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Beyond road vehicles: Survey of zero-emission technology options across the transport sector

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INTRODUCTION

Electrification continues to make strides in the passenger vehicle market, representing more than 1% of global sales and up to 40% of sales in leading markets in 2017.[1] Enabled by falling battery prices and increasing investment from traditional and new vehicle manufacturers, this trend represents an opportunity to dramatically reduce greenhouse gas emissions in the transport sector. Policymakers continue to encourage a shift toward zero-emission vehicles through CO_2 regulations, consumer incentives, and investment in associated infrastructure.

Although road vehicles currently represent about 70% of transport greenhouse gas emissions, other forms of transport—including aviation, maritime, and off-road vehicles—are substantial emissions sources and are expected to see continued growth in the coming years. Figure 1 summarizes the emissions related to these modes for 2018 and projections for 2060.[2] In total, transport represents about 25% of global greenhouse gas emissions from fossil fuel combustion; this share is expected to increase as the power sector decarbonizes.[3] As shown, whereas road vehicles are the largest sources and have received the most attention, one-fourth of transport CO_2 emissions (2.2 gigatonnes) are attributable to maritime, aviation, and rail—a share projected to grow in the coming decades. Although light-duty vehicle emissions are expected to peak around 2020 under this scenario, maritime and aviation emissions are projected to rise through 2030 as a result of increasing demand and slower efficiency improvements. This figure does not take into account the additional impacts of

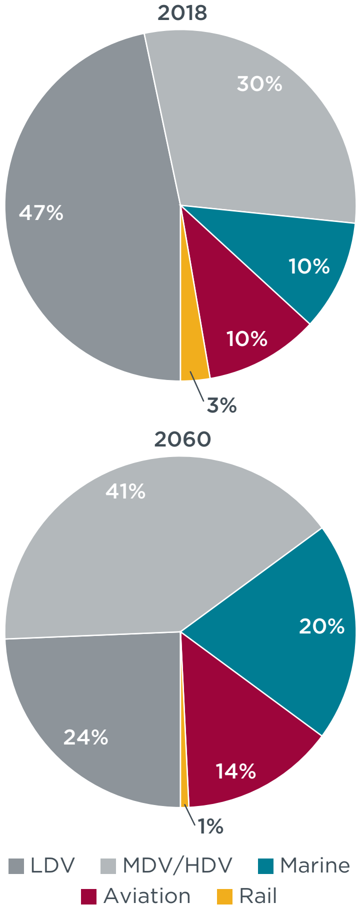

Figure 1. Share of global transport-related greenhouse gas emissions by mode in 2018, and projections for 2060.

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[1] J. Pontes, V. Irle, Global plug-in vehicle sales for 2017—final results (EV Volumes, February 2018); http://www.ev-volumes.com/news/global-plug-in-vehicle-sales-for-2017-final-results/.

[2] Using the 2-degree scenario from International Energy Agency, Energy technology perspectives 2017 (June 2017); www.iea.org/etp/. LDV, MDV, and HDV denote light-, medium-, and heavy-duty road vehicles, respectively.

[3] J. D. Miller, C. Façanha, The state of clean transport policy: A 2014 synthesis of vehicle and fuel policy developments (ICCT, December 2014); www.theicct.org/publications/state-clean-transport-policy-2014-synthesis-vehicle-and-fuel-policy-developments.

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pollutants emitted at high altitudes in the aviation sector, which have complex and potent climate impacts, nor does it include the black carbon emitted from many large ships, which has extremely severe short-term climate impacts.

Beyond these climate impacts, non-road transport sources—especially ships and off-road vehicles used for construction and agriculture—are a primary source of local air pollution and contribute to its associated health impacts. Large maritime vessels burning heavy fuel oil and off-road vehicles with older diesel engines produce substantial amounts of particulate matter, NO_x, and SO_x near coastlines and in cities. These emissions, as well as greenhouse gases and particles (e.g., black carbon) that contribute to global climate change, are expected to increase in the coming decades as shipping and air travel continue to increase.

Zero-emission technologies, including plug-in electric vehicles and hydrogen fuel cell vehicles, are advancing rapidly in cars, commercial vans, buses, and even heavier commercial trucks. Beyond these developments, could these zero-emission technologies similarly contribute to decarbonizing other transport modes? Zero-emission technologies are less mature for non-road applications, but demonstration projects and research activities are under way that could eventually enable widespread deployment of electric-drive ships, aircraft, and off-road equipment. To meet global climate and local air quality goals, governments are highly motivated to investigate options that go beyond combustion and incremental efficiency improvements. This working paper investigates recent research and ongoing projects to assess the potential of zero-emission technologies in aviation, maritime, off-road, and rail transport.

POLICY BACKGROUND

As part of their plans to limit greenhouse gas emissions, most governments are committed to reducing emissions from the transport sector. However, emissions from non-road transport modes are typically more difficult to control than on-road vehicle emissions for a variety of reasons. Accounting for the exact emission impacts is more difficult because of the cross-boundary nature of aviation, maritime, and rail, as well as the diffuse use of off-road construction and agricultural equipment. National and local emission inventories and legal authority to control many of these types of sources can be limited.

National emissions reduction targets. To meet global climate stabilization scenarios, emissions must peak in the 2020s and be reduced by at least 50 to 80% by 2050. Although emissions from international maritime transport and international aviation were excluded from the Paris climate agreement, some national and local leaders in regions with substantial domestic shipping and aviation emissions have sought ways to reduce these emissions. For example, U.S. EPA has ruled that CO_2 emissions from domestic aviation must be regulated as part of a 2016 endangerment finding; however, specific regulations have not yet been enacted. Likewise, emissions from flights within the European Economic Area are included within the European Union (EU) emissions trading scheme (ETS). Norway plans to implement a blend-in requirement for biofuels in aviation in 2019, while the EU is considering an incentive or subtarget for aviation alternative fuel within the forthcoming Renewable Energy Directive for 2020 to 2030. Off-road construction and agricultural vehicles are typically regulated at the national level to limit harmful particulate and NO_x pollution from diesel engines, but there are no fuel efficiency or greenhouse gas standards for these kinds of vehicles.

International maritime agreements. Although international maritime shipping emissions are not covered by the Paris agreement, the sector has committed to reducing its greenhouse gas emissions. The International Maritime Organization (IMO) introduced a strategy to reduce greenhouse gas emissions from international shipping in April 2018, with targets of a 40% reduction in carbon intensity [emissions per tonne–nautical mile (t-nm)] by 2030 and a 50% reduction in total greenhouse gas emissions from 2008 levels by 2050.[4] The IMO has already adopted energy efficiency standards for new ships through its Energy Efficiency Design Index (EEDI). The EEDI regulations mandate that new ships be 10%, 20%, and 30% more efficient (measured as CO_2/t-nm) than a baseline of similarly sized older ships in 2015, 2020, and 2025, respectively. The EEDI is the only mandatory energy efficiency measure for international shipping at the moment, but additional measures to reduce greenhouse gases from ships may follow as the sector implements its greenhouse gas reduction strategy. Although some studies have outlined pathways for decarbonization,[5] specific measures for deep, long-term emission cuts have yet to be set.

International aviation targets. Although international aviation emissions are similarly not included in the

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[4] D. Rutherford, B. Comer, *The International Maritime Organization's initial greenhouse gas strategy* (ICCT, April 2018); www.theicct.org/publications/IMO-initial-GHG-strategy.

[5] See, for example, O. Merk, L. Kirstein, R. Halim, *Decarbonising maritime transport: Pathways to zero-carbon shipping by 2035* (International Transport Forum, March 2018), www.itf-oecd.org/decarbonising-maritime-transport; Lloyd's Register & UMAS, *Zero emission vessels 2030* (Lloyd's Register, 2017), info.lr.org/zev2030.

Paris agreement, several emission reduction actions are under way. The EU includes aviation emissions in its ETS, but only intra-EU flights are included. The International Civil Aviation Organization (ICAO) has developed plans to reduce aviation emissions with a goal to achieve carbon-neutral growth beyond 2020 and cut sector-wide emissions by 50% in 2050 relative to 2005. The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) sets a market-based mechanism under which airlines will need to purchase out-of-sector carbon offsets for some international flights starting in 2021.[6] ICAO has also adopted a global aircraft CO_2 emission standard requiring minimum levels of fuel efficiency improvement for new aircraft beginning in 2023,[7] which further indicates the importance of deploying more advanced technologies.

REVIEW OF ZERO-EMISSION TECHNOLOGIES

There are many options to reduce the environmental and health impacts of transport, including increased efficiency, aftertreatment technologies, alternative fuels, and electrification. This assessment is based on identifying technologies that have the potential to deliver zero tailpipe emissions. We cover three broad technology types: battery electric, plug-in hybrid, and hydrogen fuel cell.

Battery electric. The most widespread form of zero-emission road vehicle technology, battery electric, is becoming increasingly common as a result of its relative efficiency, low per-mile costs, low maintenance costs, lack of emissions at the vehicle, and the widespread production and distribution of electricity. Although the total emissions reductions depend on the source of the electricity, typical grid mixes offer a >50% reduction in emissions per mile in passenger vehicles, and use of renewable electricity leads to essentially zero greenhouse gas or pollutant emissions over the entire use phase. Lithium-ion batteries of various chemistries have become the dominant battery type for transport applications. Battery costs have declined to approximately $140/kWh at the cell level for passenger vehicles, but those costs are widely projected to drop to around $100/kWh in the 2020–2025 time frame. The primary disadvantages of batteries lie in their range limitations and comparatively low energy densities, which can become a more important issue for applications with larger mass and long range.

Plug-in hybrid. Plug-in hybrid vehicles combine a battery pack capable of being recharged externally with an onboard engine and fuel to extend range. Vehicles equipped with such a powertrain partially run on electricity to reduce emissions but are not constrained by the electric-only range. In plug-in hybrid technologies, the greenhouse gas emissions depend on such factors as battery size, hybrid powertrain configuration, electric charging frequency, operation patterns, and the carbon intensity of the electricity. Although upfront costs rise with increased battery capacity, so do fuel savings and emission benefits. Because they include both electric and conventional powertrains, plug-in hybrids can have more space and weight limitations, and higher maintenance needs, than battery-electric vehicles.

Hydrogen. Hydrogen electrochemically converted to electricity in a fuel cell has no pollutant emissions at the vehicle. Hydrogen can be produced in a variety of ways and stored or transported as either a liquid or a gas. Technologies that use hydrogen for vehicle propulsion continue to fall in cost as more fuel cell–powered vehicles are deployed. Fuel cells and their associated electronic systems take up somewhat more space than comparable combustion engines but are typically much more efficient. Because hydrogen is less dense, liquefaction or compression are typically used in its transport, handling, and storage. As with battery-powered transport applications, the extent to which hydrogen's upstream energy sources are renewable is key to its emission reduction benefits.

AVIATION

Aircraft are one of the most energy-intensive forms of transport and are the only feasible mode of transport for almost all long-haul trips. Aviation today represents approximately 2% of global CO_2 emissions, along with additional climate forcing due to aviation emissions occurring at high altitudes.[8] Aviation activity is projected to continue to grow in the coming decades by as much as 4.3% annually.[9] To help mitigate the corresponding increase in international aviation emissions, ICAO has established a goal for carbon-neutral growth after 2020. As mentioned above, this goal is expected to be

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[6] N. Olmer, D. Rutherford, *International Civil Aviation Organization's Carbon Offset and Reduction Scheme for International Aviation* (CORSIA) (ICCT, February 2017); https://www.theicct.org/publications/ICAO-carbon-offset-and-reduction-scheme-international-aviation

[7] D. Rutherford, A. Kharina, *International Civil Aviation Organization CO_2 standard for new aircraft* (ICCT, February 2016); www.theicct.org/publications/international-civil-aviation-organization-co2-standard-new-aircraft.

[8] J. Faber, D. Nelissen, *Towards addressing aviation's non-CO_2 climate impacts* (CE Delft, May 2017); www.cedelft.eu/publicatie/towards_addressing_aviations_non-co2_climate_impacts/1961.

[9] S. El Takriti, N. Pavlenko, S. Searle, *Mitigating international aviation emissions: Risks and opportunities for alternative jet fuels* (ICCT, March 2017); www.theicct.org/publications/mitigating-international-aviation-emissions-risks-and-opportunities-alternative-jet.

met primarily through out-of-sector carbon offsets rather than improved efficiency or alternative fuels.[10]

Aircraft manufacturers have steadily increased the proportion of electrified onboard systems over the past several decades. A prominent recent example is the Boeing 787's electrified de-icing and pressurization systems, which are powered by >1 MW of onboard electrical generation to increase aircraft efficiency.[11] Despite these advances, the energy demands for aircraft propulsion on passenger jets far outstrip such present-day deployments of electrified systems. As a result, the initial deployment of zero-emission aviation technologies is expected in smaller airplanes traveling shorter routes. Norway's state-operated airport network, Avinor, hopes to use electric aircraft for all flights shorter than 1.5 hours by 2040. Similarly, the Swedish Air Transport Society (Svengst Flyg), an association of Swedish air carriers, has announced a plan to make flights originating in Sweden fossil fuel–free by 2045 through a mix of alternative fuels and electrification. Although this study is focused on larger-scale options, there are also developments in intra-urban air transport at the local level. For example, Dubai's Road and Transport Authority established a target for autonomous transport to provide one-fourth of the city's total trips by 2030, with some of those trips expected to be serviced by electric aerial taxis.[12] Similarly, Airbus's A^3 is developing an autonomous electric air taxi slated to begin demonstration in California by 2020.

Relative to other transport modes, aviation faces particularly challenging technological barriers to electrification, as the performance of airplanes is extremely sensitive to their mass. This increases the difficulty of incorporating zero-emission technologies already used in other types of transport applications, such as batteries or hydrogen fuel cells. The highest-density batteries available commercially today, at around 250 watt-hours per kilogram (Wh/kg), provide only one-fiftieth of the energy density of typical jet fuel. This disparity implies that at current energy densities, a battery would result in a mix of reduced range and greater aircraft mass. This limitation also has an impact on in-use aircraft efficiency because a battery's mass remains constant, whereas liquid fuel is combusted throughout a flight, lightening the aircraft. For these reasons, 500 Wh/kg has been suggested as the minimum viable battery density for fully electric aviation at a commercial scale.[13]

Although transitioning to fuel cells or batteries with lower energy density has some drawbacks, electric motors also present opportunities to improve efficiency. A conventional jet turbine has a thermal efficiency of approximately 40 to 50%, whereas electric motors can have efficiencies of up to 95%. Traditional jet fuel–powered turbines (turbofans in large commercial jets; turboprops in smaller regional airplanes) colocate the fans that generate propulsive force with the fuel combustion. In contrast, either batteries or fuel cells can power multiple engines from a single generator simply through connected electrical cables. This may create new opportunities for aircraft design, wherein motors can be distributed throughout the airframe to improve efficiency and performance.

Table 1 lists a number of innovative zero-emission aviation demonstrations that have achieved flight. As shown, smaller one- to four-seater zero-emission aircraft are under development for demonstration and testing purposes. These include battery-electric aircraft, such as the Extra 300LE designed by Siemens, and hydrogen fuel cell aircraft, such as the HY4 and Boeing's Fuel Cell Demonstrator. These aircraft have substantially lower speeds and ranges than conventional small aircraft. Pipistrel, a Slovenian manufacturer, is an early innovator in battery-electric airplanes, with two small training planes already on the market. These planes are ultralight trainers with a short range (flight time under 1 hour) and battery packs with a capacity of 7.3 kWh and 17 kWh for the Taurus Electro and Alpha Electro, respectively. Pipistrel's experience designing the Taurus Electro and Alpha Electro informs the company's current development of a larger, four-seat variant with a 200-kW engine and longer range. Although their ranges are limited by their battery capacity, both planes are capable of gliding at low power consumption levels, and the Alpha Electro is outfitted with a propeller able to "windmill" when gliding to recover some energy. Equator, a Norwegian company, is developing the P2 Xcursion, a two-seater capable of either sea- or land-based takeoff and landing, powered by an 18-kWh

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[10] N. Pavlenko, *Alternative jet fuel development and deployment in North America* (ICCT, May 2017); www.theicct.org/publications/alternative-jet-fuel-development-and-deployment-north-america.

[11] Roland Berger, *Aircraft electrical propulsion: The next chapter of aviation?* (September 2017); www.rolandberger.com/publications/publication_pdf/roland_berger_aircraft_electrical_propulsion.pdf.

[12] Dubai Future Foundation, *Mohammed bin Rashid approves Dubai Autonomous Transportation Strategy* (Government of Dubai: April, 2016); http://www.dubaifuture.gov.ae/mohammed-bin-rashid-approves-dubai-autonomous-transportation-strategy/

[13] See J. Wu, B. DeMattia, P. Loyselle, C. Reid, L. Kohout, *Silicon-based lithium-ion capacitor for high energy and high power application* (paper presented at 13th Annual Lithium Battery Materials and Chemistries, Arlington, VA, October 2017); Roland Berger (2017).

Table 1. Summary of zero-emission aviation projects.

Technology	Vehicle or project	Passenger capacity	Region	Status
Battery-electric propeller plane	Pipistrel Taurus Electro G2	2	Slovenia	Available on the market
Battery-electric propeller plane	Pipistrel Alpha Electro	2	Slovenia	Available on the market
Battery-electric propeller plane	Airbus E-Fan	1	United Kingdom	Demonstration
Battery-electric propeller plane	Siemens Extra 300LE	1 (towing glider)	Germany	Demonstration
Battery-electric propeller plane	Aero Electric Sun Flyer	2	United States	Demonstration
Battery-electric propeller plane	Wright Electric	2	United States	Prototype
Battery-electric propeller plane	Equator P2 Xcursion	2	Norway	Prototype
Solar-powered battery-electric plane	Solar Impulse	1	Switzerland	Demonstration
Battery-electric rotary-wing aircraft	AutoGyro e-Cavalon	2	Germany	Demonstration
Battery-electric rotary-wing aircraft	Volocopter Autonomous Air Taxi	2	United Arab Emirates	Demonstration
Battery-electric aircraft	Lilium	2	Germany	Prototype
Hydrogen fuel cell propeller plane	Boeing Fuel Cell Demonstrator	1	United States	Demonstration
Hydrogen fuel cell propeller plane	HY4	4	Germany	Demonstration

battery.[14] Equator is also evaluating the potential for larger hybrid and fully electric airplanes based on the two-seater platform.

Substantial developments in zero-emission aviation are under way in Germany, including small startups (Lilium and HY4) and investment by larger companies such as Siemens and Bosch. The U.S. National Aeronautics and Space Administration (NASA) also develops aviation electrification technologies through its Leading Edge Asynchronous Propeller Technology (LEAPTech) project. This project evaluates the benefits of distributed propulsion; future tests will use the X-57 experimental plane platform, dubbed "Maxwell," which uses 14 electric motors to improve cruising-altitude efficiency.

A variety of companies are developing zero-emission aviation technologies, ranging from large commercial passenger jet makers to smaller startups. Because of the inherent barriers to zero-emission commercial aircraft, many prototypes for zero-emission aircraft target niche segments with short routes and slow speeds. These include general aviation, air taxis, and commuter aircraft using traditional airplane configurations, as well as more novel architectures such as vertical takeoff and landing (VTOL), gyrocopters, and airships. Such projects include battery electric (Sun Flyer flight trainer, Uber Elevate VTOL), plug-in hybrid (Zunum Aero 12-seat commuter plane), and hydrogen (HY4 air taxi). Although a number of startups have announced plans for zero-emission aircraft, detailed plans for production or business cases have generally not been announced.

Beyond small, single-seat prototypes and demonstrations, several larger projects are in development. Table 2 summarizes three electrification projects for larger aircraft in the commercial passenger aircraft sector. Siemens, in conjunction with Airbus and Rolls-Royce, is developing a joint project that draws upon each partner's expertise in electronics, airframe design, and engine construction. Their project, called E-Fan X, adapts a BAe-146 (a four-engine, 100-seat passenger jet) to include a battery-charged 2.5-MW generator and a 2-MWh battery; the electric system will fully power a single engine, supplemented by three conventional gas turbines. Although the E-Fan X is not itself a commercial product, the collaboration is intended to evaluate the feasibility of hybridizing commercial jets. EasyJet, a European regional carrier, recently announced a partnership with Wright Electric to develop a fully electric commercial airplane to take over its shorter, regional routes by 2030. Wright Electric anticipates the improvement of batteries to 500 Wh/kg, which would facilitate the development of a 186-seat commercial plane with a range of more than 500 km.[15] Zunum Aero, a startup with backing from JetBlue Technology Ventures and Boeing, is also interested in capitalizing on underused regional airports to roll out a series of plug-in hybrid electric planes able to carry 6 to 12 passengers. Zunum Aero intends to have its technology commercialized sometime before 2025, although the company

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[14] J. O. Reimers, *Introduction of electric aviation in Norway* (Avinor, April 2018); https://avinor.no/contentassets/c29b7a7ec1164e5d8f7500f8fef810cc/introduction-of-electric-aircraft-in-norway.pdf.

[15] Reimers (2018).

has not yet completed a public demonstration of its aircraft. Nonetheless, Zunum Aero also has plans to expand its offerings to include a larger aircraft with a 1,000-mile range by 2030.

To provide an example of the tradeoffs of going full-electric, Bjorn Fehrm of Leeham Co. analyzed short-haul commuter planes (with a range of 100 to 450 nautical miles) and found that, relative to an otherwise comparable conventional plane, a fully electric version weighs 50% more and has half the range.[16] As a result, there is much interest in partially electrifying larger planes with hybrid electric technology, without major battery storage for power takeoff and general propulsion. Hybrid electric architectures can greatly improve efficiency, but takeoff and climbing require several times the peak power demand of cruising at altitude (presenting an issue for shorter flights) and substantial propulsion energy consumption is required during cruising (a greater issue on longer flights).[17] To minimize the necessary battery weight and deliver the necessary power, proposed hybrid designs use a gas turbine supplemented by batteries in a variety of parallel and series configurations, as well as auxiliary power units (APUs). For a plug-in series hybrid, a fossil fuel–powered APU and batteries would work in conjunction to deliver the power needed for takeoff and climbing, whereas while cruising, the electric motor could recharge the batteries and provide the propulsive force to reduce fuel consumption.

Incorporating zero-emission technologies into aircraft may also necessitate changes to airport infrastructure. Alternative fuels such as hydrogen for fuel cells would require installing entirely new fueling infrastructure. Hydrogen's low density necessitates either high-compression storage or cooling systems, and its low boiling point also requires that storage systems be built to minimize boil-off. Electrification of airports, for either fully electric planes or plug-in hybrids, would require new charging infrastructure and substantial new energy demand at airports. A literature review of present-day airport electricity demand suggests that airport electricity consumption can substantially vary according to geographic location and airport size; a range of 4 to 18 kWh per passenger was estimated for large international European airports in 2009.[18] Zunum Aero estimates that introducing electrification at smaller, regional airports would raise those airports' per-passenger electricity demand to between 25 and 50 kWh. A fully electric plane with a heavy battery may also necessitate use of a longer runway or substantial airframe modifications.

Table 2. Summary of passenger aviation electrification projects in development.

Technology	Company	Passenger capacity	Region	Estimated battery size	Target date
Electric turbofan added to conventional jet	Siemens (with Rolls-Royce and Airbus)	100	Europe	2 MWh	2020
Plug-in hybrid electric	Zunum Aero	6 to 12	United States	260 kWh	Early 2020s
Electric	EasyJet (with Wright Electric)	186	United Kingdom	N/A	2030

Acknowledging the high uncertainty, we provide a simplified analysis of the greenhouse gas impacts of emerging electric and hydrogen aircraft technologies for small and relatively short-haul applications. We used Piano 5 aircraft performance and design software to compare a theoretical fully electric plane to a conventional turboprop commuter, a Beechcraft King Air 200.[19] This analysis is based on technical specifications and assumptions from the projects and analysis described above, especially from Pipistrel and Leeham Co.[20] The Piano 5 model estimates that a hypothetical 10-seat battery-electric commuter plane consumes about 2,100 kWh for a 300-km trip.[21] Although longer trips may be relatively less energy-intensive on a per-passenger-kilometer basis, they are less likely to be displaced by these zero-emission technologies because of weight limitations for takeoff. For electric grid carbon intensity, we consider three cases: the average grid in Norway (nearly 100% renewable), the overall average grid in Europe, and the average grid in Germany (a higher fraction of electricity from coal). For hydrogen, we include electrolysis from the same three average electricity grids, as well as a case with steam-methane reforming (SMR) to derive hydrogen from natural gas. The Piano 5 modeling for the hydrogen drivetrain assumes aircraft mass and efficiency parame-

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[16] B. Fehrm, *Bjorn's corner: Electric aircraft, part 10* (Leeham News and Comment, September 2017); https://leehamnews.com/2017/09/01/bjorns-corner-electric-aircraft-part-10/.

[17] National Academies of Sciences, Engineering and Medicine, *Commercial aircraft propulsion and energy systems research: Reducing global carbon emissions* (National Academies Press, 2016); https://doi.org/10.17226/23490.

[18] S. O. Alba, M. Manana, Energy research in airports: A review. *Energies, 9*, 349 (2016); https://doi.org/10.3390/en9050349.

[19] For more information, see www.lissys.demon.co.uk/Piano5.html.

[20] We assume a two-motor aircraft with combined 1,000 kW power capacity and 1 MWh of on-plane battery storage. See Pipistrel (2017), www.pipistrel.si/plane/alpha-electro/technical-data; Fehrm (2017).

[21] We assume electricity use of 430 kWh for the trip (205 kWh for takeoff and climbing, 205 kWh for cruise, and 20 kWh for descent and landing). We assume similar performance characteristics for the hydrogen plane with a turbo-electric powertrain powered by a PEM fuel cell. Given the energy densities of hydrogen and electricity, we assume 13 kg of hydrogen for a comparable hydrogen-powered plane.

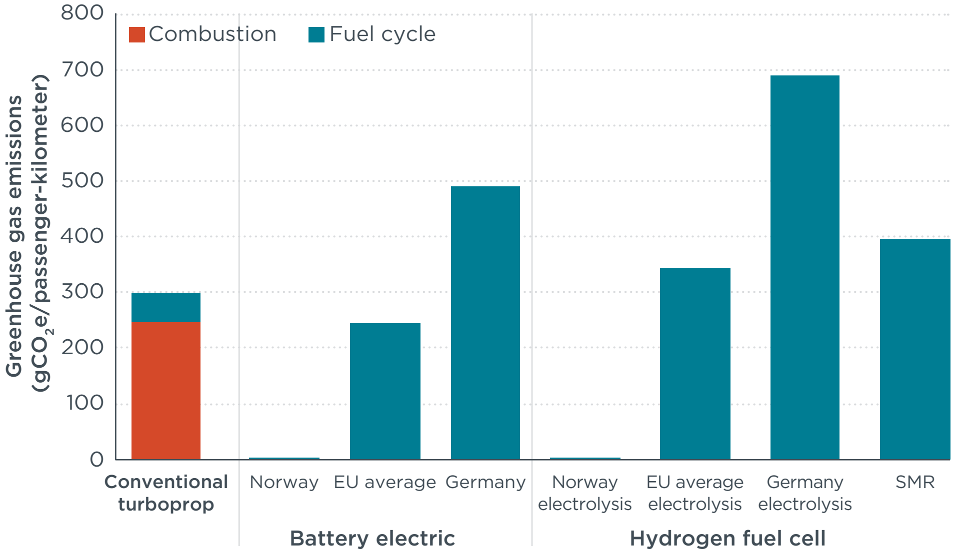

Figure 2. Greenhouse gas emissions by technology for an example small short-haul commuter plane.

ters similar to those of the fully electric plane because of the high level of uncertainty over the weight associated with onboard hydrogen storage and containment.

Figure 2 presents our illustrative analysis of the emissions intensities of various aviation propulsion systems, shown as emissions [CO$_2$ equivalent (CO$_2$e)] per unit of passenger travel. The conventional commuter plane, assumed to be a turboprop with 10 passengers traveling 300 km, emits about 300 grams of CO$_2$ per passenger-kilometer across the entire fuel cycle (extracting, refining, and transporting the fuel to the vehicle). The battery-electric emissions are estimated to be 64% higher in Germany, 18% lower on average in Europe, and essentially 100% lower in Norway. The fuel cell emissions for hydrogen derived from electrolysis are estimated to be 130% higher in Germany, 15% higher in the average European case, and again essentially 100% lower in Norway. For the case of hydrogen from SMR, we find that hydrogen has 33% higher emissions than a conventional kerosene-powered plane. This analysis does not account for the complex effects of high-altitude emissions, which are thought to have more potent climate impacts. The upstream emissions of zero emission aircraft would generally not be subject to this effect.

Across the technologies assessed here, only those in a high-renewable grid offer steep emission reductions; this finding reinforces the idea that renewable energy deployment in the power sector can outweigh the efficiency benefits of electrification. The outputs from Piano 5 indicate that the bulk of energy consumption for the theoretical battery-electric and hydrogen planes on this route occurs during takeoff and climbing. This suggests that as battery technology advances and the mass of electric planes decreases, their energy consumption will decrease and their relative efficiency versus conventional planes will improve.

We further sought to analyze the costs associated with the above zero-emission technology options. Because electric- and hydrogen-powered plane types are only just emerging, we cannot yet rigorously estimate costs for these technologies. However, a more limited analysis of the approximate fueling costs (i.e., excluding capital and infrastructure costs) is possible if we use the same assumptions as in Figure 2 together with average jet fuel and electricity prices.[22] We find that the conventional small commuter plane's kerosene fuel costs are about $0.05 (USD 2016) per passenger-kilometer, based on a value of $1.87 per gallon of fuel. Industrial electricity rates imply that the electric options would cost from 19% more (for $0.08/kWh, the median for the EU) to 48% less (for $0.03/kWh in Norway) than the conventional commuter plane. For the hydrogen fuel cell option, we find that the hydrogen would have to cost $2.50 or less per kilogram to match the cost of the conventional kerosene baseline.

The illustrative analysis above highlights the major challenges of batteries and hydrogen for use in aviation and their prospects in limited short-haul applications. The research on zero-emission electric and fuel cell technologies points to the importance of developing liquid fuel alternatives in aviation. We note that advanced biofuels have some promise, but they also bring added difficulties due to limited high-volume supply of sustainable biomass for many competing global uses. Power-to-liquid (PtL) fuels offer some promise as well but are difficult to quantify within this assessment's greenhouse gas and cost analyses. PtL fuel production in this context comprises a combination of separate processes to ultimately generate a synthetic hydrocarbon with physical characteristics similar to those

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22 Jet fuel was assumed to be $1.87 per gallon, based on International Air Transport Association Jet Fuel Price Monitor: www.iata.org/publications/economics/fuel-monitor/Pages/index.aspx. Assumed electricity prices were based on industrial rates of $0.08 per kWh for Europe and $0.03 for Norway (including taxes) from Department for Business, Energy & Industrial Strategy, *International industrial energy prices* (Gov.uk, December 2017); www.gov.uk/government/statistical-data-sets/international-industrial-energy-prices.

of jet fuel. First, hydrogen is separated either by SMR or by electrolysis of water. The hydrogen is then combined with captured carbon—either taken from a concentrated source (such as a smokestack) or directly captured from the atmosphere—using a process called a Fischer-Tropsch reaction. In this reaction, the gaseous hydrogen and carbon can be combined into a hydrocarbon of the desired length in the presence of a catalyst.

This sort of PtL process will essentially always incur higher costs and consume far more renewable energy than the fuel cycle of battery electric or hydrogen aircraft because of the similar but far more extensive energy conversion processes and lower onboard efficiency. Policy support of approximately €1 per liter may be necessary to achieve substantial production volumes of PtL fuels.[23] The primary benefits of using PtL fuels are that they sidestep the range and size limitations of batteries and hydrogen, and they may be blended with or used in place of jet fuel with minimal changes to the existing infrastructure and engines. For these reasons, PtL may be a promising mid-term step towards reducing aviation emissions while progress is made towards overcoming the substantial challenges associated with fully zero-emission aircraft.[24]

MARITIME

International maritime shipping accounts for more than 80% of the world's trade by volume and more than 70% by value. Ships are a relatively energy- and cost-efficient form of freight transport; international, domestic, and fishing vessels represent about 2.6% of global anthropogenic CO_2 emissions.[25] However, ships contribute substantially to pollution near ports and in regions with sensitive ecologies. Furthermore, greenhouse gas emissions are expected to increase 50% to 250% above 2012 levels by 2050 as trade increases. For these reasons, governments are increasingly exploring zero-emission maritime technologies, some of which are already beginning to see limited commercial use.

Several countries are working to reduce pollution and greenhouse gas emissions from the maritime sector through various initiatives. In Canada, which is affected by Arctic black carbon emissions, a proposed clean fuel standard is expected to cover the maritime sector, which would require the introduction of alternative fuels. Norway's government has formed a Green Coastal Shipping Programme with numerous industry partners. The Programme's goals include a 40% reduction in domestic shipping emissions by 2030 and 80% reduction by 2050, as well as funding for pilot projects to develop technologies.

Initial applications of zero-emission technologies in the maritime sector have targeted smaller-sized applications with short, fixed routes. Passenger ferries, which frequently operate in highly populated areas, have seen the most progress toward electrification. A number of battery-electric and plug-in hybrid ferries are already operating in Norway, Sweden, and Scotland. In Norway, more than 60 ferries with onboard battery packs will be in operation by the end of 2021, most of which will be fully electrically powered. Additional developments in this sector are getting under way. For example, in the city of Amsterdam, all canal boats will be required to be zero-emission by 2025 and several electric boats are in service. The U.S. state of Washington is also considering electric ferries for a number of routes. Electric ferries typically use lithium-ion batteries. Rapid charging and associated infrastructure upgrades are typically needed to meet the strict duty cycles of ferries.

Several small hydrogen-powered ships have been deployed on a trial basis. For example, a river touring boat called the FCS *Alsterwasser* operated from 2009 to 2013 in Hamburg, Germany, but was shut down because the refueling infrastructure could not be sustained. A hydrogen fuel cell–powered canal boat, the *Nemo H2*, was launched in Amsterdam in 2009. At least one small passenger ferry powered by hydrogen is in operation in the city of Antwerp, Belgium, although it uses a combustion turbine rather than a fuel cell. In 2017, the National Public Roads Administration of Norway launched a project to develop a hybrid hydrogen electric car ferry, where a minimum of 50% of the energy is delivered by hydrogen fuel cells. The ferry is planned to start operating in 2021. The project follows the same procurement method as with the fully electric ferry *Ampere*, which started operation in 2015.

In addition to ferries, there have also been initial steps toward zero-emission coastal and inland shipping. A fully battery-powered electric bulk cargo ship was launched in Guangzhou, China, in late 2017, initially to haul coal through the Pearl River Delta region. The ship

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[23] A. Christensen, C. Petrenko, *CO_2-based synthetic fuel: Assessment of potential European capacity and environmental performance* (ICCT, November 2017); www.theicct.org/publications/co2-based-synthetic-fuel-assessment-EU.

[24] P. Schmidtt, W. Weindorf, *Power-to-Liquids: Potentials and Perspectives for the Future Supply of Renewable Aviation Fue*l (German Environment Agency, September 2016); https://www.umweltbundesamt.de/en/publikationen/power-to-liquids-potentials-perspectives-for-the

[25] N. Olmer, B. Comer, B. Roy, X. Mao, D. Rutherford, *Greenhouse gas emissions from global shipping, 2013–2015* (ICCT, October 2017); www.theicct.org/publications/GHG-emissions-global-shipping-2013-2015.

Table 3. Summary of zero-emission maritime projects.

Technology	Vessel or project	Capacity	Route length (km)	Region	Entry into service	Status
Hydrogen fuel cell ferry	FCS *Alsterwasser*	100 passengers	—	Hamburg, Germany	2009	Decommissioned in 2013
Hydrogen fuel cell tour boat	*Nemo H2*	87 passengers	Up to 150	Amsterdam, Netherlands	2009	Unknown
Plug-in hybrid ferry	Caledonian Maritime Assets	150 passengers, 25 vehicles	~6	Scotland	2011	Operational
Electric ferry (supercapacitor)	*Ar Vag Tredan*	113 passengers	4.5	Lorient, France	2013	Operational
Electric cable ferry	Quyon Ferry	90 passengers, 21 vehicles	0.8	Ottawa, Canada	2013	Operational
Plug-in hybrid fishing boat	*Karoline*	—	—	Norway	2015	Operational
Battery-electric ferry	*Ampere*	360 passengers, 120 vehicles	5.6	Norway	2015	Operational
Plug-in hybrid tourist ship	*Vision of the Fjords*	400 passengers	36	Norway	2016	Operational
Battery-electric ferry	*Elektra*	90 vehicles	1.6	Finland	2016	Operational
Battery-electric ferry	MF *Gloppefjord* and MF *Eidsfjord*	110 vehicles	2	Norway	2017	Operational
Battery-electric ferry	HH Ferries Group	1,250 passengers, 500 vehicles, 9 train cars	4	Sweden	2017	Operational
Battery-electric service boat for aquaculture	*Elfrida*	—	—	Norway	2017	Operational
Battery-electric ferry (solar)	*Aditya*	75 passengers	2.5	Kerala, India	2017	Operational
Battery-electric cargo ship	Guangzhou Shipyard	2,000 tonnes	80	Guangzhou, China	2017	Operational
Hydrogen ferry (combustion)	*Hydroville*	16 passengers	~6.5	Antwerp, Belgium	2017	Operational
Battery-electric tourist ship	*Future of the Fjords*	400 passengers	36	Norway	2018	In development
Plug-in passenger ship	Hurtigruten	530 passengers	—	Norway	2018	In development
Plug-in offshore construction vessel	*North Sea Giant*	120 passengers, 400-ton crane	—	Norway	2018	Operational
Plug-in hybrid ferry	Color Line	Up to 2,000 passengers and 500 vehicles	67	Norway and Sweden	2019	In development
Battery-electric cargo ship	*Yara Birkeland*	2,880 tons	56	Norway	2019	Under construction
Plug-in sailing ship	*Statsraad Lehmkuhl*	190 passengers		Norway	2019	In retrofit
Hybrid hydrogen electric ferry	Fiskerstrand PILOT-E	80 vehicles	~4	Norway	2020	In development
Hydrogen fuel cell cruise ship	Viking Cruises	1,400 passengers and crew	—	Norway	N/A	In development

has a capacity of 2,000 tonnes and is powered by a 2.4-MWh lithium-ion battery pack. In Norway, a battery-electric container ship, the *Yara Birkeland*, with 7 to 9 MWh of battery capacity is under construction with entry into operation planned for 2019. The vessel will haul fertilizer along the Norwegian coast and will eventually also be capable of fully autonomous operation. Additionally, five battery-electric barges will launch in 2018 in the Netherlands and Belgium, with a planned capacity of 24 twenty-foot equivalent units (TEUs) capable of 15 hours of operation between recharging. Fuel cells have also been studied for auxiliary power on large cargo and passenger ships, but demonstration projects have so far used methanol, natural gas, or diesel as a fuel, rather than hydrogen.[26]

These zero-emission maritime projects and others are summarized in Table 3. As indicated, most zero-emission ships are operating in northern Europe, although examples exist in many countries. Norway in particular is a leader in this field; additional plug-in vessels not featured in the table are being constructed or are in operation there, such as fishing vessels and pleasure craft. Through 2017, the largest zero-emission ships in the world are the M/F *Tycho Brahe* and M/F *Aurora* of HH Ferries in Sweden, weighing approximately

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[26] e4ships, *Fuel cells in marine applications 2009–2016* (December 2016); www.e4ships.de/press.html?file=tl_files/e4ships/downloads/e4ships_Brochure_engl_final_.pdf.

12,000 gross tonnes and with a capacity of 1,250 passengers, 500 vehicles, and nine train coaches. These recent developments in several applications reflect both the maturing technologies and the growing importance of addressing maritime transport in climate and air quality plans. As shown, most of the demonstration projects are primarily focused on ferries and shorter passenger vessels.

As governments look to increase penetration of zero-emission maritime vessels, a number of technology options are under consideration for different applications. Among the most promising options are battery-electric, plug-in hybrid, and fuel cell technologies. Below, we summarize the research on these technologies, their potential emissions reductions, and the major barriers to commercialization.

The low energy density of batteries is a primary limitation for the development of battery-electric ships. Although fuel can constitute a substantial proportion of the mass of conventional cargo ships, batteries could pose a greater challenge, especially for ships traveling thousands of miles. The issues with volume are similar. For example, the batteries required to power a relatively small 800-TEU container ship over a short journey of 250 nautical miles would require a volume of about 30 TEUs and could displace up to 10% of such a ship's deadweight capacity by mass (assuming 2017 battery technology).[27]

Charging infrastructure could also pose an issue for the proliferation of zero-emission maritime vessels. Ports generally have high-power electrical connections for their daily operations, and some even employ shore power for ships at berth, including ports in Montreal, Québec; Rotterdam, Netherlands; Long Beach, California; and part of Shenzhen, China. However, the very high power needs for charging such large batteries would require new infrastructure and, potentially, local grid upgrades. To fully charge the aforementioned example 800-TEU container ship's batteries in 8 hours, a connection of about 10 MW would be required; by comparison, the average power demand from the entire Port of Los Angeles in 2012 was 27 MW.[28] Novel solutions may be required to reduce expensive infrastructure and avoid demand charges from utilities. For example, in order to reduce stress on the local power grid, electrification of the *Ampere* ferry in Norway required large battery banks at both terminals to allow for lower, more constant grid power draw; the *Future of the Fjords* will use the same strategy when it comes online in 2019. Another potential solution could lie in battery swapping at ports, allowing batteries to be charged more slowly at port and then loaded into ships as cargo is loaded and unloaded.

Rather than being powered solely by batteries, ships can also use batteries in combination with onboard generators in a plug-in hybrid configuration. Electric motors for even the largest of ships, such as the electric azimuth thrusters built by manufacturers such as Siemens and ABB, are technologically mature. In particular, most cruise ships use fuel to power an onboard generator, which powers electric motors and the additional electric loads. This system could be adapted (with the addition of batteries) for other ships. Such a configuration has been used in several ferries in Scotland and is planned for additional large ferries operated by Color Line in Norway and Sweden. For these projects, it is expected that batteries will enable zero-emission use for most daily operations. During specific conditions or abnormal operations, the onboard generators will enable long-distance operation and therefore reduce restrictions on duty cycles. In addition to ferries, this is an attractive proposition for large ships that cause high amounts of pollution at or near ports. Using battery power near ports, even if it only accounts for a small fraction of the total journey, could substantially reduce air pollution in urban areas.

Hydrogen has also attracted attention for use in many ship types. Among the more promising types of fuel cells for maritime applications are proton exchange membrane (PEM) fuel cells and solid-oxide fuel cells (SOFCs).[29] SOFCs have higher efficiency (up to 85% including heat recovery, versus ~55% for PEM fuel cells), but they operate at very high temperatures (600° to 700°C) and are heavier. Hydrogen fuel cells are generally larger than comparable marine fuel oil generators, but the sizes are not prohibitive for a large ship. For example, fuel cell manufacturer Powercell makes a 3-MW (4,000 hp) PEM system (with associated electronics) enclosed in a 40-foot shipping container. Hydrogen combustion engines of both piston and turbine design are also an option for marine propulsion. Although they are generally less efficient and produce some NO_x, these engines are more similar to today's marine engine designs than fuel cells and can also be

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[27] We assume a pack-level battery density of 0.13 kWh/kg and 89 kWh/m^3, based on 2018 stationary battery storage. In contrast to the 30 TEUs (1,155 m^3 and 901 tonnes) required by batteries, fuel oil for a similar journey would require only 17 m^3 and weigh 15 tonnes.

[28] Burns & McDonnell Engineering Company Inc., *Energy management action plan* (Port of Los Angeles, July 2014); www.portoflosangeles.org/DOC/DRAFT%20POLA%20E-MAP_July%202014.pdf.

[29] T. Tronstad, H. H. Åstrand, G. P. Haugom, L. Langfeldt, *Study on the use of fuel cells in shipping* (DNV GL–Maritime, January 2017); www.emsa.europa.eu/emsa-documents/download/4545/2921/23.html.

used with other fuels to provide flexibility. The *Hydroville*, a small passenger ferry in Antwerp, Belgium powered by a combustion engine, uses hydrogen as its primary power source but can also operate with diesel as a backup. Because of its low energy density, hydrogen storage (either liquid or compressed gas) would require substantially more volume than fuel oil or liquefied natural gas (LNG) for a journey of the same length, but would also weigh less.

Hydrogen is currently much more expensive than marine bunker fuels on a per-unit energy basis, regardless of its method of production. At current retail prices in California for compressed gaseous hydrogen derived from a mix of sources, hydrogen typically costs around $14/kg; this equates to a per-unit energy cost more than seven times that of distillate fuels, which are themselves 50 to 100% more expensive than heavy fuel oil. At $4/kg, hydrogen would still cost nearly double the per-unit energy cost of bunker fuel; this could be bridged by several factors, including economies of scale at ports, increases in fossil fuel prices, and greater fuel cell efficiency. A further discussion of costs is presented below. Additionally, storing hydrogen requires infrastructure investments to maintain high pressure and cold temperatures to minimize boil-off, and would likely require more space at ports.

Despite these barriers, the flexibility of hydrogen could align well with several maritime applications, especially for longer voyages, over the long term. A study from Sandia National Laboratory finds that hydrogen fuel cells could satisfy the demands for nearly all maritime vessels and would be a better fit than batteries for many applications.[30] Nonetheless, the high costs and technical hurdles associated with hydrogen indicate that a transition may take decades unless policy actions are taken that make hydrogen relatively more attractive than other marine fuels. A study by Lloyd's Register finds that a transition to hydrogen could cut maritime energy consumption by 40% by 2050, but could only take place with high carbon pricing.[31] In another study, hydrogen was less profitable than biofuels or ammonia,[32] which face their own challenges (discussed below). In the near term, fuel cells could be adopted for auxiliary power on vessels; such systems have already been demonstrated on a cruise ship, a yacht, and a cargo vessel in Germany as part of the e4ships project.[33]

In addition to batteries and hydrogen, which have been widely implemented in other vehicles, ammonia has also received attention for zero-emission maritime applications. Ammonia has several advantages over hydrogen. First, ammonia has a higher volumetric energy density of 11.5 MJ/liter, 35% higher than that of liquid hydrogen. Second, ammonia is more easily stored and transported as a liquid than hydrogen (it is already distributed worldwide for agricultural purposes) and experiences much less boil-off. If used in a fuel cell, ammonia is typically first reformed into pure hydrogen; however, SOFCs or alkaline fuel cells can be designed to accept ammonia directly. Cracking of ammonia into hydrogen reduces the efficiency of the system by 10 to 20% relative to using pure hydrogen, and also adds to the cost and size of the propulsion system. Finally, ammonia can be used directly in certain internal combustion engines, primarily as a substitute for natural gas in dual-fuel applications, but also in dedicated spark-ignition ammonia-powered engines that are under development.

Despite its relatively lower technology readiness level, ammonia holds promise for maritime applications. Lloyd's Register identified ammonia as the most cost-effective pathway to zero-emission vessels by 2030, with internal combustion engines being slightly less costly than fuel cells.[34] Although ammonia is more difficult to produce than hydrogen, the higher energy density of ammonia and easier storage would lead to reduced capital costs both for the ships and for associated infrastructure. We also note that ammonia has additional health and safety issues relative to other alternative marine fuels and propulsion technologies; it's highly toxic, potentially making handling more difficult and expensive.

We provide an illustrative analysis of the greenhouse gas impacts of emerging electric and hydrogen fuel cell maritime technologies based on an example short-haul feeder container ship with a short and consistent range. We compare the zero-emission technologies to similar ships powered by traditional distillate hydrocarbon fuels and LNG. Our estimates are based on a small 800-TEU container ship with a 6-MW engine designed for short journeys of up to 250 nautical miles between stops. This is reasonable for a ship in northern Europe, where emissions requirements are stringent and there has been substantial interest in decarbonizing the maritime transportation sector. Only the main engine,

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[30] J. J. Minnehan, J. W. Pratt, *Practical application limits of fuel cells and batteries for zero emission vessels* (Sandia National Laboratories, November 2017); energy.sandia.gov/wp-content/uploads/2017/12/SAND2017-12665.pdf.

[31] Lloyd's Register & Shipping in Changing Climates, *Low carbon pathways 2050* (Lloyd's Register, 2016); www.lr.org/lcp2050.

[32] Lloyd's Register & UMAS (2017).

[33] e4ships (2016).

[34] Lloyd's Register & UMAS (2017).

which propels the ship and represents most of its fuel consumption, is considered in this analysis.

Figure 3 illustrates the use-phase greenhouse gas emissions per tonne–nautical mile for four technology options on this selected vessel under various circumstances. The two conventional technologies for distillate fuel and LNG emit approximately 23 gCO$_2$/t-nm. For the electric ship, its battery pack would displace approximately 10% of cargo capacity.[35] The hydrogen fuel cell scenarios assume a PEM fuel cell and liquid storage, with no net loss in cargo capacity.[36] As shown in the figure, the small electric ship when powered by the average grid in Germany results in approximately the same CO$_2$ emissions as a distillate-powered ship. If powered by the average European grid, the electric ship results in a 48% emission reduction per tonne–nautical mile, versus nearly a 100% reduction when charged in Norway, as Norway's electricity is primarily produced by renewable energy sources (e.g., hydroelectric and wind). In the hydrogen fuel cell scenarios, the Germany, Europe, and SMR scenarios each result in increased CO$_2$ emissions per tonne–nautical mile, but the Norway case shows how hydrogen from renewable sources virtually eliminates lifecycle CO$_2$ emissions.

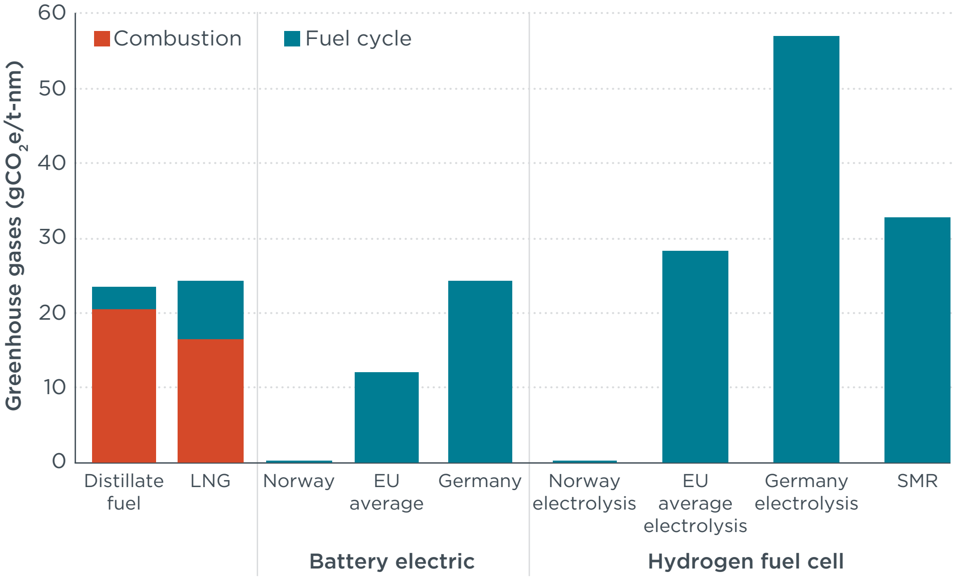

Figure 3. Greenhouse gas emissions by technology for an example small container ship.

As shown in the figure, the results depend greatly on the extent to which the zero-emission technologies are powered by renewable energy. In addition to the source of electricity used, the results for hydrogen are highly sensitive to the efficiency of the fuel cell and hydrogen electrolyzer. For example, with a SOFC with heat recovery, total efficiency could increase to 85% (up from 60% in the PEM case in the figure), making hydrogen from average European electrolysis cleaner than the baseline fuels. Additionally, the performance of LNG here assumes complete combustion with no methane slip; if this were not the case, the impacts would be substantially higher. We use a 100-year global warming potential; using a shorter time horizon would show higher emissions from the LNG ship, as methane has disproportionate near-term climate impacts. Although not shown here, using heavy fuel oil would result in greenhouse gas emissions up to 20% higher than distillate fuel because of relatively higher black carbon emissions, depending on ship type and the time scale used in accounting. We excluded ammonia fuel cells from the figure because of the greater degree of uncertainty and lack of experience with ammonia as a transportation fuel. Ammonia is produced from hydrogen but requires additional processing; our best estimate from the literature suggests that ammonia fuel cell paths would add 5 to 10 gCO$_2$/t-nm to similar hydrogen fuel cell pathways shown in Figure 3.

Maritime shipping benefits from very low fuel prices relative to other forms of transport. We estimated the fueling costs associated with the same example feeder container ship above to place these zero-emission technologies into a broader cost perspective. Distillate fuel costs an equivalent of $2.17/gallon (€0.47/liter) as of March 2018, compared to $0.67/kg for LNG fuel. These values translate to $0.40/t-nm for distillate fuel and $0.43 for LNG for the example vessel considered above. We compared these conventional costs to the zero-emission technologies on the basis of electricity rates for industrial customers in selected markets and hydrogen used in International Energy Agency projections for 2020.[37] The cost of fueling the electric ship in Norway would be 60% lower per tonne–nautical mile than distillate, and European average electric costs would be 10% lower. If hydrogen costs drop

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[35] A battery pack of 106 MWh is assumed, with a mass of 902 tonnes. We assume 93% onboard efficiency and a 20% capacity buffer for this trip. For the traditional fuel oil design, we assume a specific fuel oil consumption of 174 g/kWh at a cruising speed of 14.5 knots.

[36] We assume a 60% efficient, 6-MW PEM fuel cell with a mass of 3 tonnes, requiring approximately 4 TEUs in volume with associated electronics. Despite the larger volume of hydrogen fuel required (62 m3 versus 17 m3 of fuel oil in this example), it will require less mass, enabling equivalent cargo capacity.

[37] We assume $15.87 per MMBtu of LNG and $4.83 and $8.54 per kg of liquid hydrogen from SMR and renewable electrolysis, respectively, based on IEA projections for 2020.

to $2.50/kg or less, hydrogen fuel cells would be competitive with conventional technologies with respect to fueling costs.

Our illustrative fueling cost analysis shows that many alternative fuels are more costly than traditional bunker fuels on a per tonne–nautical mile basis. The exception is electricity, the price of which varies widely among different markets. In Norway, which has among the least expensive (and cleanest) electricity because of its abundant hydropower resources, fuel costs for a battery-electric ship are less than half those for a ship on distillate power; however, if electricity is priced at the median European industrial rate of around $0.08/kWh, the fueling cost savings are negligible. In most cases, procuring dedicated renewable electricity would cost more than average grid rates. Although ammonia fuel cell technology is more uncertain, we estimate that ammonia produced by SMR (as for the fertilizer industry) appears to be similar in cost to distillate fuels. Ammonia produced with renewable energy currently costs about twice as much as conventional ammonia, but this pathway could produce substantial amounts of ammonia fuel if renewable energy is available for $0.03/kWh.[38]

OFF-ROAD VEHICLES

Off-road land vehicles comprise a variety of platforms including agricultural, industrial, construction, and mining vehicles, almost all of which use diesel engines. Although the CO_2 emissions of these vehicles are relatively small compared to other sources, they are responsible for a large share of other pollutants: In the United States, off-road vehicles account for almost 75% of particulate matter (PM) emissions and 25% of NO_x emissions, while in Europe they are responsible for about 25% and 15% of those forms of pollution, respectively.[39] Even though the high power needs, demanding duty cycles, specialized production, and remote or rugged operating conditions can pose challenges for electrification, there is movement toward zero-emission powertrains in these sectors. These vehicles frequently have long lifetimes, meaning that delays in the introduction of new technologies or standards lead to long-lasting impacts.

Government regulation of off-road land vehicles is uneven because of the wide variety of vehicles in the sector, slow vehicle turnover, and operating models that frequently include leases and rentals. Regulations on these vehicles are primarily intended to limit PM and NO_x from diesel engines. The United States and the EU impose increasingly strict limits on PM, NO_x, CO, and hydrocarbon emissions from new diesel engines, and China is considering adopting standards similar to those currently in effect in the United States.[40] California has been a leader in this sector and operated a program for alternative-fuel agricultural vehicles for many years. The California Air Resources Board imposes additional requirements for construction, industrial, and mining vehicles through the In-Use Off-Road Diesel Vehicle Regulation, in effect since 2007. The regulation requires reporting of vehicles, limits on idling, and compliance with fleet average emissions targets by retrofitting or replacing diesel vehicles. The Bay Area Air Quality Management District provides funding for electric and hybrid off-road equipment in Northern California. Other cities, including London, Hong Kong, and Zürich, impose additional regulations on construction machinery.

Certain off-road segments have already seen substantial penetration of zero-emission vehicles; for example, a large share of forklifts already use zero-emission technology. Battery-electric forklifts, which typically use swappable lead-acid batteries, account for about 60% of the forklift market globally and 65% of the U.S. market.[41] Battery-electric forklifts allow for reduced operational costs, improved air quality, and comparable lifting performance. However, the relatively inexpensive lead-acid batteries most commonly used require substantial charging time and dedicated charging facilities, and have shorter cycle life and higher maintenance needs than the more expensive lithium-ion batteries. There is also a growing market for hydrogen fuel cell forklifts, with an estimated 16,000 hydrogen forklifts sold in the United States since 2009 and increasing sales in Europe and Japan.[42] Despite the higher fuel costs, hydrogen forklifts require less time and space for refueling than battery forklifts while producing no tailpipe emissions.

Mining equipment has also begun to be electrified. In addition to reduced fuel and maintenance costs, electric mining vehicles can offer additional savings by reducing the need for expensive underground ventilation systems. Major companies including General Electric, Atlas Copco, Aramine, and Hitachi have

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[38] Merk et al. (2018).

[39] J. Kubsh, *Managing emissions from non-road vehicles* (ICCT, April 2017); www.theicct.org/publications/managing-emissions-non-road-vehicles.

[40] T. Dallmann, A. Menon, *Technology pathways for diesel engines used in non-road vehicles and equipment* (ICCT, September 2016), www.theicct.org/publications/technology-pathways-diesel-engines-used-non-road-vehicles-and-equipment; Z. Shao, "China IV non-road standards: A golden opportunity to advance stringent limits and mandate filters" (ICCT, August 2017), www.theicct.org/blogs/staff/china-IV-non-road-standards-a-golden-opportunity.

[41] J. Bond, "Top 20 industrial lift truck suppliers, 2017" (*Modern Materials Handling,* December 2017); www.mmh.com/article/top_20_lift_truck_suppliers_2017.

[42] P. Devlin, G. Moreland, *DOE hydrogen and fuel cells program record* (U.S. Department of Energy, May 2017); www.hydrogen.energy.gov/pdfs/17003_industry_deployed_fc_powered_lift_trucks.pdf.

released electric-drive mining equipment such as loaders, dump trucks, and worker transport vehicles. The specific configurations of these mining vehicles vary widely: Battery-electric vehicles with lead-acid or lithium-ion batteries appear to be most prevalent so far, with some models (such as the Artisan Vehicles Z40 40-ton haul truck) featuring battery swapping. Plug-in hybrid diesel architectures have also been introduced, as well as trolley electric vehicles (such as large haul trucks) running on fixed routes.

Airport ground support equipment (GSE) includes vehicles such as aircraft tugs, belt loaders, scissor lifts, and other vehicles of different sizes for moving people and goods. Although most GSE vehicles are powered by diesel engines, battery-electric options are becoming increasingly popular. At least 22 airports in the United States have some electric GSE, led by Seattle-Tacoma, Philadelphia, and Dallas/Fort Worth, each with more than 230 electric vehicles.[43] A variety of companies manufacture electric GSE; Charlatte, with manufacturing in Virginia, United States, the United Kingdom, and France, is the largest manufacturer in this space, building cargo tractors, belt loaders, tow tractors, pushbacks, and water trucks. Hydrogen fuel cell tractors have been used on a trial basis at Cologne-Bonn and Hamburg airports in Germany and at Memphis airport in the United States but are not yet in regular production. The transition to zero-emission airport GSE is supported by airports, airlines, and governments alike. California is developing measures, potentially including incentives, demonstrations, and regulations, to accelerate the adoption of zero-emission GSE, with the goal of replacing 60% of vehicles with zero-emission equipment by 2032. Because airports are typically equipped with various kinds of fueling infrastructure and high-capacity electrical connections, infrastructure may be less challenging in these environments.

Port handling equipment includes a diverse array of vehicles and stationary equipment. Although some of these vehicles are extremely large and have high power needs, such as rubber tire gantry cranes (RTGs), they also tend to operate in limited spaces with predictable routes and schedules. Electric RTGs have been deployed in ports such as Long Beach, California; Savannah, Georgia; Montreal, Québec; Shanghai, China; and Evyap, Turkey. Port tractors and drayage trucks, with their regular duty cycles, are an early application of heavy-duty electric vehicles; a number of options are available on the market, led by Shenzhen-based BYD. Hydrogen fuel cell cargo tractors have also been introduced on a trial basis, such as at the Port of Los Angeles, but hydrogen has otherwise made little headway in port handling operations, with issues of cost and infrastructure cited as barriers.[44]

Major ports around the world are leading in the shift to zero-emission handling equipment. The Port of Los Angeles, for example, operates the Green Omni terminal as a showcase for clean port technologies, including electric drayage trucks, cranes, forklifts, yard tractors, and top handlers as well as stationary storage and a solar array to reduce grid stress. At the Port of Rotterdam, which has committed to being fully zero-emission by 2050, APM Terminals uses electric cranes and transport vehicles in its largely automated facilities and is investigating generating hydrogen on-site from excess renewable energy for transportation fuel and chemical feedstock. The Port of Shenzhen has shifted all of its quay cranes and RTGs to electric power, is installing shore power at all berths, and operates electric tractors. The Port of Qingdao operates 38 autonomous electric container tractors at the automated New Qianwan Automatic Container Terminal; a similar scheme is planned at the Port of Shanghai in 2018.

Table 4 lists a number of zero-emission applications in the off-road sector. Although most activity is concentrated in the aforementioned forklift, mining, and materials handling sectors, a number of prototype or demonstration projects indicate that greater electrification is feasible in various markets. John Deere, one of the largest agricultural vehicle manufacturers in the world, has unveiled a battery-electric tractor with 130 kWh of battery capacity capable of operating many attachments and implements. Several small companies build battery-electric or tethered electric construction equipment, including Huppenkothen of Austria, Sennebogen in Germany, and Pon Equipment in Scandinavia. Among larger companies, Wacker Neuson produces several small construction vehicles with battery-electric or plug-in hybrid powertrains, and Volvo Construction Equipment released a prototype electric compact excavator in mid-2017. Other major companies, including Komatsu, Hitachi, and New Holland, produce hybrid excavators and loaders for construction applications.

The examples discussed above suggest that a variety of solutions will be needed to decarbonize the diverse off-road sector. The ideal zero-emission technology for a given application will depend on its mobility needs, duty cycle, location, and vehicle architecture. Although it is difficult to provide an accurate evaluation of each technology across this wide variety of applications, some qualitative benefits and barriers are discussed below.

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[43] National Renewable Energy Laboratory, *Electric ground support equipment at airports* (U.S. Department of Energy, December 2017); www.afdc.energy.gov/uploads/publication/egse_airports.pdf.

[44] J. Serfass, *Hydrogen and fuel cells in the ports workshop report* (California Hydrogen Business Council, November 2016); www.californiahydrogen.org/wp-content/uploads/files/CHBC%20Final%20Ports%20Workshop%20Report.pdf.

Table 4. Examples of zero-emission off-road land vehicles in production or demonstration.

Technology and application	Vehicle or project	Region	Status
Battery-electric forklift	Multiple (e.g., Nichiyu Electric Forklift FB10)	Worldwide	Market leader
Hydrogen fuel cell forklift	Multiple (e.g., PlugPower GenDrive)	North America, Europe	Commercial production
Battery-electric farm tractor	John Deere SESAM	United States	Prototype
Battery-electric mining loader	Atlas Copco Scooptram ST7 Battery	North America	Limited commercial use
Catenary electric mining dump truck	Multiple (e.g., Siemens SIMINE)	Worldwide	Commercial production
Battery-electric mining dump truck	Komatsu e-Dumper	Switzerland	Demonstration
Battery-electric 40-ton mining haul truck	Artisan Vehicles Z40	California	Prototype
Battery-electric and plug-in hybrid construction loader and mini-excavator	Wacker Neuson Zero-Emission	Germany	Commercial production
Battery-electric snowmobile	Taiga Motors	Québec, Canada	Prototype, deliveries in 2019
Battery-electric ATV	Multiple (e.g., Polaris Ranger EV)	Worldwide (primarily in U.S.)	Commercial production
Battery-electric ATV	Multiple (e.g., Polaris Ranger EV)	Worldwide (primarily in U.S.)	Commercial production
Cable-tethered electric excavator	Sennebogen Material Handler	Germany	Limited commercial use
Battery-electric excavator	Huppenkothen TB 1140E	Austria	Limited commercial use
Electric rubber-tire gantry crane	Georgia Port Authority eRTG	Georgia, United States	In operation

Batteries have been integrated into a number of off-road vehicles, including construction equipment (e.g., excavators), recreational vehicles (e.g., snowmobiles), port equipment, and forklifts. As shown in Table 5, battery-electric off-road vehicles have a variety of battery sizes but are generally on the order of 100 kWh, whereas power requirements are generally less than 100 kW. Duty cycles vary widely, but the battery capacities listed are typically designed to last for one day of regular use. For comparison, the Tesla Model S sedan has a battery capacity of 75 to 100 kWh and a maximum power output of 567 kW, indicating that light-duty powertrains could be transferred to a number of off-road applications. Battery volume and weight are commonly issues for light-duty vehicles, but off-road vehicle designs are often more flexible; in fact, batteries can be useful as counterweights in vehicles such as forklifts and front-loaders.

Table 5. Specifications of selected battery-electric off-road vehicles.

Vehicle type	Battery capacity (kWh)	Motor power (kW)
Battery-electric forklift (Hyundai 32B-9)	36 (lead acid)	31
John Deere farm tractor	130	300
Atlas Copco mining loader	165	149 traction, 113 hydraulic
Huppenkothen TB1140E excavator	170 to 250	75
Charlatte aircraft pushback tractor	64	52
Taiga Motors snowmobile	15	80

All batteries are lithium-ion unless otherwise noted.

This comparison indicates that today's battery-electric powertrain technology is technologically capable of powering many common off-road applications. The challenges therefore lie mostly in infrastructure and cost. The rough operating conditions encountered by construction, agricultural, and mining vehicles (including extreme temperatures, vibration, and dirt) may require additional modifications or different battery chemistries, potentially adding to the cost. These types of vehicles also often operate in remote areas or in situations with inconsistent electricity grid access, meaning that regular overnight charging is not always possible; fast charging between shifts is still less likely to be easily accessible except in industrial and port settings. Battery swapping could also be an option for specific applications; this is widely practiced for forklifts.

Another option for electric drive is direct connection to a power supply by cable, rail, or catenary system. The primary benefits of this design include reduced costs from batteries or engine and higher efficiency, resulting in low operational costs. In current practice, this has been implemented on large mining vehicles using overhead lines, underground mining loaders connected by cable, RTGs using a ground-level rail, and indoor cranes connected by overhead cable to mains electricity. Coupling such a design with mobile power supplies such as large stationary battery packs, fuel cells, or generators could improve mobility where necessary. This is the approach taken by the Wacker Neuson mini-excavator with an attachable generator trailer. For many construction, materials handling, and port applications, this could be an inexpensive pathway toward zero emissions.

Lastly, hydrogen fuel cells have been explored for several applications, although there are few examples currently in production or service. As with battery electric, the fuel cell powertrains currently used in passenger vehicles could fit the needs of many off-road applications: The fuel cell stack of the Honda Clarity Fuel Cell is capable of 138 horsepower (103 kW) and the vehicle carries hydrogen fuel equivalent in energy to 22 liters of diesel. The primary barriers to hydrogen fuel cells, as with other transport modes, are the availability of fueling infrastructure, fuel cell stack cost, and hydrogen fuel cost. Fueling infrastructure is likely to be particularly problematic in rural or remote areas; by contrast, many vehicles in ports, airports, and urban environments could take advantage of new hydrogen fueling stations and absorb the high upfront costs.

To illustrate the cost implications of zero-emission off-road equipment, we performed a short analysis of a small excavator, similar to the popular Caterpillar 316F. Several zero-emission demonstrations of this vehicle type have been built, including the Huppenkothen/Suncar TB1140E. Relative to a Tier 4–compliant diesel drivetrain, a 200-kWh lithium-ion battery and high-torque electric motor present an upfront cost premium of approximately $41,000. Using diesel prices of $3.16/gallon and electricity costing $0.10/kWh, the electric excavator would face per-hour costs of $3.71 as opposed to $8.69 for the diesel excavator. Nonetheless, it would take approximately 8,300 hours of operation to make up this price premium in fuel savings, approaching the expected lifetime of an excavator.[45]

In contrast to the battery-electric example, a hydrogen fuel cell drivetrain would likely face both upfront and operational cost disadvantages with respect to current technologies. We estimate an upfront cost premium of approximately $8,000 for a hydrogen fuel cell excavator, with the most expensive component being the heavy-duty motor; this is almost $33,000 less expensive than the battery-electric powertrain.[46] However, unlike with battery electric, the per-hour operating cost of hydrogen would be higher than for diesel, ranging from approximately $9.10 (1.05 times that of diesel) to $16.10 (1.85 times diesel) for hydrogen derived from SMR and renewable electrolysis, respectively. Therefore, hydrogen is not currently competitive without subsidies for this application. With price reductions both in the powertrain and hydrogen fuel costs, hydrogen could be competitive on a total cost of ownership basis with diesel relatively sooner than for other modes, owing to the low efficiency and high amount of idling in conventional diesel construction equipment. In the case of both of these zero-emission options, costs could potentially rise because of the specific needs of construction vehicles, for which few zero-emission options have been developed. In the future, it may be possible to reduce this cost difference through lower maintenance expenses, falling component prices, and more stringent emission control requirements for diesel engines.

RAIL

A large number of rail systems around the world are already electrified using overhead catenary or third-rail conductive systems; most of the remainder use diesel-electric powertrains. Approximately 30% of track-miles worldwide were electrified as of 2015, although that share exceeds 60% in Europe, Japan, and Korea; electricity made up about 40% of railway energy demand worldwide.[47] This share is expected to rise with increasing electrification of rail, especially in markets in Asia.

Electrification through overhead lines reduces fuel costs and offers the potential for higher performance. Electric trains run at speeds well over 300 km/hour in many markets and are capable of speeds up to 600 km/hour, whereas the fastest diesel-powered train (the InterCity 125 in England) reaches a top speed of 238 km/hour. Although diesel trains typically have relatively high efficiency, electrification can improve efficiency by capturing braking energy, offsetting electricity consumption by 5 to 30% depending on the specific application.

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[45] Based on a comparison between the Caterpillar 316F diesel excavator and Huppenkothen/Suncar TB1140E battery-electric excavator with 117 and 102 horsepower, respectively, assuming medium fuel consumption. Motor specifications are for Siemens SIMOTICS severe-duty, high-efficiency motors. Diesel costs were assumed at $3.16 per gallon (the average U.S. price in April 2018), with industrial electricity rates of $0.10/kWh.

[46] We assume a PEM fuel cell with 55% electrical efficiency and 87 kg of hydrogen capacity at 750 bar, with the same motor as described previously. Hydrogen fuel cell and fuel cost estimates are the same as in the marine and aviation sections.

[47] International Energy Agency and UIC (International Union of Railways), *Railway handbook 2017* (IEA, November 2017); https://uic.org/uic-iea-railway-handbook

For traditional electrified trains, the primary barrier lies in the cost of the electrical infrastructure. Although costs vary according to such factors as property values, labor rates, and terrain, the cost of overhead lines has been estimated to be $1 million per track-mile for long-distance trains.[48] These costs are higher when retrofitting an existing line than when constructing a new line because of the inconvenience and risks associated with working on active tracks. Additionally, electrified train lines require higher maintenance than diesel trains, although maintenance for electric locomotives is likely to be less costly because they have fewer moving parts. Therefore, electric trains are more economical with higher use, where ongoing fuel savings can offset the higher upfront infrastructure costs.

In addition to overhead-line electric rail, additional zero-emission technologies have been developed for various applications. Hydrogen fuel cell–powered trains, sometimes referred to as hydrail, have been built in a variety of demonstration projects. These projects range from a switchyard freight locomotive developed by BNSF Railway in the United States to a hydrogen-powered urban tram line in Foshan, China. The world's first intercity hydrogen passenger train, manufactured by Alstom in France, is scheduled to enter service in Lower Saxony, Germany in 2018. All hydrail projects to date have used PEM fuel cells; however, designs for SOFC-powered trains have also been created, particularly for long-distance freight trains.

Battery-electric trains are likewise in use for niche applications. Norfolk Southern railroad uses a demonstration plug-in battery-electric locomotive, the NS 999, at a switchyard in Pennsylvania. The locomotive uses 1,080 lead-acid batteries and is capable of producing 1,119 kW. Battery-electric locomotives are used for maintenance and engineering in several rail systems, including 29 in service for the London Underground. Zephir of Italy produces railcar shunting vehicles with lead-acid batteries, while Nordco in the United States produces similar shunters with lithium-ion batteries. Batteries could also be paired with overhead-line electric trains in a hybrid architecture to provide backup power and allow for limited distances without supporting infrastructure; a China Railway High-speed (CRH) passenger train in Inner Mongolia, China is testing this approach, with a range of up to 200 km possible on batteries.

Traditional (overhead line) electrification appears likely to expand around the world in the coming decades, primarily for heavily trafficked passenger service in Asia and Europe. With falling battery costs, battery-hybrid designs may become practical in some cases, reducing infrastructure and maintenance expenses. Nonetheless, for many long-distance freight and low-frequency passenger services, the initial infrastructure investment makes electrification financially unappealing; hydrogen may play a role in these applications. Hydrogen currently lags diesel locomotives in terms of engine (fuel cell stack) cost, fuel cost, engine (stack) lifetime, and volumetric energy density; however, a PEM fuel cell passenger locomotive has been estimated to cost less than $3.5 million as economies of scale are realized, similar to the cost of a diesel locomotive with emission control equipment.[49] Trains are somewhat flexible in terms of fuel weight and volume limitations, so hydrogen could potentially be stored as a compressed gas, as a liquid, or in metal hydrides.

Several studies allude to the feasibility of hydrogen rail in the near- to medium-term future. An analysis of passenger and freight rail in California finds that liquid hydrogen is the most cost-effective form of zero-emission passenger rail at low traffic volume, only 10% more expensive than traditional diesel.[50] A study of freight lines in rural Norway found hydrogen, coupled with large batteries for regenerative braking, to be the lowest-cost alternative, assuming that the fuel can be generated relatively cheaply using Norway's abundant hydropower.[51] When considering an upgrade of the commuter rail system in Ontario, Metrolinx found that hydrogen trains could be cost-competitive on a lifetime basis with overhead-line electrification while reducing emissions substantially relative to the diesel baseline and also reducing strain on the electric grid.[52]

A number of studies have also investigated the emissions from rail electrification in various contexts. Chan et al. evaluated several alternatives for the commuter rail system of Montreal,

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[48] R. Isaac, L. Fulton, *Propulsion systems for 21st century rail* (paper presented at World Conference on Transport Research 2016, Shanghai); https://itspubs.ucdavis.edu/wp-content/themes/ucdavis/pubs/download_pdf.php?id=2703.

[49] California Air Resources Board (California ARB). *Technology Assessment: Freight Locomotive* (November 2016); https://www.arb.ca.gov/msprog/tech/techreport/final_rail_tech_assessment_11282016.pdf

[50] Isaac & Fulton (2016).

[51] S. Møller-Holst, F. Zenith, M. S. Thomassen, *Analyse av alternative driftsformer for ikke-elektrifiserte baner* (Sintef, 2016); www.sintef.no/publikasjoner/publikasjon/?pubid=CRIStin+1334627.

[52] CH2M HILL Canada Ltd., Ernst & Young Orenda Corporate Finance Inc., & Canadian Nuclear Laboratories, *Regional express rail program hydrail feasibility study report* (February 2018); www.metrolinx.com/en/news/announcements/hydrail-resources/CPG-PGM-RPT-245_HydrailFeasibilityReport_R1.pdf.

Québec, and found that electrification (with hydroelectric power) would reduce greenhouse emissions by more than 98% relative to the diesel baseline, with hydrogen bringing a reduction of 24% if produced via SMR or 82% if produced via renewable electrolysis.[53] A study from nearby Ontario found that an electric passenger train using electricity generated from coal produced greenhouse gas emissions similar to those of an equivalent diesel-powered train, whereas hydrogen fuel cell trains could reduce emissions by up to 91% when derived from renewable sources.[54] As part of an electrification project in 2011, the UK government estimated that electric trains emit 20 to 35% less greenhouse gases per passenger-mile than a diesel train, with that gap growing as the grid decarbonizes.[55]

CONCLUSION

This report identifies promising demonstrations and discusses barriers for each of these technologies. Here, we summarize the status and potential of the technologies described above for each transport mode in three ways: technological readiness and feasibility, costs, and emission reduction potential. To provide a comparable assessment of these diverse and dissimilar modes of transport, Table 6 describes our qualitative scoring rubric for these three criteria. We apply these criteria consistently across the various modes in Tables 7, 8, 9, and 10 according to our research results. As we have not quantitatively assessed every application, there are, of course, exceptions and caveats, and technologies may develop more quickly or slowly than anticipated. At the close of this section, we offer several policy implications.

Table 6. Qualitative scoring rubric for technology assessments applied below.

Score	Technological readiness and feasibility	Cost	Greenhouse gas emission reduction potential
5	Currently in widespread use	Least expensive option available	Lifecycle zero-emission using widely available fuel pathways
4	Appears poised for commercial introduction	Cost-competitive with conventional alternative	>50% emissions reduction from fossil fuel baseline
3	Early demonstration, but not yet ready for commercial deployment	Lower upfront or fuel cost, but uncertain or somewhat negative total cost of ownership	1 to 50% emissions reduction from fossil fuel baseline
2	Not yet built, but appears possible with near-term technology	Would require substantial financial support in the short to medium term	Approximately even with fossil fuel baseline using widely available fuel pathways
1	Faces extreme difficulties using near-term technology, or not logistically feasible to implement	Prohibitively expensive	Higher emissions than fossil fuel baseline under most circumstances

AVIATION

The unique technological barriers, safety requirements, and high performance demands of aviation make it among the more difficult modes to shift toward zero-emission technologies. Although many modes of transport are constrained by the low energy density of present-day batteries, aviation is uniquely sensitive to weight; batteries in 2018 are an order of magnitude less energy-dense than jet fuel. This added weight from electric aircraft technology affects the power needed for takeoff, reduces the operational efficiency, and ultimately limits range. Until there are dramatic increases in battery density, developments in zero-emission technologies within aviation will likely remain in the general aviation category or smaller, lighter, shorter-range commercial planes, such as air taxis and commuter planes. Hybridization of passenger flights, which is likely to occur before 2040 for shorter flights, could pave the way for plug-in hybrid systems.

Long-range flights present the steepest barriers to electrification, largely because the added mass of batteries more than offsets the efficiency benefits of electrification over long distances. Instead, this sector is more likely to see the implementation of fuel-switching or the introduction of fuel cells. Transitioning to fuel cells requires substantial new advances in containment and pressurization, likely necessitating new airframe designs; however, the relatively lighter weight of hydrogen may ensure sufficient energy density to travel longer distances, coupled with the benefits of electric propulsion.

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[53] S. Chan, L. Miranda-Moreno, Z. Patterson, Analysis of GHG emissions for city passenger trains: Is electricity an obvious option for Montreal commuter trains? *Journal of Transportation Technologies, 3,* 31811 (2013); https://doi.org/10.4236/jtts.2013.32A003.

[54] Y. Haseli, G. Naterer, I. Dincer, Comparative assessment of greenhouse gas mitigation of hydrogen passenger trains. *International Journal of Hydrogen Energy, 33,* 1788–1796 (2008); www.sciencedirect.com/science/article/pii/S0360319908001420#.

[55] Department for Transport, "Green light for new trains and rail electrification" (Gov.uk, March 2011); www.gov.uk/government/news/green-light-for-new-trains-and-rail-electrification.

Table 7. Qualitative assessment of readiness, costs, and emission reduction potential for battery-electric, hybrid electric, and fuel cell aircraft.

	Battery electric			Hybrid electric			Fuel cell		
	Readiness/ feasibility	**Cost**	**Emissions**	**Readiness/ feasibility**	**Cost**	**Emissions**	**Readiness/ feasibility**	**Cost**	**Emissions**
Single-seaters and air taxis	3	3	5	4	4	3	3	2	3
Short-haul passenger flights	2	2	4	3	2	3	2	1	3
Long-haul passenger flights	1	1	4	1	1	3	1	1	3

MARITIME

Zero-emission maritime vessels are becoming increasingly viable in a number of settings. Battery-electric ferries have been deployed in several countries in Europe and appear to be poised for expansion. Although batteries appear to be the most cost-effective option for this application, hydrogen ferries are also in development. Electrification is expanding to inland shipping in China and Europe. Even for short-sea shipping, batteries and hydrogen both represent feasible and compelling options that offer substantial greenhouse gas emissions reductions and major air quality improvements; however, upfront cost and mass (for batteries) and fuel costs and fuel storage difficulties (for hydrogen) will likely limit commercial deployment in the near term. Financial support or other economic measures (e.g., a price on greenhouse gas emissions) and the provision of infrastructure may be necessary to accelerate the transition in these sectors and drive down the costs of these nascent technologies.

For the largest vessels, such as container ships and tankers, the transition to zero emissions remains much more challenging. The low energy density of batteries makes this technology infeasible because of the extremely long voyages between refueling, and even storing hydrogen in a compressed or liquid form could require substantial modifications to ship design. Ammonia has been proposed as an attractive alternative in terms of storage and energy density but is currently still in the research phase, and its use would incur health and safety issues that must be carefully considered. Additionally, the relatively high efficiency of marine engines and low cost of marine fuels (especially when run on heavy fuel oil) make the operational costs of fuel cell–powered ships financially unattractive. Upgrading ports to handle alternative fuels, including high-power battery-charging infrastructure, will be a difficult and costly endeavor.

Hydrogen- or ammonia-powered ships cannot provide long-distance cargo transport without substantial improvements in the underlying technologies, and many logistical barriers would need to be solved through government and industry collaboration.

OFF-ROAD VEHICLES

In this broad category of vehicles, there is no one-size-fits-all zero-emission solution. These vehicles, including construction equipment, agricultural vehicles, and materials-handling equipment at ports and airports, frequently have strenuous duty cycles and operate in rugged conditions. They also remain in use for many years, indicating that the market will develop slowly and that a full transition will take decades. However, many types of off-road vehicles have power and daily energy needs similar to those of light-duty road vehicles, making it easier to transfer battery-electric or hydrogen fuel cell technology. In many cases,

Table 8. Qualitative assessment of readiness, costs, and emission reduction potential for battery-electric, hydrogen fuel cell, and ammonia fuel cell maritime vessels.

	Battery electric			Hydrogen			Ammonia		
	Readiness/ feasibility	**Cost**	**Emissions**	**Readiness/ feasibility**	**Cost**	**Emissions**	**Readiness/ feasibility**	**Cost**	**Emissions**
Ferries and harborcraft	4	4	5	3	2	3	2	2	2
Inland and short-sea shipping	3	3	4	3	2	3	2	2	2
Transoceanic container ships	1	1	4	2	2	3	2	3	2

Table 9. Qualitative assessment of readiness, costs, and emission reduction potential for battery-electric, tethered electric, and hydrogen fuel cell off-road vehicles.

	Battery electric			Tethered/overhead electric			Hydrogen		
	Readiness/ feasibility	Cost	Emissions	Readiness/ feasibility	Cost	Emissions	Readiness/ feasibility	Cost	Emissions
Agricultural tractor	3	3	4	1	4	5	3	2	4
Construction excavator	3	3	4	4	4	5	2	3	4
Port and airport cargo tractor	5	4	4	3	4	5	3	2	3

therefore, the limiting factors are cost (a battery-electric excavator could have a payback period of 6 to 8 years) or infrastructure (especially for agricultural or mining uses). Nonetheless, zero-emission vehicles have gained a substantial foothold in a number of applications, notably forklifts, mining equipment, and airport GSE.

In general, battery-electric drivetrains appear to be a promising option for many forms of port and airport equipment, industrial vehicles such as forklifts and loaders, recreational vehicles, and potentially even agricultural tractors; prototypes or commercial examples of these products exist and will become more attractive as battery costs fall. For specific applications where mobility is limited, such as cranes, excavators, or some port tractors, a direct electrical connection via cable, overhead line, or rail may be a cost-effective and highly efficient zero-emission option. For other off-road vehicle types, where range is a concern and frequent recharging is infeasible, hydrogen fuel cells offer a flexible solution and current technologies are capable of fitting most applications. As with other modes, upfront and operational costs remain a barrier for hydrogen equipment. Although the long lifetimes and low production volumes of many off-road vehicles reduce the speed of turnover, the future of zero-emission off-road vehicles is promising and offers the potential for substantial air quality and fuel savings benefits.

RAIL

Electric rail has been in widespread use for many decades, and in many markets passenger rail is largely electrified. Overhead-line electrification is by far the most popular form of zero-emission rail for heavily trafficked rail lines, presenting substantial operational savings and enabling faster speeds and acceleration. Electrification of passenger rail is expected to continue in many markets; however, high upfront infrastructure costs make the electrification of long-distance freight and some passenger services prohibitively expensive. Alternatives, including hydrogen rail and battery-catenary hybrids, are becoming increasingly viable and are beginning to enter commercial use. Finally, freight switchyards can use battery-electric or hydrogen locomotives to reduce local air pollution, although these technologies still face high costs. Although rail boasts the highest rate of electrification of any mode of transport today, lower costs and government action may be needed to fully electrify remaining services.

POLICY IMPLICATIONS

The transport sector is one of the largest and fastest-growing contributors to global greenhouse gas emissions and local air pollution. For passenger vehicles, the transition to zero-emission technologies is well under way. Many zero-emission commercial truck technologies are also emerging. However, focusing solely on road vehicles

Table 10. Qualitative assessment of readiness, costs, and emission reduction potential for overhead-line electric, battery-electric, and hydrogen fuel cell rail.

	Overhead-line electric			Battery electric			Hydrogen		
	Readiness/ feasibility	Cost	Emissions	Readiness/ feasibility	Cost	Emissions	Readiness/ feasibility	Cost	Emissions
Urban and commuter rail	5	5	5	2	2	4	3	2	3
Intercity passenger rail	5	3	5	3	2	4	4	3	3
Freight rail	4	2	5	3	2	4	3	2	3

neglects one-fourth of the transport sector's emissions globally, including the fastest-growing share (aviation). Hence, we have investigated whether zero-emission technologies can also contribute to decarbonizing transport modes beyond road vehicles.

This research has led us to conclude that zero-emission technologies are coming to aviation, maritime vessels, off-road vehicles, and rail transport, but at different rates of progress in each application. To the broader, future-looking question about whether these technologies can contribute to decarbonizing the entire transport sector, the answer is also yes. However, it is difficult to say which decarbonization technologies will ultimately prevail over the next few decades. Going forward, the questions are *which* electric and hydrogen technologies will be best suited in different contexts, and *how quickly* they can fill niche applications and eventually grow into larger segments of the market.

Our findings underscore the importance of developing policy frameworks that track and require technology improvements in each mode. As a complement to international policy venues to control these emissions, national, state, and local agencies can continue to develop improved inventories of these non-road emission sources to track and spur the technology developments. With the great uncertainty about near-term breakthroughs in zero-emission technologies, policy to ensure steady and robust improvements over conventional technology becomes even more crucial. Policymakers can ensure a foundation for technology investments by continuing to increase the stringency of performance standards. Regardless of technology, emissions and efficiency standards would ensure that industry stakeholders innovate and deploy technology. Regulatory standards are in place for off-road engines as well as for aircraft and maritime applications; however, these regulations only promote incremental improvements and do not yet constitute requirements for zero-emission technology deployment.

Policymakers can play a key role in helping to better understand which technologies can penetrate which transport modes. In addition, government leaders can continue to innovate by conducting or supporting demonstration projects. A mix of technologies will be required to move the various transport sectors toward zero emissions, but most of these technologies are only in the early stages of development. Many more demonstration projects like those assessed in this report will be needed to overcome the technical challenges and the upfront cost barriers while also generating a reliable, low-cost, and renewable energy supply. The qualitative ratings above (Tables 6 to 10) are a simple initial step toward assessing early technology prospects and could indicate which areas are most ripe for new demonstrations.

On the basis of this research, we recommend that governments continue with follow-on projects based on those above that have demonstrated partial success, to push them toward larger scale and in new directions. Governments can do so with cost-sharing projects to expand charging and hydrogen infrastructure, which would lower one of the largest barriers to enabling technology providers and commercial fleets to implement new technologies. They can also do so with public-private partnerships that engage multiple industry leaders and suppliers in precommercial technologies. In addition, governments can spur industry leaders with procurement contracts that require zero-emission technologies (e.g., with off-road equipment or maritime vessels) as part of larger contracts for conventional technology.

We also recommend further research to more deeply assess the technology potential and policy designs that will advance zero-emission technologies in the aviation, maritime, and off-road sectors. For maritime, such work could include research to identify priority ports and routes to support zero-emission vessel deployment, including which coastal/short-sea routes are most likely to support battery-electric ships given traffic patterns and access to renewable electricity. For larger, oceangoing vessels, research is needed to assess the relative costs and benefits of hydrogen and ammonia applications for different ship types, along with priority ports to support bunkering infrastructure for alternative fuels. Both types of studies could inform policy to promote these technologies at the national, regional, or international level, such as by integrating zero-emission technologies into post-2025 EEDI targets.

Aviation, for the reasons outlined above, is likely to be relatively late in adopting zero-emission technologies. Further work is needed to assess available technologies, relative costs, and benefits (e.g., fuel savings, maintenance impacts, safety issues) of nearer-term electrification in suitable short-haul and general aviation applications. For the longer term and for long-haul applications, hydrogen use is more appropriate given its high energy density on a mass basis, although volume constraints will need to be overcome. Dedicated research on alternative airframe configurations capable of storing sufficiently large volumes of hydrogen, along with other enabling technologies such as distributed propulsion, may be appropriate. Although this study has focused on truly zero-emission aviation applications, it suggests that PtL fuels produced with renewable energy could be an appropriate mid-term decarbonization step. Further work is recommended to clarify questions of potential market size, promising market segments, geographic distribution, relative costs, and supportive policies as PtL fuels and zero-emission technologies continue to develop.

Zero-emission transport demonstrations and pilot projects like those identified here will eventually help us to understand which technologies will be most viable, deliver the greatest cost reductions, and offer the most emission reductions. Realistically, it is too early to definitively say which zero-emission technologies will win out, and on what time frame. However, when we consider the success of electric drive in road vehicles, it seems clear that the innovations enabling sustainable zero-emission vehicles across the transport sector will eventually emerge.