Evaluating Sustainable Fuels to **Decarbonize the Transportation Sector**

Alexa Sanchez | Western Resource Advocates
Sustainable Transportation Fuels Internship

Table of Contents

Executive Summary

Decarbonization in the transportation sector has become a very popular topic in recent years. Nearly all segments of the automotive industry are making strides toward decarbonizing, with car companies producing more and more alternative fuel models, rental companies and delivery services buying electric [1], and aviation and maritime groups pledging to reduce emissions and publishing plans to do so [2][3]. As commitments to decarbonize continue, it can be difficult to keep track of what fuels and technologies are primed to make an impact. This paper seeks to outline what technologies are available and how they can play a role in decarbonizing different segments of the transportation sector.

Forms of transportation to be discussed include light, medium, and heavy-duty vehicles, as well as the aviation and marine sectors. Light duty vehicles are the largest category of greenhouse gas (GHG) emissions and have the most technologies available currently. Medium and heavy-duty vehicles have less available technologies, and this sector is decarbonizing much slower than the light duty sector. Aviation and marine transportation have the least amount of technology available for decarbonization and will therefore be some of the most difficult areas to decarbonize.

The main technologies discussed here will include battery, hydrogen, and biofuels. These, of course, are not the only opportunities available, there is always potential to reduce emissions through increased efficiency of fossil fuel engines and reducing overall travel, but these techniques will have their limitations. Improvements in fuel efficiency and reducing miles traveled are important and should be prioritized by policy makers where possible. But battery, hydrogen, and biofuel technologies are essential to remove all emissions from the transportation sector, because unlike increased efficiency and reducing travel they can support completely decarbonized modes of transportation.

Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), to keep global temperature rise under 1.5 C and to avoid the most catastrophic effects of climate change, emissions must reach net zero by midcentury. The transportation industry will play an important role in achieving this goal, as transportation was responsible for 29% of emissions in the US in 2019 [4] or 8.5 Gt globally [5]. The International Energy Agency (IEA) estimates that emissions from transportation must be reduced to 0.7 Gt globally by 2050. This will be made even more challenging as passenger levels are expected to double, and freight transportation is expected to increase by a factor of 2.5 over the same 2050 timeframe [5].

Reducing emissions from the transportation sector at the pace necessary to avoid catastrophic warming will require quick adoption of market-ready technologies, as well as market penetration of many developing technologies. Light duty vehicles are expected to decarbonize the fastest, while other forms of transportation lag behind. This is due to lower technology availability for sectors like heavy duty vehicles, aviation, and marine. These are the sectors that will require extensive technological advancement to make decarbonization feasible.

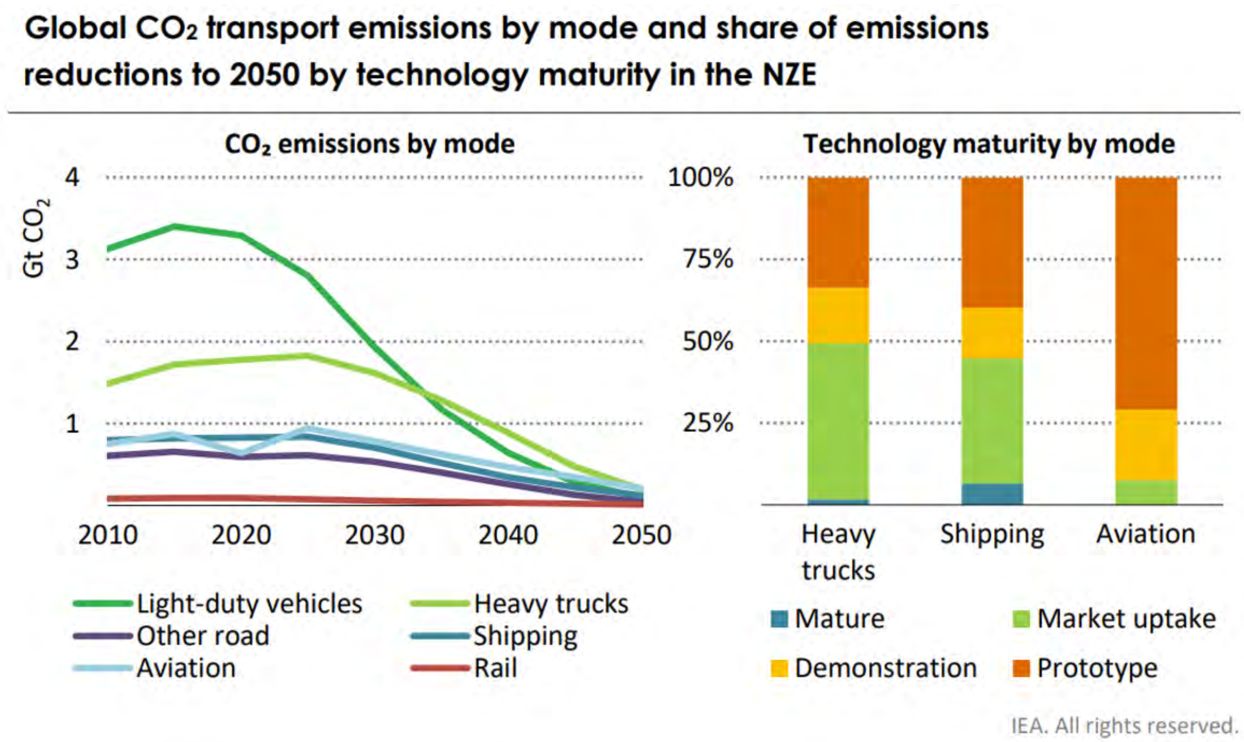

Figure 1: Global CO_2 transport emissions by mode and share of emissions reductions to 2050 [5]

While it is true that some sectors are waiting for technological breakthroughs, there are still several tools available to start reducing emissions from transportation now. Electrification via battery powered vehicles is already occurring in the light duty sector, hydrogen “hubs” are in the planning stage in several areas, and biofuels are becoming more popular as drop in fuels, i.e. they can be directly substituted with fossil fuels. The technologies that are already available today should be implemented as fast and as widely as possible to keep us on the path to net zero by 2050.

Technologies to Decarbonize the Transportation Sector

Battery

Battery technology is one of the most familiar and most developed technologies for decarbonizing the transportation sector. Already, battery powered vehicles are on the road in significant volumes, and dozens of new models from nearly every car manufacturer are being developed. Electrification is a powerful tool for decarbonizing the transportation industry because it is widely available today, has a cheap fuel source that is widely available, and is the most market ready technology. However, it presents challenges in meeting all transportation use cases, specifically due to longer fueling times, potential impacts to the electric grid, heavy batteries, and a complex supply chain of source materials. As such, other types of fuel will also be critical to fully decarbonizing the sector.

Some issues with battery electric vehicles (BEVs) include the charging time and charging infrastructure. Electric vehicles are most effectively fueled via slower overnight charging, and then "topped off" with faster charging as is necessary along the way [6]. Overnight charging on slow chargers (Level 1 or Level 2) is the most common form of charging for light-duty vehicles, with over 80% of EV driver's charging happening at their homes [7]. While charging is unlikely to be a problem for those who have access to home charging on a daily basis, it can become difficult when considering long trips. In this case, getting a full charge will take at least 20-30 minutes, even on the most rapid existing charging technology [6]. Rapid charging technology might also cause issues in grid distribution in isolated use cases due to a combination of high power demand, centralized load demand, and the potential for such demand to occur at peak hours [8]. In general, BEV charging requires further widespread build-out and development, but we have the means to do it, and it will be a very powerful tool for decarbonization.

The batteries used in BEVs present one of the most complicated problems. Batteries are not as energy dense as gasoline, in fact a gallon of gasoline is equivalent to about 240 pounds of battery [9]. However, electric vehicles are much more efficient than internal combustion engine (ICE) vehicles. Because of this, the battery in a Tesla Roadster is only 900 pounds [10]. So, the size of batteries is not problematic for the light and some of the medium duty sectors. However, this can become problematic as the size of a vehicle increases, and more power is needed to maintain the range.

The materials in a typical battery are another potential issue. The batteries contain lithium, nickel, manganese, and cobalt [11]. Research is still being done to determine ways to reduce the amount of these metals in batteries. The main concern is cobalt, because about two-thirds of the global supply is located in the Democratic Republic of the Congo, and there are concerns over humanitarian conditions of the mining processes [11]. Because of this, and worries about shortages of nickel, many scientists are looking into eliminating or substituting cobalt and nickel in batteries. One other option is recycling old batteries, but due to the diversity of materials in lithium-based batteries, this process is fairly difficult and still needs further improvement.

In general, battery electric technologies are the most advanced and most available today to decarbonize the transportation sector. Battery will play a large role in multiple sectors of transportation. Clearly though, there is still a need for improvements to make the technology even more efficient and sustainable.

Policy Considerations

- Charging Infrastructure
- Battery Materials

As mentioned above, most BEV charging occurs overnight via slow charging, and due to the current status of charging infrastructure, this favors people who live in houses. People who live in apartments, for example, are at a disadvantage when it comes to BEVs because they do not have access to their own chargers. Policies should focus on making charging more accessible for everyone, which in turn could encourage more people to switch to BEVs. Material security should also be a main focus for policy. Ensuring that we have enough supply to keep up with increasing demand for batteries will be very important to facilitate a smooth transition away from fossil fuels.

Hydrogen

Hydrogen has the potential to reduce emissions in the transportation sector, but only if the right technologies are used to produce and consume it. Most hydrogen is currently produced by steam methane reformation (SMR), which involves the emission of carbon dioxide, therefore this is not a viable pathway to reduce emissions. However, there are several other forms of hydrogen production that are zero or low emissions.[1] Hydrogen can be utilized in transportation by a fuel cell or by direct combustion.

Green Hydrogen

Green hydrogen is defined as hydrogen that is produced by the electrolysis of water, using electricity only from renewable sources [12]. This is the most desirable process for hydrogen formation, as it does not lead to any emissions of GHGs from the entire process. However, this technology is currently very expensive and inefficient, and there are some perceived concerns related to water usage for this process.

The current price of green hydrogen is approximately $5/kg [13], although price reductions are expected as renewable energy becomes more widespread and efficient. Energy Earthshot's Hydrogen Shot seeks to reduce the cost of green hydrogen by 80% to $1/kg by 2030. This price reduction will allow green hydrogen to be competitive with other marketed technologies, but significant improvements to the technology are needed to make this possible. The electrolyzers

---

[1] Hydrogen is referred to in kilograms in most studies, which is approximately equivalent to the amount of energy in 1 gallon of gasoline [3].

used in the process are an area for potential improvement, as they currently only run at about 65% efficiency and their capital expenditure (CAPEX) is 840 USD/kW. The CAPEX is expected to drop to 200 USD/kW as electrolyzer technology improves, but is not forecasted to happen before 2040 [14]. Improvements in the efficiency and cost reductions of electrolyzers will help to reduce the cost of green hydrogen.

Water usage is also an important topic in green hydrogen production, especially when considering areas in droughts. Producing 1 kg of green hydrogen can use approximately 10 gallons of water, if the renewable energy used is wind [15]. The water usage comes mainly from the hydrogen production and compression steps, with a small portion used for transportation purposes. Fortunately, studies show that green hydrogen water usage can actually lead to water savings since the process is less water-intensive than fossil fuel production [16]. Of course, future improvements should still attempt to reduce the amount of water needed in each of these steps, but it is unlikely that a drastic reduction will be possible.

Blue Hydrogen

Blue hydrogen is hydrogen produced using SMR, similar to grey hydrogen, with the difference being that blue hydrogen involves carbon capture and storage (CCS) [4]. This process is considered a low emissions route to produce hydrogen, since carbon capture technology is currently only around 85-95% efficient [14]. The captured carbon can be stored in long-term geological storage, and the US has the capacity to store thousands of years worth of emissions this way [17]. Potentially exploitable sites are shown in the figure below, but currently there are no operational blue hydrogen facilities in the US, according to the Pillsbury Law hydrogen map [18]. Some potential issues with geological storage are leakage and economics. Leakage can be caused by over pressurization of an aquifer, leading to cracks in the cap rock that is trapping the carbon dioxide. Faults and fractures may also be pre-existing in a site, and careful surveying of sites for carbon capture should check for these [19].

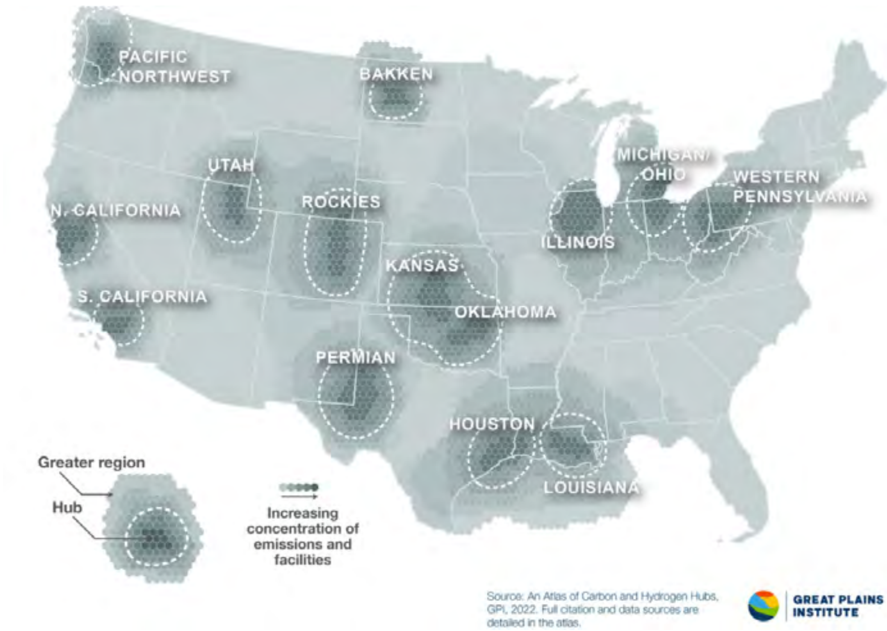

Figure 2: Potentially exploitable sites for carbon storage [17]

Blue hydrogen is an attractive option because it is cheaper than green hydrogen and more sustainable than other forms of hydrogen production. The current cost of blue hydrogen is around $1.40/kg, and the price could drop as carbon capture technology becomes cheaper [20]. This cost, however, does not include transportation and other additional costs that may be present if blue hydrogen is not produced on site for usage. It does have the added benefit of lower water usage than green hydrogen, although the process does still require water for steam. The minimum water usage for SMR is 4.5 kg of water per kg of hydrogen produced, plus water used for cooling the process [20].

Other Technologies

Grid-based electrolysis is another technology that has come into question, but because electrolysis is so energy intensive, using grid electricity would actually be more carbon intensive than SMR-produced hydrogen [21]. Until the grid contains a significantly higher percentage of renewable energy, grid-based electrolysis will not be a sustainable option. Grid-based electrolysis may also present efficiency losses when it comes to hydrogen production since the renewable energy will become an intermediate source instead of a direct source, like with green hydrogen.

Pink and turquoise hydrogen are some other technologies to keep in mind. Pink hydrogen is hydrogen produced by nuclear powered electrolysis, which could be a viable technology depending on the classification of nuclear energy in the future. This may be a necessary consideration if green and blue hydrogen technologies cannot meet the demand of hydrogen in the future. Turquoise hydrogen uses methane pyrolysis to form hydrogen and solid carbon, and could be classified as a low emissions technology. This process has not been proven at scale though, so it will be dependent on technological investments and breakthroughs in the coming years [12].

Policy Considerations

Some key issues to keep in mind with hydrogen will include:

- Fuel Station Availability and Siting
- Transportation of Hydrogen
- Direct Combustion
- Fuel Cell Materials
- Water Sourcing and Usage

If freshwater use can be avoided in hydrogen production, then it should be. Policies should be directed at using wastewater, saltwater, or other alternatives. And of course, continued work should focus on every possible opportunity to reduce overall water usage in the process. Fuel station availability will need to grow as hydrogen-based technologies reach the market. Currently, nearly all hydrogen fueling stations available in the US are located in California [22]. Expansions into other states will make fuel cell electric vehicles (FCEVs) more feasible in the future. As expansions occur, siting of fuel stations should try to match production locations. This will reduce transportation costs, and therefore the overall cost of hydrogen. Of course, this will not always be possible, since refueling station locations will be based on transportation needs whereas production locations will be based on geographical criteria (carbon storage, energy production, etc.). Specifically, in regard to blue hydrogen, carbon pricing could act as a motivator for pushing more grey hydrogen to blue.

Direct combustion of hydrogen should be approached with caution, since there are some associated emissions risks with it. As long as policies ensure that these emissions are regulated properly though, direct combustion is still a viable option. Fuel cell catalysts may cause some issues as well, since they are made of platinum, which is an expensive and rare metal. Efforts should be directed at finding substitutions for platinum in fuel cells.

Biofuels

Biofuels are a solution whose primary role is to “fill in the gap” where electrification or other technologies are not possible or financially viable. Biofuels have the potential to reduce dependence on crude oil, offering a renewable and less carbon intensive option. Again though, the sustainability of biofuel technology is dependent on the methods used to produce them.

First Generation

Biofuels classified as first generation are produced using sugar crops, starch crops, oilseed crops, and animal fats [23]. In other words, first generation biofuels directly compete with food supply, which makes them an unattractive option. Most fuel ethanol currently used in the US is from corn distillation [24]. This has caused direct competition with a food source, which can be seen in the distribution of corn for food versus biofuel production. In 2000, only about 5% of corn was used in biofuel production, but in 2013 more than 40% was used for biofuels [25]. As biofuel usage increases, there will need to be a shift away from first generation biofuels to avoid risking food competition or shortages.

Second Generation

Second generation biofuels are produced from cellulosic crops or waste biomass. This is a more attractive option than first generation from a sustainability perspective because there is no food competition. Cellulosic crops have the additional benefit of marginal land use, while waste biomass uses no additional land [23]. Cellulosic ethanol has shown the potential to reduce greenhouse gas emissions by up to 86% compared to fossil fuels [26], offering a substitution to corn-derived ethanol.

Even still, second generation biofuels can put a strain on agriculture by utilizing resources that could otherwise be used for food crops, such as water and land. The type of land use will also affect the overall GHG's of biofuel usage. Biofuels produced on land that was previously rainforest, for example, would cause significantly higher emissions than biofuels produced from marginal land [23]. Both of these issues can be avoided if the biomass source is waste from other crops, such as crop stalks, leaves, roots, shells, and peels. It is estimated that there are approximately 140 Gt of waste biomass produced annually, which can cause management problems and also potentially cause negative environmental impacts [27]. This waste material would be much better utilized as biofuels, but that doesn't mean that this biomass will be easily collected and utilized for biofuels [28]. Supply chains collecting this waste fuel and transporting it to locations to be productively used would need to be developed in order to widely scale this fuel.

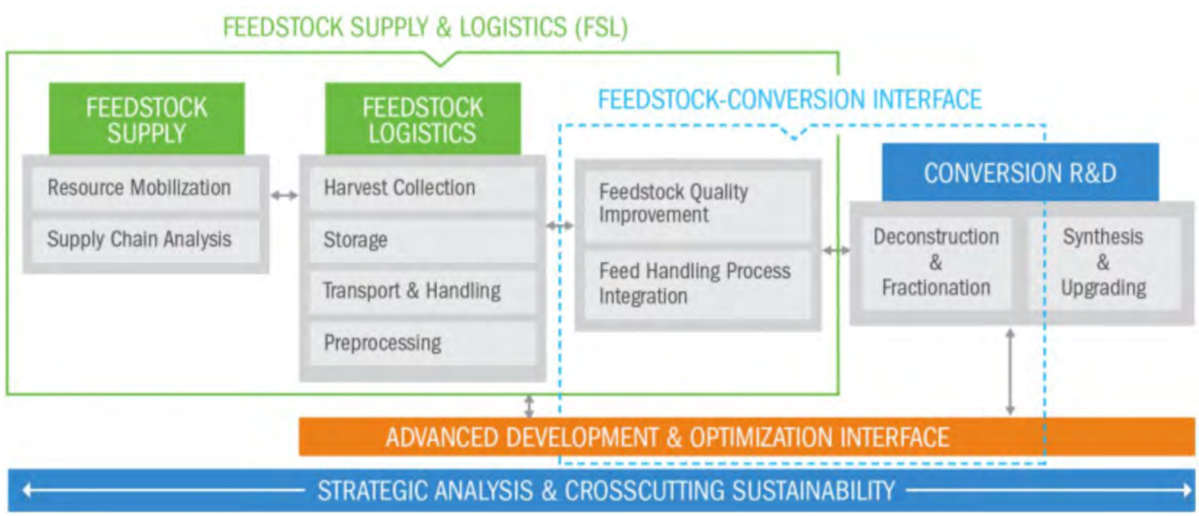

Figure 3: Feedstock supply and logistics [28]

Third Generation

Third generation biofuels are produced using algae, and have lots of benefits when compared to first- and second-generation biofuels. Algae have the potential to produce up to 30 times as much energy per acre than land crops, based on experimental findings [29]. In terms of biofuel production, up to 9,000 gallons of biofuel can be produced per acre of algae, which is 10 times more than the next best feedstock [30]. Some strains can even be grown in wastewater [31], which addresses the major problem of freshwater usage, like in first- and second-generation biofuels.

However, there are still some downsides to the third-generation biofuels, which need to be addressed before their production becomes more widespread. Algae growth requires a very large amount of water, and even if wastewater is used, this is still problematic [30]. Wastewater or saltwater could replace up to 90% of freshwater usage in algae production, but some freshwater is still necessary. And producing 1 L of algal-derived biodiesel could require as much as 3,000 L of water, a very large water footprint [32]. The fertilizer demand for algae production would also increase, so much so that net GHG emissions could actually be higher for third generation biofuels than fossil fuels [30]. More breakthroughs will be needed to reduce the water and fertilizer demand, and to produce cleaner fertilizer or “green ammonia”. Green ammonia is produced by using green hydrogen and nitrogen separated from the air, which is then fed into the Haber-Bosch process[2] which would be fully powered by clean electricity [33].

Policy Considerations

Policy on biofuels should keep the following in mind:

- Land and Water Use
- Types of Crops Used
- Fertilizer Production

As mentioned above, the type of land usage will determine how beneficial biofuels actually are. If a biome such as a rainforest is cleared for biomass growth, this will ruin any potential emissions reductions. Likewise, if a previously dedicated food crop is then directed towards biomass growth, this will cause food competition and ruin the overall benefits of biofuels. Water usage will also be problematic, especially in areas facing droughts. If wastewater or saltwater can be used instead of freshwater, then they should absolutely use the alternative option. Fertilizer usage for algae growth may also pose a problem, as mentioned above. More research should be done to provide greener ways of producing fertilizer.

[2] The Haber-Bosch Process is one of the most popular ways to produce NH3. The process needs a temperature of 400°C and a pressure of about 150 bar to perform the reaction properly. [34]

Considerations for Decarbonizing Different Transportation Use Cases

Light Duty Vehicles

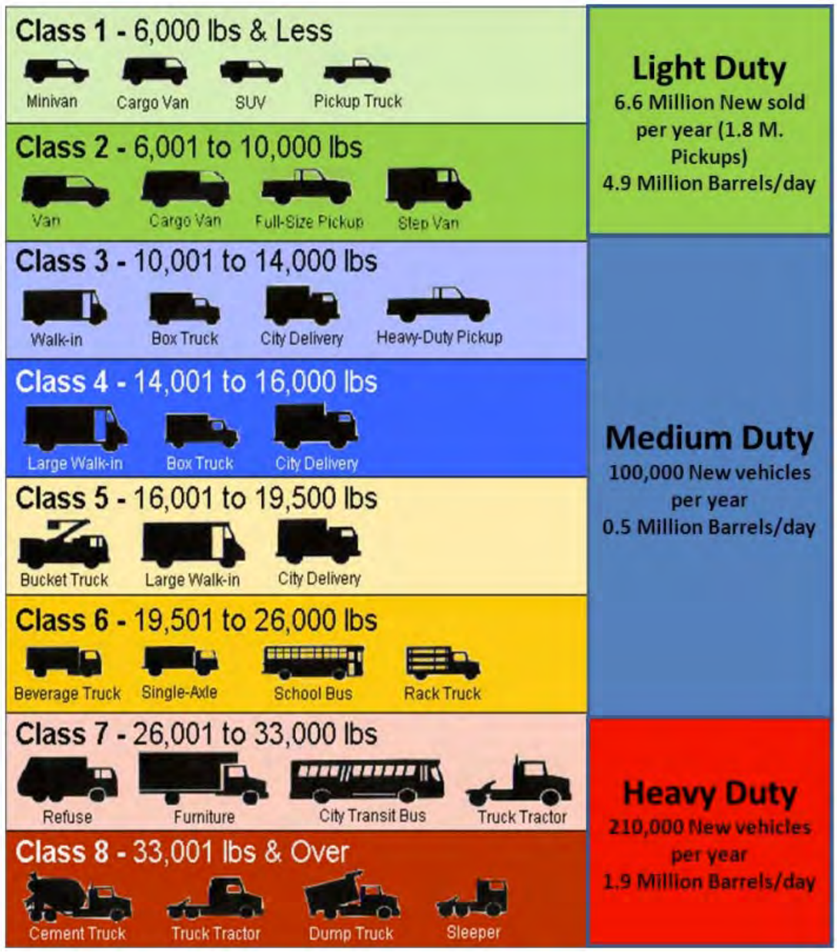

Figure 4: Different classifications of vehicles [35]

This category includes Class 1 and 2 vehicles, which range from 0-10,000 pounds [35]. Despite this category containing the lightest vehicles, it is responsible for 58% of current transportation GHG emissions in the US [36]. Luckily, light duty vehicles (LDVs) offer some of the easiest options for decarbonization. Because these vehicles are in the lightest category, they can easily use battery and hydrogen technologies.

BEVs are already leading the race to decarbonize light duty vehicles. The sale of BEVs in the US nearly doubled between 2020 and 2021, going from approximately 251,000 to 473,000 [37]. Projections estimate that BEVs could make up anywhere from 15% to nearly 50% of the global fleet by 2040 [38], [39]. BEV market-ready technology encompasses several types of light duty vehicles, from sedans to pickup trucks and electric buses. Battery powered vehicles have the potential to significantly reduce GHG emissions over the lifetime of the vehicles. Sedans show a savings of 45 metric tons (mt), SUVs save 56 mt, and pickup trucks save 74 mt of carbon dioxide equivalent over their lifetime as compared to their gasoline powered counterparts [36].

BEVs should not be the only technology considered for LDVs. FCEVs are also a good opportunity for this category of vehicles. They utilize hydrogen and convert it to electrical energy in a fuel cell, which leads to no tailpipe emissions and allows for a driving range of over 300 miles [40]. FCEVs also have a fueling time similar to gasoline powered vehicles, offering an advantage in that respect when compared to EVs. Additionally, although BEVs are sufficient for the majority of individuals driving needs, those that may need to use their vehicle in a more rugged manner, such as long-distance towing, may find FCEVs more attractive. The main problems with FCEVs are that green hydrogen is still too expensive, very few FCEV models are available, and hydrogen infrastructure is not built out.

As can be seen in the figure below, the cost of hydrogen fuel is one of the main reasons that FCEV owners see an increase in total cost of ownership compared to an ICEV. The other large cost difference is in the incremental vehicle price. FCEVs are significantly more expensive than other types of vehicles available now. Hopefully, as more FCEVs are developed, the upfront cost of the vehicles will be reduced so they can compete with ICEVs. And as FCEVs become more common, hydrogen fueling stations will need to expand. There are currently zero publicly accessible hydrogen refueling stations outside of the state of California in the continental United States [41].

Total cost of ownership over 10 years for individual ZEV and PHEV buyer compared to baseline ICEV, 2026 MY Passenger Car (PC) in Single-Family Home (SFH) *

	BEV (300-mile range)		FCEV	PHEV
	With home charger	No home charger		With home charger
Incremental vehicle price	$ 3,102	$ 3,102	$ 10,448	$ 4,681
Home Level 2 circuit (not including the charger)	$ 680			$ 680
Finance costs & sales tax (for incr veh price and Level 2 circuit)	$ 798	$ 655	$ 2,205	$ 1,131
Incremental Fuel costs	$ (5,068)	$ (3,306)	$ 8,670	$ (649)
Incremental Maintenance costs	$ (4,540)	$ (4,540)	$ (1,249)	$ (1,249)
Incremental Insurance	$ 631	$ 631	$ 2,124	$ 952
Incremental Registration	$ 758	$ 758	$ 952	$ 800
Total (10 years)	$ (4,267)	$ (3,216)	$ 21,416	$ 5,456
Initial annual savings	**1 year**	**1 year**	**>10 years**	**>10 years**

*Finance costs include a 5-year loan at 5-percent interest; operation and ownership costs over 10 years (~150,000 miles) shown as net present value for 2026 at a discount rate of 10-percent.

Figure 5: Total Cost of Ownership comparison for BEV, FCEV, and PHEV compared to an ICEV in 2026 [42]

Medium and Heavy-Duty Vehicles

Medium duty vehicles (MDV's) are defined as Class 3 through Class 6, or 14,001 to 26,000 pounds and heavy-duty vehicles (HDV's) are the remainder of on-road vehicles, including Class 7 and 8, or anything over 26,001 pounds [35]. In both of these categories, the use case is what determines the best mode of decarbonization. Mainly, the distance a vehicle will need to travel and the travel pattern it follows will determine if battery or hydrogen will be best.

An easy opportunity to electrify part of this sector is in buses and local delivery vehicles, i.e. vehicles that follow specific and repetitive paths over short or medium distances. Since they mostly stay in the same area, there is frequent opportunity for recharging or refueling [9]. Electric buses have been widely demonstrated as market ready, and China already has around 400,000 electric buses in their fleet.

A more difficult use case for battery electric technology is trucking which requires long distance traveling and less regular routes. Some companies have still decided to test BEVs in this category, including Amazon, PepsiCo, and Daimler Trucks, the largest truck maker in the US [43]. With current technology though, a battery with 500 miles of range for a semi-truck would weigh around 10,000 pounds, significantly reducing the amount of payload it can carry [9],[44]. This also changes the charging time to around 20 hours using a typical LDV fast charger (max 350 kW) [45]. The easy solution is to reduce the range that the truck has, therefore reducing the battery size. This is not ideal for long-distance trucking applications though, and feeds into the "range anxiety" that many companies are facing. Significant advances in fast charging technology or on route charging would be needed to reduce charging times for long distance trucking. And advancements in battery technology, including lighter batteries, is necessary to increase the range while not interfering with the payload.

Fuel cells are another strong option for trucking that requires longer distances driven each day. Fuel cells offer a larger range potential than batteries do, with estimates showing that fuel cells can reach up to 600 miles of range, as shown in Figure 6 [5]. This number is helping significantly reduce range anxiety while not drastically increasing the weight of the vehicles. It is highly likely that FCV's will be more effective and efficient for long hauls, since batteries are not reasonably able to achieve these distances. However, with the current dearth of hydrogen refueling stations outside of California, it is currently impossible for fuel cell trucks to be viable options for long haul trucking, as there is simply nowhere for them to refuel. Increasing hydrogen refueling, especially along heavily used trucking routes, will be essential if this technology is going to live up to its potential as a decarbonized option for long distance travel.

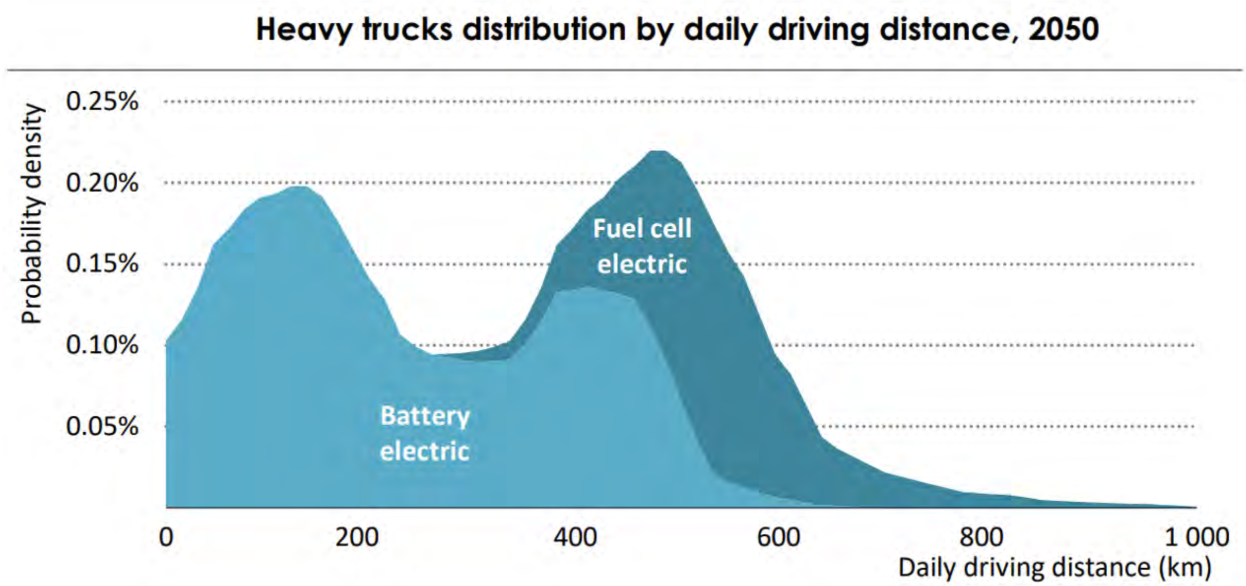

Figure 6: Probability versus distance for battery or fuel cell heavy trucks [5]

Aviation

Aviation was responsible for approximately 915 million tons of CO_2 emissions in 2019, which makes up 12% of transportation emissions, or 2-4% of all worldwide GHG emissions [46]. Unfortunately, aviation will be one of the most challenging areas to decarbonize since there are limited technologies available in this sector. Planes must be capable of traveling large distances and carrying a large amount of weight. Because of these requirements, it is not feasible to use battery or fuel cell technology in a plane. A battery large enough to power a plane would be far too heavy to be realistic for long haul commercial flying, and a fuel cell does not provide enough thrust to drive a plane into the air [9]. This essentially leaves the direct combustion of hydrogen or biofuels as the main opportunities to decarbonize aviation.

Direct combustion of hydrogen has already shown some potential issues. Hydrogen is four times less energy dense by volume than aviation fuel, meaning that a significantly larger volume of hydrogen would be necessary to provide the same amount of energy [9]. Because of this, direct combustion of hydrogen would not be usable in existing planes because the tank will not be large enough. So, unless newer planes are engineered with larger tanks specifically for hydrogen, biofuels are really the only viable option. The IEA predicts that biofuels will play a major role in the decarbonization of the aviation sector especially after 2030. By 2050, biokerosene, a form of sustainable aviation fuel (SAF) is expected to supply 45% of aviation fuel demand [5]. The use of biofuels in this industry has the potential to reduce emissions by up to 80% over their lifecycle usage [46]. However, as discussed earlier, there is much work that needs to be done to develop economically viable and environmentally sustainable biofuel options, so much progress is needed to decarbonize this important sector.

Marine

Similar to aviation, the marine sector does not have many technologies available to decarbonize. The maritime sector makes up around 2.5% of worldwide emissions currently, and this industry is also expected to grow in the next several decades [9]. The International Maritime Organization (IMO) has already set into motion a plan to decarbonize their sector. In the near time, ships with increased efficiency will be required [47]. Many ships are also switching to liquefied natural gas (LNG) because of recent sulfur restrictions placed on marine fuels. Using LNG shows potential to reduce emissions by approximately 10-28%, with the wide range being due to potential methane emissions from evaporating fuel.

For long term decarbonization, alternative fuels such as biofuels, hydrogen, and ammonia will need to come into play. The IEA estimates that hydrogen and ammonia will make up most of marine fuel demand in 2050, coming in at around 60%, while biofuels are around 20% [5]. Similar to aviation, much work needs to be done in order to develop fully decarbonized options for the marine sector.

Conclusions

There are lots of opportunities for decarbonization with technologies that we have access to right now, and there are also plenty of technologies that still need breakthroughs before they will be feasible. Efforts should be directed at increasing the implementation of these existing technologies as quickly as possible, especially in the light duty sector, which currently has the most opportunities available for decarbonization. As more technologies become available for the medium and heavy-duty sectors, as well as for aviation and maritime, these should also be pushed into implementation. Of course, this means that research and development in these sectors will need to be a top priority.

Policies related to battery, hydrogen, and biofuel usage in transportation should ensure that while these technologies will be implemented quickly, they are still implemented in the cleanest ways possible. Policies centered around battery technology should focus on the materials needed for batteries, and the security of our supply chain for these materials. Research on alternative materials should also be a priority. As hydrogen demand begins to grow, it will be very important that hydrogen supply is implemented in the cleanest way possible. Policy for hydrogen should ensure that we do not remain dependent on fossil fuel derived hydrogen, pushing for green hydrogen first and using blue hydrogen when necessary. And as biofuels become more widespread, policy should ensure that the correct types of feedstocks are being utilized and that biofuels are only being used where they are needed most.

References

1. J. Korn, Hertz to buy up to 65,000 electric cars from polestar, CNN. (2022). https://www.cnn.com/2022/04/04/tech/polestar-hertz-purchase/index.html (accessed June 14, 2022).
2. Our commitment to fly net zero by 2050, IATA. (2021). https://www.iata.org/en/programs/environment/flynetzero/ (accessed June 14, 2022).
3. IMO, ISWG-GHG 12: Reducing GHG emissions from ships, International Maritime Organization. (2022). https://www.imo.org/en/MediaCentre/PressBriefings/pages/ISWGHGMay2022.aspx (accessed June 14, 2022).
4. Sources of Greenhouse Gas Emissions, EPA. (2022). https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions (accessed June 14, 2022).
5. Net zero by 2050 - A Roadmap for the Global Energy Sector, (2021). https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf (accessed June 23, 2022).
6. How long does it take to charge an electric car?, Pod Point. (2021). https://pod-point.com/guides/driver/how-long-to-charge-an-electric-car#:~:text=A%20typical%20electric%20car%20(60kWh,with%20a%2050kW%20rapid%20charger (accessed June 14, 2022).
7. M. Blonsky, P. Munankarmi, S. Balamurugan, Incorporating residential smart electric vehicle charging in ... - NREL, (2021). https://www.nrel.gov/docs/fy21osti/78540.pdf (accessed June 14, 2022).
8. L. Wang, Z. Qin, T. Slangen, P. Bauer, T. van Wijk, Grid impact of electric vehicle fast charging stations: Trends, standards, issues and mitigation measures - an overview, IEEE Xplore. (2021). https://ieeexplore.ieee.org/document/9336258 (accessed June 14, 2022).
9. S. Gross, The challenge of decarbonizing heavy transport, Brookings. (2022). https://www.brookings.edu/research/the-challenge-of-decarbonizing-heavy-transport/ (accessed June 14, 2022).
10. M. Eberhard, A bit about batteries, Electric Cars, Solar & Clean Energy. (2010). https://www.tesla.com/pt_PT/blog/bit-about-batteries#:~:text=But%20here%20are%20a%20few,and%20weighs%20about%20900%20pounds (accessed June 14, 2022).
11. D. Castelvecchi, Electric cars and batteries: How will the world produce enough?, Nature News. (2021). https://www.nature.com/articles/d41586-021-02222-1 (accessed June 14, 2022).

12. The hydrogen colour spectrum, National Grid Group. (n.d.). https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum (accessed June 14, 2022).
13. Hydrogen shot, Energy.gov. (2021). https://www.energy.gov/eere/fuelcells/hydrogen-shot (accessed June 14, 2022).
14. D. Gielen, E. Taibi, R. Miranda, Hydrogen: A renewable energy perspective, IRENA International Renewable Energy Agency. (2018). https://www.irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective (accessed June 14, 2022).
15. A. Elgowainy, J. Han, U. Lee, J. Li, J. Dunn, M. Wang, Life-cycle analysis of water consumption for hydrogen production - energy, (2016). https://www.hydrogen.energy.gov/pdfs/review16/sa039_elgowainy_2016_o.pdf (accessed June 14, 2022).
16. R.R. Beswick, A.M. Oliveira, Y. Yan, Does the green hydrogen economy have a water problem?, ACS Energy Letters. 6 (2021) 3167–3169. doi:10.1021/acsenergylett.1c01375.
17. D. McFarlane, GPI releases carbon and hydrogen hubs Atlas for US decarbonization, Great Plains Institute. (2022). https://betterenergy.org/blog/gpi-carbon-and-hydrogen-hubs-atlas/ (accessed June 14, 2022).
18. Hydrogen Energy Map Tracker: Pillsbury Law, Hydrogen Energy Map Tracker | Pillsbury Law. (2022). https://www.thehydrogenmap.com/?type=13 (accessed June 14, 2022).
19. T. Ajayi, J.S. Gomes, A. Bera, A review of CO2 Storage in geological formations emphasizing modeling, monitoring and capacity estimation approaches, SpringerLink. (2019). https://link.springer.com/article/10.1007/s12182-019-0340-8 (accessed June 14, 2022).
20. J. Robinson, Cost, logistics offer 'Blue Hydrogen' market advantages over 'green' alternative, S&P Global Commodity Insights. (2020). https://www.spglobal.com/commodity-insights/en/market-insights/latest-news/electric-power/031920-cost-logistics-offer-blue-hydrogen-market-advantages-over-green-alternative (accessed June 14, 2022).
21. Reclaiming hydrogen for a renewable future, (2021). https://earthjustice.org/sites/default/files/files/hydrogen_earthjustice_2021.pdf (accessed June 23, 2022).
22. Stations map, Stations Map | H2 Station Maps. (2022). https://h2stationmaps.com/ (accessed June 18, 2022).
23. Economics of Biofuels, EPA. (2013). https://www.epa.gov/environmental-economics/economics-biofuels (accessed June 18, 2022).
24. Biofuels Explained, Biofuels Explained - U.S. Energy Information Administration (EIA). (2022). https://www.eia.gov/energyexplained/biofuels/#:~:text=Biofuels%20are%20transportation%20fuels%20such,be%20used%20on%20their%20own (accessed June 18, 2022).

25. J. Conca, It's Final -- Corn Ethanol Is Of No Use, Forbes. (2022). https://www.forbes.com/sites/jamesconca/2014/04/20/its-final-corn-ethanol-is-of-no-use/?sh=649b5fc167d3 (accessed June 18, 2022).
26. Biofuels & Greenhouse Gas Emissions: Myths versus facts - energy, (n.d.). https://www.energy.gov/sites/prod/files/edg/media/BiofuelsMythVFact.pdf (accessed June 18, 2022).
27. N. Tripathi, C.D. Hills, R.S. Singh, C.J. Atkinson, Biomass waste utilisation in low-carbon products: Harnessing A Major Potential Resource, Npj Climate and Atmospheric Science. 2 (2019). doi:10.1038/s41612-019-0093-5.
28. Feedstock logistics, Energy.gov. (n.d.). https://www.energy.gov/eere/bioenergy/feedstock-logistics (accessed June 20, 2022).
29. A promising oil alternative: Algae Energy, The Washington Post. (2008). https://www.washingtonpost.com/wp-dyn/content/article/2008/01/03/AR2008010303907.html?noredirect=on (accessed June 20, 2022).
30. Third generation biofuels, Biofuel.org.uk. (n.d.). https://biofuel.org.uk/third-generation-biofuels.html (accessed June 20, 2022).
31. Y. Dahman, K. Syed, S. Begum, P. Roy, B. Mohtasebi, Biofuels, Biomass, Biopolymer-Based Materials, and Bioenergy. (2019) 277–325. doi:10.1016/b978-0-08-102426-3.00014-x.
32. Nagarajan, R., Jain, A., Vora, K.: Biodiesel from Microalgae. SAE Tech. Pap. 2017-Janua, 601–628 (2017). https://doi.org/10.4271/2017-26-0077
33. Green Ammonia: Royal Society, Green Ammonia | Royal Society. (2020). https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/green-ammonia/#:~:text=What%20is%20green%20ammonia%3F,nitrogen%20separated%20from%20the%20air. (accessed June 20, 2022).
34. A. Darmawan, M. Aziz, M.W. Ajiwibowo, M.K. Biddinika, K. Tokimatsu, B. Lokahita, Integrated ammonia production from the Empty Fruit Bunch, Innovative Energy Conversion from Biomass Waste. (2022) 149–185. doi:10.1016/b978-0-323-85477-1.00006-3.
35. Vehicle Technologies Office - Energy, (2013). https://www.energy.gov/sites/prod/files/2014/03/f13/wr_trucks_hdvehicles.pdf (accessed June 20, 2022).
36. Greater Greenhouse Gas reductions for pickup truck electrification than for other light-duty vehicles, ScienceDaily. (2022). https://www.sciencedaily.com/releases/2022/03/220304112018.htm (accessed June 20, 2022).
37. Electric vehicle sales dashboard, Electric-Vehicle-Sales-Dashboard. (n.d.). https://www.autosinnovate.org/resources/electric-vehicle-sales-dashboard (accessed June 21, 2022).

38. Maps and data - U.S. plug-in electric vehicle sales by model, Alternative Fuels Data Center: Maps and Data - U.S. Plug-in Electric Vehicle Sales by Model. (2020). https://afdc.energy.gov/data/10567 (accessed June 21, 2022).
39. 2019 World Oil Outlook 2040, OPEC. (2019). https://www.opec.org/opec_web/static_files_project/media/downloads/publications/WOO_2019.pdf (accessed June 21, 2022).
40. Fuel Cell Electric vehicles, Alternative Fuels Data Center: Fuel Cell Electric Vehicles. (n.d.). https://afdc.energy.gov/vehicles/fuel_cell.html (accessed June 21, 2022).
41. Hydrogen fueling station locations, Alternative Fuels Data Center: Hydrogen Fueling Station Locations. (n.d.). https://afdc.energy.gov/fuels/hydrogen_locations.html#/find/nearest?fuel=HY (accessed June 21, 2022).
42. California Air Resources Board Public Hearing to consider the proposed ..., ACC II ISOR. (2022). https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/isor.pdf (accessed June 22, 2022).
43. J. Stinson, Battery-electric vs. Hydrogen Trucks: The debate heads into 2022, Utility Dive. (2022). https://www.utilitydive.com/news/Trucking-battery-electric-versus-fuel-cell-hydrogen/617722/?utm_source=Sailthru&utm_medium=email&utm_campaign=Issue%3A+2022-02-01+Utility+Dive+Newsletter+%5Bissue%3A39480%5D&utm_term=Utility+Dive (accessed June 21, 2022).
44. M. Kah, SIPA Center on Global Energy Policy, Columbia. (2019). https://www.energypolicy.columbia.edu/research/global-energy-dialogue/prospects-global-truck-electrification-and-autonomy-and-new-delivery-models (accessed June 22, 2022).
45. Electric vehicle charging speeds, U.S. Department of Transportation. (2022). https://www.transportation.gov/rural/ev/toolkit/ev-basics/charging-speeds (accessed June 22, 2022).
46. Facts and Figures, Facts & Figures. (2020). https://www.atag.org/facts-figures.html (accessed April 19, 2022).
47. Initial IMO GHG strategy, International Maritime Organization. (n.d.). https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx (accessed June 22, 2022).