore receives the financial benefit from any fuel savings (Sekimizu, 2013).

Operational measures that are currently at the forefront of emissions-saving efforts include: slow steaming, voyage optimization, ship size and capacity utilization, and hull design. Currently, there are no international regulations regarding slow steaming, though there is a push for the IMO to include specific regulatory measures concerning slow steaming. To create effective policy regarding slow steaming, "speed design would need to be addressed, as well as commercial considerations for "just in time" delivery, transparency, safety and competition in the shipping market" (Serra and Fancello, 2020). Regulated global speed reductions will likely be unpopular, and as slow steaming is already widely adopted, further emission reductions may be very limited if there isn't, in tandem, a switch to alternative fuels.

Voyage optimization utilizes modern technologies that predict weather and maritime conditions, allowing shipmen to select the most energy-efficient navigation routes. It's extremely cost-effective, allowing companies to reduce their emissions and fuel burn by bypassing routes where the ship will not run as efficiently (Serra and Fancello, 2020). Ship size and capacity utilization will likely play a moderately influential role, as the CO_2 could be reduced by as much as 30% at a negative abatement cost by replacing the existing fleet with larger vessels (Lindstad et al., 2014). As newer and more energy efficient ships are more likely to be larger ships, the effect of ship size and capacity utilization could be overestimated (Halim et al., 2018). The design of efficient hull shapes has the potential to reduce CO2 emissions within the sector by anywhere from two to 30%, and refers to the ability of the hull dimensions, shape, and weight, and their ability to improve the hydrodynamic performance and minimize resistance (Bouman et al., 2017).

D.3.3. Long Haul Trucking

Forecasting a long haul trucking storyline for 2050 depends on the policy and economic levers to incentivize alternative fuels, regulate efficiency, and fuel standards, and to a degree, managing demand. There are limitations and opportunities presented in the near term and in the long term for heavy duty trucking; in the near term, the sector will require systemic improvements like supply chain improvements, logistical improvements, and energy efficiency improvements. In the longer term, decarbonization will rely on a shift of fuel and powertrain type. All aspects of the technical outlooks include different potential policy levers for implementation, which are also covered below.

D.3.3.1. Technical Outlook

The technical outlook for long haul trucking relies on opportunities for alternative fuels and powertrains and improvements in technological and operational efficiency measures.

Currently, in the alternative fuel space, there are two outlying categories: biofuels and hydrogen. In this discussion, biofuels include biodiesel, HVO, and biomethane. The main advantage of biofuels is that they do not require massive shifts in infrastructure, including the investment that pairs with infrastructure improvement. With hydrogen, emission reductions would depend on whether it is produced and liquefied using low-carbon energy (Sharmina et al., 2021). There has been movement in the market toward the deployment of hydrogen, with Daimler, the world's largest maker of heavy trucks, announcing that it would convert to zero-emission vehicles within 15 years at the latest (Ewing, 2021).

Electrification in this sector is mentioned in several studies, though alternative powertrains are not enough to achieve CO_2 emissions goals for the road freight sector alone. Electrification can include different infrastructure systems, including conductive power transfer (through overhead catenary lines), in-road conductive charging, and inductive transfer of power, which requires the installation of coils (Mulholland et al., 2018).

Improvements in technological and operational efficiency measures include optimized routing, platooning, last mile efficiency, physical internet systems and supply chain coordination, and co-loading. Optimized delivery routes utilize GIS and real-time routing data that enables for time and fuel savings (Mulholland et al., 2018). Platooning refers to the practice of reducing the gaps between trucks on the highways using smart vehicle communication in order to reduce drag and fuel consumption (Mulholland et al., 2018). Last-mile efficiencies refers to the allocation and prediction of dynamic demand can help mitigate delivery demand peaks (Mulholland et al., 2018). The physical internet indicates an open, shared, and modular global logistics system in contrast to proprietary logistics systems while co-loading is a way of increasing vehicle utilization through bundling shipments across product categories with similar shipment parameters (Mulholland et al., 2018). In the most transformational of scenarios within the storylines, all these measures could add up to a reduction in road freight activity (tkm) of 13.5%, and a decline in vehicle activity of more than 20% in 2050 (Mulholland et al., 2018). Energy efficiency measures include: aerodynamics, low rolling resistance, engine efficiency, idling reducing tech, hybridization.

D.3.3.1. Policy Outlook

In terms of policy, there is a recognition that the two main policy groupings needed to reach net zero by 2050 include incentivizing a fuel and powertrain shift and incentivizing operational efficiencies. There is also a smaller set of research that is focused on demand reduction and modal shifts to rail and maritime shipping, but discussion will be limited in this appendix.

Policies targeted to address biofuel incentivization in relation to long haul and heavy-duty trucks are like those of the sectors above: price competitiveness within nascent markets and sustainability concerns. One of the main barriers facing biofuel adoption is their long-term economic competitiveness relative to highly volatile oil prices, and the researched storylines suggest the importance of fiscal-based policy tools, include de-risking measures for advanced biofuel plant investment while costs remain high in the market’s near-term nascency.

Policy support for biofuels is growing, with marked support in China, India, and Thailand, as well as Europe and North America (IEA, 2017). Legislation that stipulates defined reductions in life-cycle carbon intensity of transport fuels have been established in Germany and

California, and these policies act to stimulate demand for biofuels with the highest emissions reduction potential (IEA, 2017). On another hand, advanced biofuel mandates will be essential to accelerating uptake. Sustainability concerns are paramount to the success of biofuel, and policies targeted toward incentivization for biomass and bioenergy feedstocks are similar to the sectors above.

Supporting hydrogen development and deployment requires the support of a renewable energy source in tandem, as hydrogen is only as carbon free as the manufacturing of its fuel supply. The development of refueling infrastructure is also a main barrier; investment at the state level of organization and scale is essential to create a feasible refueling structure (Moultak et al., 2017).

Supporting electrification of heavy-duty trucks includes market support and fiscal measures for equipment manufacturers, but it is also essential to design measures to help road freight vehicle fleet owners investing in electric vehicles. Fiscal and market measures to catalyze the industry's competitiveness are also essential and mentioned in many researched storylines, though the weight of batteries in heavy duty trucks often undermines their effectiveness.

Incentivization of technological and operational improvements related to long haul trucking includes policy support for open data systems which will be most useful for physical internet systems. Within the researched storylines, there is a focus on policies that reward efficiency and collaboration, along with policies that include regulation or pricing measures to discourage prompt and same- or next-day deliveries (Mulholland et al., 2018).

Reduction in freight demand would include localizing the production and storage of goods, shorter trip distances and combined with high utilization rates for vehicles. Demand reduction could also use policy levers like providing incentives for distributed manufacturing and local storage to reduce the need for freight (Sharmina et al., 2021). A modal shift to more efficient forms of transport (rail and maritime) requires policy work in either incentive structures or infrastructure investments.

D.3.4. BAU, Stated, and Transformational Storylines

Aviation - BAU Scenarios

AUTHOR	TITLE	YEARS CONCERNED	GENERAL OUTLINE OF STORYLINE	MARKET DEVELOPMENT AND GROWTH	EMISSIONS TRENDS	ASSUMED TECH	ASSUMED POLICIES	SOURCE
AIR TRANSPORT GROUP	Waypoint 2050	2019-2050	Continuation of current trends	Traffic growth: Central scenario: 3.0% compound annual growth rate (CAGR) 2019-2050	Order of 740-1,100Mt of offsets needed to meet 2050 industry goal (325 million tons of CO_2 annually)	Continuation of current development cycle and performance improvement (the next generation of 'tube-and-wing')	Mid-range improvements and airline load factor improvements Low- to high-range continuation of current investment curve delivering between 20 — 144 Mt (25 — 180 billion liters) of SAF with a 90% emissions reduction factor by 2050	Air Transport Group. Waypoint 2050. 2019. https://aviationbenefits.org/media/167187/w2050_full.pdf

Aviation - Stated Policy Scenarios

AUTHOR	TITLE	YEARS CONCERNED	GENERAL OUTLINE OF STORYLINE	MARKET DEVELOPMENT AND GROWTH	EMISSIONS TRENDS	ASSUMED TECH	ASSUMED POLICIES	SOURCE
KHALIL ET AL	Global Transportation Demand Development with Impacts on the Energy Demand and Greenhouse Gas Emissions in a Climate-Constrained World	2020-2050/2060	Increased global transportation demand by 2050 can be managed by a stable final energy demand compared to 2015 with known technologies	Airfreight demand is projected to grow by 6% per year until 2035, annual growth rates of 6.4% and 6.0% and 5.5% for 2040, 2045, and 2050, Passenger b p-km by 2050: 21,520 Aviation freight b t-km by 2050: 1,514	Storyline works within reaching 1.5C of warming, with emissions peaking in aviation ~ 2035	2050: 18.7% of the flights measured in passenger kilometers representing short haul flights of < 1.5 h and half of the flights between 1.5 and 3 h will be electric 2050: 37.4% of flights will be fuel-cell-based flights fueled by hydrogen 2050-2060: 80% of short haul flights should be served by all-electric flights in the longer term,	Not a big focus on policy but "ambition requires public insisting on achieving the targets, identification and overcoming of barriers, integrated in an overall societal discourse on the transition"	Khalili et al. Global Transportation Demand Development with Impacts on the Energy Demand and Greenhouse Gas Emissions in a Climate-Constrained World. Energies. 20219, 12, 191-244

GOSSLING ET AL	COVID-19 and pathways to low-carbon air transport until 2050	2022-2050	Models a COVID-19 recovery based on a feed-in quota and a carbon price	Until 2050, air transport demand will continue to grow, exceeding 2018 demand by 3.7–10.3 trillion RPK	This scenario would avoid emissions of up to 26.5 Gt CO2 until 2050	Synthetic fuels, produced by 14–20 EJ of photovoltaic energy, Expect to be costly but least amount of barriers compared to electric or hydrogen	Relies on a feed-in quota for non-biogenic synthetic fuels that will decarbonize fuels by 2050 Carbon price to account for negative externalities and as an incentive to increase fuel efficiency	Stefan Gössling et al 2021 Environ. Res. Lett. 16 034063
ICAO	Global Environmental Trends	2020-2045	Growth forecasts without consideration of policy or tech	Up to 2.6% of fuel consumption could potentially consist of sustainable aviation fuels by 2025 By 2045, compared with an anticipated increase of 3.3 times growth in international air traffic, fuel consumption is projected to increase by 2.2 to 3.1 times compared to 2015	In 2045, [NOx emissions from landing and take-off] are projected to range from 0.44 to 0.80 Mt depending on the technology and ATM scenario, which represents a growth of between 2.4 and 4.4 times since 2015			ICAO. ICAO Global Environmental Trends Working Paper. 2019. https://www.icao.int/Meetings/a40/Documents/WP/wp_054_en.pdf
AIR TRANSPORT GROUP	Waypoint 2050	2019-2050	Pushing technology and operations with continued growth trends	3.0% CAGR 2019-2050	Meeting industry 2050 goal (325 million tons of CO2 annually)	Prioritized development of electric and hybrid electric aircraft in the short-range and <100 seat category with entry into service from 2035/2040 Back cast of what is required (around 900 Mt CO2 reduction) to meet the goal: a range of 290 — 390 Mt (360 — 490 billion liters) of SAF with a 74- 100% emissions reduction factor by 2050	High-range improvements and airline load factor improvements Carbon offsets: if required to address any remaining emissions above the 2050 goal	Air Transport Group. Waypoint 2050. 2019. https://aviationbenefits.org/media/167187/w2050_full.pdf
MARKETS AND MARKETS	Sustainable Aviation Fuel Market Forecast to 2030	2020-2030	Market growth estimations	SAF market projected to grow from USD 66 million in 2020 to USD 15,307 million by 2040, at a CAGR of 72.4%			Emerging economies (China, India) projected to be lucrative markets from 2020-2030	Markets and Markets. Sustainable Aviation Fuel Market Forecast to 2030. 2020. https://www.marketsandmarkets.com/Market-Reports/sustainable-aviation-fuel-

								market-70301163.html?gclid=CjwKCAjwgb6IBhAREiwAgMYKRjBYP5WzSbXVZ3geowA2mmtk9OlkHKvb2UDaV0eRwSyOh7eDpWVn_BoCWVIQAvD_BwE
SHARMINA ET AL	Decarbonising the critical sectors of aviation, shipping, road freight and industry to limit warming to 1.5–2°C	2020-2050	Focuses on the need for demand reduction	Storyline relies on slower growth in sectoral activity, air travel decreasing in some markets, given an expectation of growth in industrializing nations	Within 1.5 and 2 degree scenarios - 429 Mt CO2/year in 2050 for 2.0 and 380 Mt CO2/year in 2050 for 1.5	Development and deployment of low-CO2 fuels, such as hydrogen and synthetic paraffinic kerosene are needed	Reductions in energy intensity, demand management, operations, carbon pricing	M. Sharmina, O. Y. Edelenbosch, C. Wilson, R. Freeman, D. E. H. J. Gernaat, P. Gilbert, A. Larkin, E. W. Littleton, M. Traut, D. P. van Vuuren, N. E. Vaughan, F. R. Wood & C. Le Quéré (2021) Decarbonising the critical sectors of aviation, shipping, road freight and industry to limit warming to 1.5–2°C, Climate Policy, 21:4, 455-474, DOI: 10.1080/14693062.2020.1831430
STAPLES ET AL	Aviation CO2 emissions reductions from the use of alternative jet fuels (AJF)	2020-2050	Mid-ambitious storyline - quantifies AJF production if available feedstocks were allocated to competing uses in proportion to final energy demand in 2050	AJF production volume in 2050: 349.9 Mt/y Number of biorefineries in 2050: 3317 New biorefineries each year: 110	To reach 27.8% emissions reductions, there would be a need for ←	Lignocellulosic feedstocks (cultivated feedstock crops, agricultural and forestry residues, and MSW) are allocated in proportion to final energy demand for aviation	Arable land areas needed for bioenergy cultivation for this scenario: 314Mha Policy needs in this scenario: prices or policies emphasize the production and use of that bioenergy and waste as feedstock; and prices or policies emphasize AJF production relative to other potential uses for primary bioenergy resources	Staples, Mark & Malina, Robert & Suresh, Pooja & Hileman, James & Barrett, Steven. (2018). Aviation CO 2 emissions reductions from the use of alternative jet fuels. Energy Policy. 114. 342-354. 10.1016/j.enpol.2017.12.007.

Aviation - Aggressive/Transformational Scenarios

AUTHOR	TITLE	YEARS CONCERNED	GENERAL OUTLINE OF STORYLINE	MARKET DEVELOPMENT AND GROWTH	EMISSIONS TRENDS	ASSUMED TECH	ASSUMED POLICIES	SOURCE
AIR TRANSPORT GROUP	Waypoint 2050	2020-2050	High ambition storyline	Traffic forecast: 3.0% CAGR 2019-2050	Within line with Paris Agreement's "well below" 2 degrees C - (325 million tonnes of CO_2 annually)	Backcast of what is required (around 740 Mt of CO_2) to meet the goal: a range of 235 — 340 Mt (290 — 420 billion litres) of SAF with a 70-100% emissions reduction factor by 2050 Very aggressive acceleration of the introduction of electric, hybrid, and hydrogen aircraft in the 2035-2040 timeframe	High-range improvements and airline load factor improvements, offsets only if required to address any remaining emissions above the 2050 goal. Substantial investments in operations and infrastructure result in (net) CO_2 reductions of 0.20% per annum, a 6+% overall contribution in 2050.	Air Transport Group. Waypoint 2050. 2019. https://aviationbenefits.org/media/167187/w2050_full.pdf
						A shift towards zero emissions aircraft (potentially hydrogen) for the narrow body segment from 100 to 200 seats. Assumes electrification of the small aircraft segment and hybridization of the larger aircraft segments		
INTERNATIONAL COUNCIL ON CLEAN TRANSPORT	Vision 2050	2020-2050	"Ambitious yet feasible" scenario - presents sets of assumptions		Estimate that the aviation sector's emissions can be reduced by about 77% from 2050 projections and 47% from our 2020 baseline 85%, if including biofuels devoted to aviation	Estimate that 50% of emissions from regional flights could be reduced through electrification by mid-century, with net-zero lifecycle emissions 10% of fuel use replaced by electric aircraft by 2050	Demand management: carbon pricing and consumer information can reduce baseline passenger-kilometer growth by 0.7% to 4% per year	International Council on Clean Transportation. Vision 2050: A strategy to decarbonize the global transport sector by mid-century. 2020. https://theicct.org/publications/vision2050

							Improving new-aircraft efficiency: engineering and design innovations can further reduce aircraft fuel burn by 30% by 2050	
VALDES ET AL	How Much Can Carbon Taxes Contribute to Aviation Decarbonization by 2050	2020-2050	Outlook for application of a fuel tax	The application of a fuel tax of 0.333 €/L will lead to a global 12% reduction of demand, reduction of 13% of fuel and CO2 produced with respect to the do-nothing scenario			Aviation CO2 tax would only be effective in reducing demand if it is common and equal among countries - the 20% of the regions that generates 80% of the traffic, should agree to the implementation of the tax for a significant CO2 saving	Valdés, Rosa M.A., Victor F.G. Comendador, and Luis M.B. Campos 2021. "How Much Can Carbon Taxes Contribute to Aviation Decarbonization by 2050" Sustainability 13, no. 3: 1086. https://doi.org/10.3390/su13031086
STAPLES ET AL	Aviation CO2 emissions reductions from the use of alternative jet fuels (AJF)	2020-2050	Study outlines market growth scenarios - outlined most ambitious	Reductions of 68.1% by 2050 would require construction of ~268 new bio-refineries annually, and capital investment of ~21.9-87.6 billion USD2015 per year Considers growth in air transport demand based on a growth rate of 4.45% yr	Analysis shows that even 100% replacement of petroleum-derived jet fuel with AJF in 2050 may result in an absolute increase in aviation lifecycle GHG emissions compared to a 2005 baseline cont.→	Total 2050 aviation CO2e emissions are 1101 Mt/yr this scenario and lifecycle GHG emissions from global aviation were approximately 711 Mt in 2005. This points to the need of offsets	Scenarios require that: environmental and societal constraints allow for large quantities of primary bioenergy and waste in 2050, prices or policies emphasize the production and use of that bioenergy and waste as feedstock; and prices or policies emphasize AJF production relative to other potential uses for primary bioenergy resources	Staples, Mark & Malina, Robert & Suresh, Pooja & Hileman, James & Barrett, Steven. (2018). Aviation CO 2 emissions reductions from the use of alternative jet fuels. Energy Policy. 114. 342-354. 10.1016/j.enpol.2017.12.007.

Maritime - BAU Scenarios

AUTHOR	TITLE	YEARS CONCERNED	GENERAL OUTLINE OF STORYLINE	MARKET DEVELOPMENT AND GROWTH	EMISSIONS TRENDS	ASSUMED TECH	ASSUMED POLICIES	SOURCE
DNV GLOBAL	Energy Transition Outlook	2019-2050	BAU	Forecast global maritime transport, as measured in tonne-miles, to increase by 39% towards 2050 compared to 2018 Most of the growth will come before 2030, at a forecast average annual growth rate of 2.3%/yr	If carbon intensity remains static, emissions in 2050 would be 1,210 MtCO2 based on the 39 per cent growth in demand for seaborne trade	Results indicate that even with low to moderate seaborne trade growth, the IMO's ambition for a 50 per cent absolute reduction in CO2 emissions by 2050 is stricter than its 70 per cent carbon-intensity reduction ambition	A partial transition to other fuels, the energy mix in 2050 being 93 per cent fossil fuels, specifically 50 per cent liquefied natural gas (LNG) and 43 per cent liquid fuels	DNV Global. Energy Transition Outlook 2019. Maritime Forecast to 2050. https://sustainableworldports.org/wp-content/uploads/DNV-GL_2019_Maritime-forecast-to-2050-Energy-transition-Outlook-2019-report.pdf

Maritime - Stated Policy Scenarios

AUTHOR	TITLE	YEARS CONCERNED	GENERAL OUTLINE OF STORYLINE	MARKET DEVELOPMENT AND GROWTH	EMISSIONS TRENDS	ASSUMED TECH	ASSUMED POLICIES	SOURCE
KHALILI ET AL.	Global Transportation Demand Development with Impacts on the Energy Demand and	2020-2050	Increased global transportation demand by 2050 can be managed by a stable final energy demand compared to 2015 with known technologies	Passenger b p-km by 2050: 491 Maritime freight b t-km by 2050: 276,879		Fuel-to-H2 efficiency is assumed to increase from 53% to 65%, from 2030 to 2050		Khalili et al. Global Transportation Demand Development with Impacts on the Energy Demand and Greenhouse Gas Emissions in a Climate-Constrained World. Energies. 20219, 12, 191-244.

	Greenhouse Gas Emissions in a Climate-Constrained World							
SHARMINA ET AL	Decarbonising the critical sectors of aviation, shipping, road freight and industry to limit warming to 1.5–2°C	2030-2040	Focus on demand reduction alongside efficiency/intensity improvements, i.e. slow steaming	Assumes a market shift from fossil energy to bioenergy trade	Presents options that would be within 1.5 and 2 degree scenarios - 342 Mt CO_2/year in 2050 for 1.5 / 453 Mt CO_2/year in 2050 for 2.0	Improvements in CO_2 intensity: improving vessels propulsion efficiency, wind-assisted propulsion, slow steaming, alternative fuels such as (biofuels, hydrogen, ammonia)	Demand reductions: successful mitigation implies a move away from fossil fuels that constitute around 45% of global shipped trade by weight Operational: slow steaming, retrofits	M. Sharmina, O. Y. Edelenbosch, C. Wilson, R. Freeman, D. E. H. J. Gernaat, P. Gilbert, A. Larkin, E. W. Littleton, M. Traut, D. P. van Vuuren, N. E. Vaughan, F. R. Wood & C. Le Quéré (2021) Decarbonising the critical sectors of aviation, shipping, road freight and industry to limit warming to 1.5–2°C, Climate Policy, 21:4, 455-474, DOI: 10.1080/14693062.2020.1831430
IEA	Net Zero by 2050	2020-2050	Scenario in which maritime does not reach net zero		Emissions from shipping decline by 6% annually to 120 Mt CO_2 in 2050	Medium to long term: switching to low-carbon fuels such as biofuels, hydrogen, ammonia Ammonia: chosen candidate scaling up, and a critical fuel for long-range transoceanic journeys that need fuel with high energy density Sustainable biofuels provide almost 20% of total shipping energy needs in 2050	Short term: slow steaming, use of wind-assistance technologies Electricity: plays a minor role for short distance routes	IEA (2021), Net Zero by 2050, IEA, Paris https://www.iea.org/reports/net-zero-by-2050
IMO	GHG Strategy	2020-2050	International goal scenario		Reduce CO_2 emissions per transport work, as an average across international shipping,	Updated EEDI reduction rates plus energy efficiency		IMO. Initial IMO GHG Strategy. 2018. https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reduci

					by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008 Total annual GHG emissions from international shipping should be reduced by at least 50% by 2050 compared to 2008	management plan, improved voyage planning, plus increased technical measures		ng-greenhouse-gas-emissions-from-ships.aspx

Maritime - Transformational Scenarios

AUTHOR	TITLE	YEARS CONCERNED	GENERAL OUTLINE OF STORYLINE	MARKET DEVELOPMENT AND GROWTH	EMISSIONS TRENDS	ASSUMED TECH	ASSUMED POLICIES	SOURCE
HALIM ET AL	Decarbonization Pathways for International Maritime Transport: A Model-Based Policy Impact Assessment	2021-2035	Decarbonize by 2035 using today's technologies with maximum intervention	Reduced sea transport demand could lead to a reduction of approximately 1.2 MTons of CO2 emissions	CO2 emission levels down to 56 million tons, which is equivalent to a 93% emissions reduction from the adjusted demand level	Electric ship penetration - 10% Zero-carbon fuels such as hydrogen and ammonia would have to see a rapid uptake and should constitute the majority of the fuel mix by 2035 (more than 70%)	*Operations*: Increase in ship size, drastic speed reduction could reduce CO2 emissions by 43% by 2030	Halim, Ronald A., Lucie Kirstein, Olaf Merk, and Luis M. Martinez 2018. "Decarbonization Pathways for International Maritime Transport: A Model-Based Policy Impact Assessment" *Sustainability* 10, no. 7: 2243. https://doi.org/10.3390/su10072243
INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION	Vision 2050	2020-2050	"Ambitious yet feasible" scenario - presents sets of assumptions	Potential to cut marine emissions 67% from the current projection for 2050	Factoring in use of low-life-cycle emissions biofuels in the marine sector can increase that estimated reduction to 71% from BAU	Improved operational efficiencies, such as slow steaming, and technology-based efficiency improvements, i.e. hull air lubrication and wind-assisted propulsion Ship energy efficiency improved by 70% by 2040 →	Targeted fees on marine bunker fuels can raise funding for developing/ incentivizing ship electrification 17% of energy demand can be met by zero-emission vessels by 2050	International Council on Clean Transportation. Vision 2050: A strategy to decarbonize the global transport sector by mid-century. 2020. https://theicct.org/publications/vision2050

Long Haul Trucking - BAU Scenarios

AUTHOR	TITLE	YEARS CONCERNED	GENERAL OUTLINE OF STORYLINE	MARKET DEVELOPMENT AND GROWTH	EMISSIONS TRENDS	ASSUMED TECH	ASSUMED POLICIES	SOURCE
CARLOS CALVA AMBEL	Roadmap to climate-friendly land freight and buses in Europe	2020-2050	BAU for land freight in Europe	Freight activity: 3928b tkm in 2050 The HHGV share in EU is projected to be 66% whereas in the Nordic countries the share is expected to be 71%	Direct freight transport carbon dioxide equivalent emissions (tank-to-wheel [TTW] CO2e i.e. tailpipe emissions) increases by 116 million tonnes (Mt) in the EU and by 5.4 Mt in the Nordic countries	Electric delivery trucks will not penetrate the market until 2050 Limited market demand for biofuels due to policy caps No serious uptake of hydrogen	Without targeted policy measures, the vehicle efficiency of long haul and regional delivery trucks would only gradually improve by 10% in the 2010-2030 period	Ambel, Carlos Calva. Roadmap to climate-friendly land freight and buses in Europe. Transport & Environment. 2017. https://www.transportenvironment.org/publications/roadmap-climate-friendly-land-freight-and-buses-europe

Long Haul Trucking - Stated Policy Scenarios

AUTHOR	TITLE	YEARS CONCERNED	GENERAL OUTLINE OF STORYLINE	MARKET DEVELOPMENT AND GROWTH	EMISSIONS TRENDS	ASSUMED TECH	ASSUMED POLICIES	SOURCE
MULHOLLAND ET AL	The long haul towards decarbonising road freight – A global assessment to 2050	Through 2050	Reference truck scenario	By 2050, three-quarters of global road freight activity is covered by HFTs, up from 63% today Overall global road freight tkm grows by 2.4-fold over the period 2015–2050 HFT stock increases by 2.6-fold to 64 million vehicles	WTW GHG emissions increase by 55% between 2015 and 2050 to 53 EJ and 4.8 gigatonnes of CO2-equivalent (Gt CO2-eq) respectively in 2050	Partially realized in comparison to Modern Truck Scenario	Partially realized in comparison to Modern Truck Scenario	Mulholland, Eamonn & Teter, Jacob & Cazzola, Pierpaolo & McDonald, Zane & O Gallachoir, Brian. (2018). The long haul towards decarbonising road freight – A global assessment to 2050. Applied Energy. 216. 678-693. 10.1016/j.apenergy.2018.01.058.

Long Haul Trucking - Transformational Scenarios

AUTHOR	TITLE	YEARS CONCERNED	GENERAL OUTLINE OF STORYLINE	MARKET DEVELOPMENT AND GROWTH	EMISSIONS TRENDS	ASSUMED TECH	ASSUMED POLICIES	SOURCE
IEA/NACEUR ET AL	Energy Technology Perspectives	2020-2060	Cost-related optimization of the technology portfolio used in various industries on a global level - three electrification scenarios	By 2060, AFP market share of about 90% in HDV stock in their most ambitious climate scenario (less than 2 degrees warming) and AFP market share of 17% in HDV stock in their BAU scenario				IEA (2017), Energy Technology Perspectives 2017, IEA, Paris https://www.iea.org/reports/energy-technology-perspectives-2017
MAI ET AL	Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States	2020-2050	Examines potential for how HDV electrification might influence demand in the USA - three scenarios	Within their most optimistic scenario, they forecast an AFP market share of 41% in 2050				Mai, Trieu, Paige Jadun, Jeffrey Logan, Colin McMillan, Matteo Muratori, Daniel Steinberg, Laura Vimmerstedt, Ryan Jones, Benjamin Haley, and Brent Nelson. 2018. Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-71500. https://www.nrel.gov/docs/fy18osti/71500.pdf.
SHARMINA ET AL	Decarbonising the critical sectors of aviation, shipping, road freight and industry to limit warming to 1.5–2°C	2020-2050/2100	Policy pathways to reach Paris goals		Within 1.5 and 2 degree scenarios - 330 Mt CO2/year in 2050 for 1.5 / 979 Mt CO2/year in 2050 for 2.0	Short-term: use biodiesel or alcohol fuels such as bioethanol w/ little change needed to infrastructure Batteries: For light and medium trucks, extensive use of batteries, heavy trucks need	Energy intensity improvements: optimising routes, linking trucks in a convoy and maximising load factors Reduction in freight demand: localising the production and storage of goods, shorter trip distances and combined with high utilisation rates for vehicles	M. Sharmina, O. Y. Edelenbosch, C. Wilson, R. Freeman, D. E. H. J. Gernaat, P. Gilbert, A. Larkin, E. W. Littleton, M. Traut, D. P. van Vuuren, N. E. Vaughan, F. R. Wood & C. Le Quéré (2021) Decarbonising the critical sectors of aviation, shipping, road freight and industry to limit warming to 1.5–2°C, Climate Policy, 21:4, 455-474, DOI:

						developments in hydrogen fuel cells	Operational improvements: 'physical Internet' system could improve efficiency across the system by 20% but would require unprecedented collaboration across supply chains	10.1080/14693062.2020.1831430
MULHOLLAND ET AL	The long haul towards decarbonising road freight – A global assessment to 2050	Through 2050	Modern truck scenario	Road freight tkm in the MTS are reduced by 13.5% relative to the RTS Reduced activity in the MTS leads to a reduction in stock - HFTs by 25% by 2050 relative to RTS	Limits global temperature rise to 1.75 °C w/ probability of achievement at 50% Reductions in WTW GHG emissions in the MTS by 2050 of 60% relative to 2015	Alternative fuels: most promising = biodiesel, HVO, biomethane 30% of HFTs use hybrid powertrains	Adopting policies targeting vehicle efficiency, including fuel economy standards, and differentiated taxes on vehicle purchase Systematic improvements in road freight operations and logistics - optimized routing, platooning, last mile efficiency, physical internet → reduction in road freight activity (tkm) of 13.5%, and a decline in vehicle activity of more than 20% in 2050	Mulholland, Eamonn & Teter, Jacob & Cazzola, Pierpaolo & McDonald, Zane & O Gallachoir, Brian. (2018). The long haul towards decarbonising road freight – A global assessment to 2050. Applied Energy. 216. 678-693. 10.1016/j.apenergy.2018.01.058.
INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION	Vision 2050	2020-2050	"Ambitious yet feasible" scenario - presents sets of assumptions	Electric heavy heavy-duty trucks will be 29% of the global stock	Assume that the real-world CO_2 emissions of new ICE heavy-duty vehicles decline at an annual rate of 2% The majority of black carbon reductions over the next 30 years will be from the HDV (70%)		Improved compliance with HDV efficiency standards, brought about by improved enforcement as needed, could boost efficiency gains for new ICE (including non-plug-in hybrid vehicles) by an additional 0.5% per year in 2020–2030 and 0.25% per year in 2030–2050	International Council on Clean Transportation. Vision 2050: A strategy to decarbonize the global transport sector by mid-century. 2020. https://theicct.org/publications/vision2050

D.4. Gap Analysis and Research Needs

D.4.1. Policy and Institutional

D.4.1.1. Aviation

Policy research needs for aviation include the role of environmental organizations in ICAO programs, deregulation in current policy initiatives, and fuel subsidies. Additional topics may include airports as a center for decarbonization efforts and aircraft manufacturers as a point of regulation.

D.4.1.2. Maritime Shipping

For maritime shipping, research needs include efforts to update outdated policy frameworks with the climate crisis in mind, green port governance, equity between developed and developing countries, and NGO certifying bodies. The issue of "flags of convenience" is a primary focal point for decarbonization policies in maritime shipping.

D.4.1.3. Long-Distance Trucking

In long distance trucking, researchers can consider the role of manufacturers in emissions regulation, national governance initiatives and ways to disseminate national programs globally, and the issues with international regulation. Additional research efforts can be placed into electric vehicle infrastructure policies and the transition away from fossil fuels.

D.4.2. Transition Incentives

The policy incentives designed to spur on the transition within the hard-to-decarbonize transport sectors can be categorized into two broad types: alternative fuel and operational/technological. These incentive structures combine regulatory, market, fiscal, and innovation policy mechanisms and can be applied in similar manners in each sector to catalyze markets. There is a more detailed discussion on specific incentive policies within the storylines discussion in section D3.

In further research, incentive packages could be designed for each sector that could be presented as models for international bodies and national governments that align with current thought leadership on policy and market development.

D.4.3. Equity: Access and Participation

In existing storylines, especially for passenger aviation, there is a focus on demand reduction (including carbon taxes, fuel levies) as a pathway to decarbonization. Demand reduction often includes increasing the cost for the passenger, which in turn creates a question of equity: how do we decarbonize forms of transportation without decreasing access for low-income populations globally? There is an opportunity, and a priority, for continued research to examine the creation of policy packages that address the dichotomy between the need for global transportation to be both accessible *and* sustainable. Existing policy storylines do not readily grapple with this question beyond the suggestion of carbon tax and fuel levy policies, failing to address the question of what populations would be most affected by these policies.

D.5. Relevant Groups at MIT

1. Institute for Data, Systems, and Society
2. Center for Energy and Environmental Policy Research
3. Environmental Solutions Initiative
4. Joint Program on the Science and Policy of Global Change

D.6. References

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